International Conference-School on Plasma Physics and Controlled Fusion

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BOOK OF ABSTRACTS

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CONTENTS

International Conference and School on Plasma Physics and Controlled Fusion ICPPCF-2018 is dedicated to the centenary of the National Academy of Sciences of Ukraine and 90-th anniversary of the National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT). This Conference follows the previous International Conferences, which were held in Alushta in 1998, 2000, 2002, 2004, 2006, 2008, 2010, 2012 and in Kharkiv in 2014 and 2016. There were organized by the National Science Center "Kharkov Institute of Physics and Technology" of the National Academy of Science, N.N. Bogolyubov Institute for Theoretical Physics and V.N. Karazin Kharkiv National University. More than 140 participants (from 13 countries) presented about 200 reports during previous ICPPCF-2016 Conference

ICPPCF-2018 is sponsored by the National Academy of Science of Ukraine, National Science Center "Kharkov Institute of Physics and Technology", Bogolyubov Institute for Theoretical Physics and European Physical Society (EPS). About 200 abstracts were submitted by Ukrainian and foreign authors and selected by the Program Committee for presentation at the ICPPCF-2018 Conference. All the abstracts have been divided into 7 groups according to the topics of the Conference Program.

Since the abstracts presented in this volume were prepared in camera-ready form, and the time for the technical editing was very limited, the Editors and the Publishing Office do not take responsibility for eventual errors. Hence, all the questions referring to the context or numerical data should be addressed to the authors directly.

We hope that the contributed papers and invited talks, to be given at the Conference, will supply new valuable information about the present status of plasma physics and controlled fusion research. We also hope that the Conference will promote further development of plasma physics and fusion oriented research as well as the scientific collaboration among different plasma research groups in Ukraine and abroad.

Program and Local Organizing Committees

I-01

ELECTROMAGNETIC FIELD ENERGY AND RADIATION INTENSITY IN THE MEDIUM WITH TEMPORAL AND SPATIAL DISPERSION OUTSIDE THE TRANSPARENCY DOMAIN

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It is well known that the energy density of an electromagnetic wave in a medium with spatial and temporal dispersion can be consistently defined only in the transparency domain (see, for example, [1–4]). At the same time there are no general relations for the energy of electromagnetic field in the absorptive regions. Although the general idea of electromagnetic field energy description was formulated many years ago [5, 6] and some specific calculations for the medium with frequency dispersion outside the transparency domain were made [7–11] this problem requires further consideration. The matter is that the energy of an electromagnetic perturbation contains the “pure” electromagnetic energy and the kinetic energy of charge carriers obtained due to their motion in the electromagnetic field. If neutral particles (i.e. atoms or molecules) are present, the additional potential energy acquired by bound electrons in such field also should be added [8–11].On the other hand, in the general case of a medium with temporal (or, temporal and spatial) dispersion, the macroscopic Maxwell equations generate a Pointing-like equation that does not provide explicit identification of the total energy of electromagnetic perturbations in contrast to the case of a nondispersive medium for which the total energy of the field is well defined. Consistent results can be obtained from such equations only for the transparency domain or for the case of weak absorption [8]. The purpose of the present contribution is to derive a general relation for the energy of electromagnetic perturbation in the medium with temporal and spatial dispersion. We use the idea proposed in [5–9], namely we treat the energy of the perturbation as a sum of the electromagnetic field energy and particle energy (both kinetic and potential) acquired by the particles in the field. It is shown that charged particle contribution to the energy of electromagnetic perturbations in the general case can be described in terms of a bilinear combination of the dielectric polarizability of the medium. The explicit form of such contribution is found. The relations thus obtained are applied to calculate the fluctuation field energy and to generalize the Planck formula and the Kirkhoff law for the case of non-transparent medium with spatial and temporal dispersion.

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I-02

PROGRESS IN EUROPEAN FUSION RESEARCH

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The **European Roadmap to the realisation of fusion energy** breaks the quest for fusion energy into eight missions. For each mission, it reviews the current status of research, identifies open issues, proposes a research and development programme and estimates the required resources. It points out the needs to intensify industrial involvement and to seek all opportunities for collaboration outside Europe.

A long-term perspective on fusion is mandatory since Europe has a leading position in this field and major expectations have grown in other ITER parties on fusion as a sustainable and secure energy source. The roadmap covers three periods: The short term which is roughly until 2030, the medium term until 2040 and the long term.

ITER is the key facility of the roadmap as it is expected to achieve most of the important milestones on the path to fusion power. Thus, the vast majority of resources proposed in the short term are dedicated to ITER and its accompanying experiments. The medium term is focussed on taking ITER into operation and bringing it to full power, as well as on preparing the construction of a demonstration power plant DEMO, which will for the first time supply fusion electricity to the grid. Building and operating DEMO is the subject of the last roadmap phase: the long term. It might be clear that the Fusion Roadmap is tightly connected to the ITER schedule. A number of key milestones are the first operation of ITER (presently foreseen in 2025), the start of the DT operation foreseen in 2035 and reaching the full performance at which the thermal fusion power is 10 times the power put in to the plasma.

DEMO will provide first electricity to the grid. The Engineering Design Activity will start a few years after the first ITER plasma, while the start of the construction phase will be a few years after ITER reaches full performance. In this way ITER can give viable input to the design and development of DEMO. Because the neutron fluence in DEMO will be much higher than in ITER (atoms in the plasma facing components of DEMO will undergo 50-100 displacements during the full operation life time, compared to only 1 displacement in ITER), it is important to develop and validate materials that can handle these very high neutron loads. For the testing of the materials a dedicated 14 MeV neutron source is needed. This **DEMO Oriented Neutron Source (DONES)** is therefore an important facility to support the fusion roadmap

The presentation will focus on the strategy behind the fusion roadmap and will describe the major challenges that need to be tackled on the road towards fusion electricity. Encouraging recent results will be given to demonstrate the outcome of the focused approach in European fusion research.

I-03

COMPREHENIVE SIMULATIONS OF PLASMA TRANSIENT EVENTS AND THEIR EFFECTS ON ALL PLASMA FACING AND NEARBY COMPONENTS

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Significant efforts are being made to mitigate transient events during disruptive operations in ITER device. These transient events include disruptions, edge-localized modes (ELMs), vertical displacement events (VDEs), and runaway electrons. A reliable and acceptable ITER design must however, withstand few unmitigated transient events. In the case of a hard disruption or a giant ELM near the strike point on the divertor plate will melt and vaporize the divertor material shortly after the start of the disruption. Continuous heating of this vaporized material will ionize and create mini-plasma of the divertor plate. The evolution of this secondary plasma, its intense radiation in the divertor area, and its propagation through the SOL in the strong magnetic field may expose nearby and hidden components as well as the first walls to high heat loads. We have developed and implemented extensive models in our comprehensive integrated HEIGHTS package for 3D simulation of detailed photon and particle transport in the evolved secondary plasma during various instabilities. HEIGHTS is capable to simulate full 3D real ITER geometry, including all fine details of the cassette and first wall designs, to assess the damage of these components resulting from various plasma instabilities. Our preliminary simulations showed significant increase of the radiation and scattered particle fluxes to various components as a result of this secondary plasma evolution. This intense radiation and particle sources could seriously damage most hidden and nearby components such as baffles, reflector plates, stainless steel umbrella tubes, dome structure, and even the Be first wall. HEIGHTS predicted, for the first time, the fine details of heat loads and temperatures evolution of both divertor and all nearby components due to transient events of disruptions and ELMs. This secondary radiation generated from the divertor material showed to be the cause of serious damage to internal components that were not directly exposed to the DT disrupting plasma. Current ITER divertor design needs to be changed or modified to be able to mitigate the damage produced from unmitigated disruptions. A single unmitigated disruption event can cause serious damage to many components that were not directly exposed to disruptions causing significant downtime and costly repair.

I-04

OVERVIEW OF KINR RESULTS OBTAINED WITHIN EUROFUSION PROJECTS

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Kyiv Institute for Nuclear Research takes part in three work packages of EUROfusion Consortium: JET1, MST2, and S2. The following topics are covered: (i) Spatial channelling in toroidal plasmas; (ii) Sawtooth oscillations and concomitant transport of energetic ions in tokamaks; (iii) Alfven eigenmodes during ECRH; (iv) ICRH avoiding production of trapped particles.

The main results obtained will be reviewed within this presentation. Details can be found in the following works (they are available also on the EUROfusion pinboard):

1. Ya.I. Kolesnichenko, V.V. Lutsenko, T.S. Rudenko and P. Helander "*Ways to improve the confinement of fast ions in stellarators by RF waves: general analysis and application to Wendelstein 7-X*" , 2017 Nucl. Fusion **57,** 066004.
2. Ya.I. Kolesnichenko, V.V. Lutsenko, M.H. Tyshchenko, H. Weisen, Yu.V. Yakovenko and JET Contributors "*Analysis of possible improvement of the plasma performance in JET due to the inward spatial channelling of fast-ion energy"*, 2018 Nucl. Fusion **58,** 076012.
3. Yu.V. Yakovenko, V.V. Lutsenko, B.S. Lepiavko, Ya.I. Kolesnichenko, V. Kiptily, L. Giacomelli, T. Craciunescu, and JET contributors , *Simulations of the sawtooth-induced redistribution of fast ions in JET and ITER*, 2018, 27th IAEA Fusion Energy Conference, Ahmedabad, India, accepted.
4. V.S. Marchenko and S.N. Reznik, *Non-thermal effect of electron cyclotron resonance heating on the Alfven eigenmodes,* 2018 Physics of Plasmas, accepted.
5. Ya.I. Kolesnichenko, A.V. Tykhyy. "*Temperature gradient driven Alfvén instability producing inward energy flux in stellarators*", 2018 Phys. Lett. A, accepted.
6. Ya.I. Kolesnichenko, A.V. Tykhyy, 2018 "*Landau damping of Alfvénic modes in stellarators*", Plasma Phys. Contr. Fusion, submitted.

I-05

EFFECT OF PRE-FORMED PLASMAS ON TARGET NORMAL SHEATH ACCELERATION FOR EFFICIENT LASER-DRIVEN NEUTRON SOURCES

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Efficient laser ion acceleration is essential for applications such as laser neutron source and laser-accelerated ion based fast-ignition in inertial confinement fusion (ICF). We investigated the effects of pre-formed plasma profiles at both sides of the target on the Target Normal Sheath Acceleration (TNSA) of deuteron ions. We have developed two-dimensional radiation hydrodynamic simulations package. Initial results show a largely deformed target and a long scale length of pre-formed plasma at the front of the target foil, and a dip in the temporal evolution of the pre-formed plasma scale length at rear side. The PIC simulations for selected initial conditions confirmed that the pre-formed plasma profile can be optimized for efficient TNSA acceleration of deuteron ions. Larger amount and maximum energy of the accelerated energetic deuteron ions can be obtained by optimizing the pre-formed plasma condition at both sides of the target simultaneously. Detail computational results of radiation hydrodynamic simulations of the foil target irradiated by the pre-pulse of ultra-intense laser, optimization of pre-formed plasmas for efficient TNSA, and the interaction of ultra-intense laser with the plasmas will be presented. Furthermore, in addition to the application of neutron sources, the pre-formed plasma characteristics related to the warm dense matter (WDM) research and fast ignition of ICF will be discussed.

I-06

FIRST DIVERTOR OPERATION ON THE W7-X: HIGHER PLASMA DENSITIES, LONGER DISCHARGES

A. Mishchenko for the W7-X Team

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A summary of the recent experimental campaign (OP1.2a) in the stellarator Wendelstein 7-X (W7-X) is given. Fifteen weeks of operation were conducted and major machine components worked without failures allowing an efficient use of the machine time. After the previous campaign, ending in March 2016, W7-X was equipped with a new island divertor with ten divertor units installed. The test divertor units lack water-cooling and are more tolerant to unexpected loads and thus can be used for first divertor tests. The observed divertor temperatures matched the theoretical predictions, the heat loads were under control, longer discharges of up to 30 s became routine by the end of the campaign. With the longer discharges, the divertor allowed deposit of up to 75 MJ of heating energy in W7-X, more than 18 times larger than the energy limit of the previous campaign. In order to successively extend the heating power and pulse lengths, small deviations from the ideal magnetic fields, caused by small inaccuracies in the construction of the superconducting coils and leading to asymmetric power loads, needed to be overcome. Supplementary trim coils have been used to correct small magnetic field errors, successfully equalizing the heat load to each divertor unit as confirmed by the infrared cameras. With these symmetrized power loads it was possible to extend the heating power and increase the plasma density up to 1.4×10^{20} m^{-3} in the core, which is more than 4 times larger than the result of the previous campaign. This achievement was possible due to the new pellet injection system and a new X2-O2 heating scheme developed for the high-density operation. The microwave beam polarization is changed after the initial low-density phase creating plasmas with excellent energy confinement and high ion temperatures. The capability of plasma operation at high plasma density appears to be a key ingredient to operate the divertor under favorable detachment conditions. In this campaign, we could reach stable, complete detachment for several seconds reducing the power loads by an order of magnitude on all 10 divertors. The extension of achievable plasma densities at different heating powers allowed crucial aspects of stellarator optimization to be addressed such as the control of internal currents and stellarator-specific neoclassical heat transport. First insights into plasma turbulence and the flows of impurities were possible with new and upgraded diagnostics systems. All experiments performed included variations of the magnetic configuration which is an important parameter influencing the plasma transport and stability properties. In summary, the 2017 experimental campaign has been successfully completed.

I-07

STELLARATOR RESEARCH AT IPP KIPT: STATUS AND PROSPECTS

V.E. Moiseenko, G.P. Glazunov, A.V. Lozin, A.L. Konotopskiy, D.I. Baron, A.A. Beletskii, M.N. Bondarenko, V.V. Chechkin, M.B. Dreval, L.I. Grigor'eva, M.M. Kozulya, S.M. Maznichenko, Yu. K. Mironov, R.O. Pavlichenko, V.S. Romanov, A.N. Shapoval, V.B. Korovin, V.G. Konovalov, N.V. Zamanov, E.V. Turianska, Yu.S. Kulyk, T. Wauters[1], A.I. Lyssoivan[1], I.E. Garkusha and the Uragan Team

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For the recent Uragan-2M campaign, a new variant of the movable B_4C-limiter has been designed, manufactured and installed. The influence of the limiter position relative to the minor axis was investigated on plasma parameters in the regime of plasma heating with pulsed RF discharge. The CIII line intensity essentially decreases and OV line increases under limiter positioning at the distance of 15 cm from the wall. The soft X-ray signals appreciably increase at the same time. This can be explained by input of sputtered boron carbide into plasma or increase of plasma temperature.

An appearance of various 1-20 kHz oscillations was observed in Uragan-2M. Two multichannel pinhole cameras were recently installed in U-2M for monitoring the oscillations of visible light emission from two positions in the same plasma cross-section. New electronics was designed and manufactured for measuring the plasma density, electron temperature and plasma potential profiles with high time resolution in cold, low density RF conditioning discharges using triple Langmuir probe technique.

Three-Half-Turn (THT) ICRF antennas that have 3 phi-phased straps oriented perpendicular to the magnetic field lines are used for plasma heating in the Uragan-3M and the Uragan-2M. It is found that THT antennas are capable of creating dense plasma at slightly decreased magnetic fields compared to regular regime, but with longer plasma production time. Such feature is investigated in both experimental devices.

The thermal desorption method has been developed for diagnosing impurity level on the Uragan-2M vacuum chamber surfaces *in situ*. Using this method the investigations of outgassing rate were carried out and estimation of the number of molecules layers was done in the Uragan-2M torsatron after wall conditioning by RF plasma discharge in different regimes combined with pumping. With this method the influence of plasma treatment on the hydrogen retention and release from 321 (12X18H10T) stainless steel was examined under different kinds of plasma conditions. The contributions of RF pulsed discharges during wall cleaning and RF pulsed plasma heating regime to the hydrogen release were evaluated in the Uragan-2M stellarator.

A numerical model of RF plasma production in stellarators in the ion cyclotron and electron-cyclotron frequency ranges is developed. This model is aimed for numerical analysis of the plasma discharge for the vacuum chamber wall conditioning. New features of the model presented are account of molecular ions, H_2^+ and H_3^+, in the particle balance equations. The radio-frequency module of the code is modified accordingly. A new module that calculates second harmonic electron cyclotron heating in the case of weak wave damping is created and incorporated into the code.

Other developments including Uragan-2M refurbishment, preparations to experiments in support of fusion-fission hybrid concept and diagnostics improvements are discussed. The prospects of stellarator research at IPP KIPT are strongly determined by integration of the studies to the Eurofusion Consortium activity within S1 work package.

I-08

ION CYCLOTRON RANGE OF FREQUENCY HEATING EXPERIMENTS IN LHD

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In the Large Helical Device (LHD), the ion cyclotron range of frequencies (ICRF) heating has been carried out since 1998. LHD is super-conducting helical device. The major and the minor radius are 3.9 m and 0.65 m, respectively. The magnetic field strength is less than 3 T. The ICRF antenna is based on a single strap current loop and the two straps in poloidal or toroidal direction make one antenna pair. Three antenna pairs were maximum available. The wave frequency is 25 to 100 MHz. The maximum injected power is 4.5 MW.

Minority heating was mainly adopted. The majority and the minority ion species are helium and hydrogen, respectively. The magnetic field strength is 2.75 T and the wave frequency is 38.47 MHz. The ion cyclotron resonance layers of hydrogen ion are located at slightly off-axis and ion cyclotron heating by hydrogen ion is expected. It was experimentally shown that minority heating worked effectively in LHD. The LHD plasma was sustained by the ICRF heating only and the line-averaged electron density up to 6 x 10^{19} m^{-3} was obtained. The high-energy ions more than 1 MeV were observed during the ICRF heating.

Mode-conversion heating, second harmonic heating, third harmonic heating, and so on were also possible by change of the magnetic field strength and/or the wave frequency. These heating mechanisms were proven to be effective in LHD and contributed to improve the plasma parameters.

The ICRF heating has been used for main heating power for long pulse plasma discharge experiment. The injected heating energy reached 3.4 GJ, which was the highest value in the fusion experiments. The plasma discharge time was about 48 minutes and the total heating power including the ECH power was 1.2 MW. The line-averaged electron density was 1.2 x 10^{19} m^{-3} and the ion and the electron temperatures were both 2 keV. The steady-state experiments have progressed by the improvements of the operation technique and the RF system such as the antennas and impedance matching system.

LHD has started the experiment using deuterium in 2017. Minority heating using deuterium as a majority ion is possible. Second harmonic heating of deuterium ion is also expected as an effective heating mode.

I-09

W7-X PLASMA DIAGNOSTICS FOR IMPURITY TRANSPORT STUDIES

M. Kubkowska[1], B. Buttenschön[2], A. Langenberg[2], and the W7-X Team

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Wendelstein 7-X (W7-X) stellarator which is located in Greifswald, Germany is an experimental device for demonstration of steady-state plasma operation. It was commissioned at the end of 2015 and at the beginning, it was operated in the limiter configuration (5 poloidal uncooled graphite limiters) while started from the 2017 it has been equipped in carbon uncooled divertor. With the launch of the device, new diagnostics have been also commissioned and tested. Understanding of impurity transport in stellarator is a crucial task in optimisation process. At W7-X there are several spectroscopic systems which deliver information about plasma impurities. One of them is a pulse height analysis system (PHA) which collects soft X-ray spectra in energy range from about 600 eV up to 20 keV with 100 ms temporal resolution. There are also X-ray imaging spectrometers XICS and HR-XIS which are devoted for measurements of spatio-temporal impurity emissivities of He-like ions. Spectra in the VUV region are measured by High-Efficiency XUV Overview Spectrometer (HEXOS).

In the presentation, general overview of the W7-X stellarator will be given with the special focus on diagnostics delivered information about plasma impurities. Problems of impurity transport studies will be introduced with an examples of resent results.

I-10

STUDIES OF IMPURITIES BEHAVIOUR FOR THE OPTIMIZATION OF PLASMAS AND HEATING SCENARIOS AT TOKAMAKS IN PERSPECTIVE FOR ITER

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JET can make unique contributions to fusion research due to its capability to operate with hydrogen (H), deuterium (D), tritium (T) and deuterium-tritium (DT) mixtures, with an ITER-like wall (ILW) and its main mission is to support ITER and DEMO. Up to 2020, the main objective of the JET campaigns is the preparation of the DT campaigns and development of ITER plasmas and heating scenarios. The major challenge is integration of high confinement operation with the tungsten (W) divertor constraints at full applied heating power with low core W concentration. To reach these high level objectives, high-Z impurities control and avoidance of their accumulation in the plasma core has become a main issue. Therefore, dedicated plasmas were examined at JET in conditions as close as possible of ITER scenarios dimensionless parameters. This contribution reports on the recent progress of integration methods to control and minimise W and mid-Z impurity contamination in baseline ELMy H-mode and hybrid operational regimes leading to stationary fusion performance. Measurements of mid-Z impurities content such as nickel (Ni), iron (Fe) and copper (Cu) were obtained based on analysis of VUV spectra. The soft x-ray cameras were used to deduce the profiles of W concentration and 2D tomographic reconstruction of the plasma radiation. It was found out that different parameters such as auxiliary heating power, deuterium gas injection rate, impurity seeding and ELM's frequency affect the behavior of impurities. Impact of separatrix density and core density profile peaking performed by several collisionality (υ^*) scans in various plasma operation scenarios is also featured. Accumulation of impurities is often observed after appearance of the MHD modes. Furthermore, Ion Cyclotron Resonance Heating (ICRH) use in scenario development is reviewed and methods for optimisation simultaneously RF coupling in different heating schemes and impurity control are presented. It was found out that impurity control with ICRH is crucial for extending the duration of high-performance phase. The distributed mid-plane gas injection have a beneficial impact on RF-induced impurity content. For core impurity control, fundamental H minority with low minority concentration have shown the best results but He^3 heating as well as combined $H+He^3$ ICRH heating also proved to be effective. The main effects of ICRH that cause reduced impurity peaking are related to temperature peaking, density flattening and fast ion collisions with the W ions but the importance of each of these effects depends strongly on the properties of the plasma in question. Different impurity production is also associated with A2 antennas and ITER-like antenna (ILA) operation.

I-11

COMMENTS ON RECENT ACHIEVEMENTS OF RESEARCH ON DENSE MAGNETIZED PLASMAS IN POLAND

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This invited lecture presents author's comments on the most important results of experimental studies of dense and high-temperature plasma, which have been carried out in Poland since the previous ICPPCF held in 2016. Dense magnetized plasmas were produced by high-current pulse discharges in two experimental facilities: PF-360U at NCBJ and PF-1000U at IFPiLM. Attention was focused on studies of a microstructure of a current sheath and pinch column, and particularly on the formation of plasma-current filaments and tiny regions of an increased x-ray emission (so-called hot-spots), characterized by much higher plasma density and temperature. Local electron densities above 10^{19} cm^{-3} and temperatures ranging several keV were measured. An influence of the application of a nitrogen admixture, or a thin metal-wire placed at the anode axis, was investigated. The influence of small admixtures of other heavy gases on transformations of the pinch column was also studied. Laser Multi-frame interferometry technique and x-ray diagnostics were applied to investigate a helium pinch column. Optical emission spectroscopy (OES) studies of deuterium- and helium-plasma jets, which were emitted from discharges in PF-1000U facility, showed that dimensionless parameters (Mach-, Reynolds-, Péclet's-numbers, and density contrast) corresponded to those observed in astrophysical jets, and such PF-discharges might be used for laboratory simulations of astrophysical phenomena. Those observations were compared with experiments performed with other facilities: PF-3 in Moscow and KPF-4 in Sukhumi. Further detailed studies concerned behaviour of filaments in the pinched column and transformations of the ordered internal micro-structures during the acceleration of fast charged particles in a dense plasma focus. An increase in the neutron yield from PF-1000U discharges was obtained due to the application of a conical tip placed in the anode end-plate centre. Other efforts concerned characterization of fast deuterons involved in the production of fusion neutrons in PF-discharges. The influence of gas conditions on electron temperature inside a pinch column was investigated in details. Other experiments concerned studies of materials damages and modifications by high power plasma exposures, e.g., an analysis of optical spectra from steel samples exposed to pulsed plasma streams, as performed by the joint Polish-Ukrainian team. Recently, attention has been focused on research on the evolution of a pinch column during the acceleration of fast electrons and deuterons in a dense plasma focus, and particularly on experimental studies of hard x-ray and neutron emission from PF-discharges. The authors' critical comments are followed by proposals of future theoretical and experimental studies.

I-12

PREDICTED AND VALIDATED THEORETICAL RESULTS FOR STELLARATORS IN THE FRAME OF EUROFUSION WPS2

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The main results of the work performed under EUROfusion for stellarator optimization and development are shown. This work package comprises both physics and engineering activities in order that the optimization criteria provided by the two work teams are taken into account from the very beginning and the physics optimization takes into account the engineering constrains. In this way it will be possible that a designed next step device has a design, which is a balance between the physics optimization. The HELIAS (W7-X like) configuration has been chosen as a starting point for the optimization, taking advantage of the isodinamicty. A target of the research is to produce proxies for both the physics and engineering optimization criteria that allow one to perform quick optimization process.

The physics criteria comprises reduction of neoclassical transport to improve NC confinement, reduction of bootstrap current to keep constant the edge value of the rotational transform in order to have a feasible island-based divertor, reduction of turbulent transport, improving the MHD stability and improving the fast ion confinement. All these criteria are evaluated with codes that can be validated in present devices, like TJ-II and W7-X.

The coils for the optimised configurations are designed using the NESCOIL code and they are optimised to reduce the manufacturing complexity using the ONSET code. The feasibility of electron cyclotron heating of the new configurations is explored using the TRAVIS code, which produces operation scenarios for W7-X. Electron Bernstein waves are explored as a method to heat high density plasmas. ICRH and NBI heating methods are also studied and, again, the predicted results will be validated on W7-X. A particular output of ion heating is the generation of fast ions, which confinement will be explored in W7-X. The possible couple of the power to Slow Wave, which will be absorbed in the edge, is also explored. The edge topology and transport are also studied to explore the properties of the island divertor configuration.

Regarding the engineering studies, the PROCESS code has been modified to include specific stellarator modules and has been used to estimate the performance of the future stellarator reactors. Breeding blanket studies have been started by calculating the 3Dneutron flux on the wall of an HALIAS-like optimized configuration. This flux is taken as input for the breeding blanket design. The Tritium breeding ratio of the several blanket concepts is estimated to look for the most suitable design for the stellarator necessities.

I-13

MODELLING OF NEOCLASSICAL TOROIDAL VISCOUS TORQUE IN TOKAMAK PLASMAS WITH PERTURBED AXISYMMETRY

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Non-axisymmetric magnetic field perturbations are always present in real tokamak devices. These include external perturbations due to toroidal field ripples, error fields and resonant perturbations specially created by external coils for mitigation or suppression of edge-localised modes (ELMs) [1]. Besides those, there are also perturbations from internal MHD modes. Such perturbations create a toroidal torque onto plasma and thus affect the toroidal plasma rotation profile. Apart from their resonant behaviour around low-order rational flux surfaces where they tend to modify the topology of embedded flux surfaces and produce highly localized resonant torque, in the remaining plasma volume, where perturbations are non-resonant, they lead to toroidal non-ambipolar stellarator-like transport which modifies the radial electric field and thus produces a toroidal torque commonly known under the term "neoclassical toroidal viscosity" (NTV) [2]. The dependence of toroidal torque on plasma collisionality and radial electric field can be idealised in distinct asymptotical regimes where NTV can be described by integral expressions [2, 3]. In the more general case, where a particular asymptotical regime cannot be identified (e.g. at regime boundaries) and where realistic device geometry is taken into account calculation of NTV needs a numerical treatment. Here, different numerical approaches to computation of NTV are presented which have been realised in the codes NEO-2 [4, 5, 6] and NEO-RT [7] together with their applications to NTV computations in realistic device geometries. While the numerical code NEO-2 covers quasilinear transport regimes at subsonic rotations over the full collisionality range and for plasma with multiple ion species, the semi-analytical code NEO-RT specialises on quasilinear and non-linear regimes in the lowcollisionality limit important for ion NTV at reactor conditions and allows for finite orbit width. The relevance of the mentioned features in different transport regimes is demonstrated based on experimental results from the tokamak ASDEX Upgrade with ELM mitigation coils at ITERrelevant collisionality [8].

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I-14

ENERGY EQUATION IN THE PROBLEM OF ELECTRIC ARC PLASMA STATE DETERMINING

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Using of non-equilibrium properties of plasma is one of the ways to improve the energy efficiency of plasma technology processes. In particular, the effects caused by the transfer of resonance radiation in the electric arc channel may be used in this connection. The character of the non-equilibrium depends primarily on the gradients of the radial distribution of the population of resonance and metastable levels of the plasma-forming atoms. It is therefore necessary to determine as precisely as possible the spatial profile of the plasma parameters.

The free-burning axisymmetric electric arc between evaporating copper electrodes was studied. The radial distribution of plasma parameters is determined by energy balance in the form of Elenbaas-Heller equation. In the case of one-dimensional arc this equation in its simplest variant is:

$$\frac{1}{r}\frac{d}{dr}\left(\lambda r\frac{dT}{dr}\right)+\sigma E^{2}=0, \tag{1}$$

where r – radial coordinate, T – plasma temperature, $\lambda(T)$ – heat conductivity and $\sigma(T)$ – electrical conductivity. The arc current I with known electric field E is given by Ohm law in integral form:

$$I=2\pi E\int_{0}^{R}\sigma(r)rdr\ , \tag{2}$$

where R is radius of electric arc channel.

The boundary conditions are

$$\left.\frac{dT}{dr}\right|_{r=0}=0,\ T\big|_{r=R}=T_{w}, \tag{3}$$

where T_w – temperature at the boundary of electric arc channel.

Despite its apparent simplicity, the Elenbaas-Heller equation do not become quite common tool for studies of the arc plasma as authors may conclude based on the known volume of published data. The results of its application to study of plasma properties obtained by authors as well as in the papers of other scientists further illustrate the complexity of their interpreting.

A detailed analysis of the use of the Elenbaas-Heller equation for determining the state of equilibrium of the electric arc plasma will be presented in the report.

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I-15

SPECTROSCOPY OF PLASMA WITH METAL VAPOR ADMIXTURES

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The wide class of diagnostic techniques of electric discharge plasma in gases and liquids is presented in this report. The admixture of metals vapours in plasma takes typically place in considered discharges. So, even insignificant amount of such admixture not only changes plasma properties, but gives an opportunity for its diagnostics. Experimental techniques, which allow to determine the electric discharge plasma properties in different media, and after all, plasma composition, are described. The techniques are based on optical emission or laser absorption spectroscopies approaches.

Peculiarity of emission registration, data treatment and computation of plasma properties, as well as its composition are widely discussed. Extra attention is paid for spectral lines selection, which are acceptable for diagnostics, careful accounting of experimental setups features and controlling of experimental conditions. Proposed techniques are illustrated in examples for studying of discharge plasma with metal vapours in argon flow, underwater spark discharge between metallic granules and high-current discharge in liquid between copper electrodes.

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- Taras Shevchenko Kyiv National University, Kyiv, Ukraine and National University of Life and Environmental Sciences of Ukraine.

I-16

RECENT RESULTS ON THE PLASMA-WALL INTERACTION STUDY AT THE LINEAR PLASMA DEVICE PSI-2

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Understanding the plasma wall interaction represents one of the most critical issues in fusion plasmas. Linear plasma devices, such as PISCES, MAGNUM or PSI-2 contribute to the fusion program addressing the topics which are difficult or hardly possible to study directly in fusion devices. In this talk the overview of the results obtained in the Linear Plasma PSI-2 with the accent on the new spectroscopic data will be given. The new experimental and the theoretical data related as to the principal problem of sputtering of heavy Z materials such as W or Mo by plasma ions and its modeling, application of laser physics for plasma-wall interaction studies, but also the development of new methods to measure the optical properties of materials in fusion such as mirrors will be presented.

I-17

DEVELOPMENT OF PLASMA AND ION BEAM TECHNOLOGY FOR MATERIAL ENGINEERING AT NCBJ

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The Plasma/Ion Beam Technology Division (FM2) is one of several laboratories forming the Material Physics Department (DFM) at the NCBJ in Świerk, Poland. Scientific activity of the FM2 Division concerns different aspects of research related with material engineering, surface engineering, functional properties characterization, as well as synthesis and modification of different materials. The main tools used by our research groups are plasma and plasma-related techniques. The plasma surface engineering, as an important scientific field investigated at the FM2 laboratory, allows improve, modify and develop modern and unique methods of the material synthesis. The investigations include also research on plasma diagnostics, which is important and indispensable part of studies performed by our teams. Basic features of plasma-surface interactions, as well as the characteristics of the plasma generation in various experimental and technological facilities, are studied extensively. Other very important tools used in our research are ion- and electron-beams produced by various implantation devices. These corpuscular beams are considered as a promising technique for modifications of a material structure, and synthesis of non-equilibrium structures.

The FM2 Division is divided into two specialized laboratories: 1. Nuclear Microanalysis Laboratory, and 2. Ion/Plasma Material Modification Laboratory. The first lab conducts investigations of nuclear microanalysis, focused on structural changes of various materials after implantation, as well as on development and validation of the McChasy–Rutherford Backscattering Spectrometry in computer simulation and analysis of some archeological relics. The second lab runs research on material modifications, which covers issues related with the modification of different material surfaces by means of ion/electron beams or plasma streams. These studies are focused on the synthesis of non-equilibrium structures in chosen materials and determination of their influence on the material properties, as well as on the synthesis of completely new materials. In the field of the plasma surface engineering research is focused on the determination of pulse energies and masses which are delivered to samples during plasma processes. In addition, some research is also carried out in the domain of the synthesis and characterization of various layers deposited upon chosen materials. Studies performed by this group are focused on the development of plasma surface engineering techniques.

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I-18

LARGE AMPLITUDE ELECTRON ACOUSTIC WAVES IN QUANTUM PLASMA AT FINITE TEMPERATURE

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The study of electron acoustic solitary waves in a quantum plasma at finite temperature containing relatively warm electrons, non-degenerate cold electrons and stationary ions has been carried out by using nonlinear analysis. A linear dispersion relation is derived for electron acoustic waves. The change in density of electrons for various parameters has been observed using Sagdeev's pseudo potential approach. The formation and properties of large amplitude solitary structure is thus investigated. The present analysis may be important to understand the collective interaction in finite temperature quantum plasma.

1-01

GENERATION OF INWARD ENERGY FLUX BY ALFVÉN EIGENMODES DRIVEN BY PLASMA INHOMOGENEITY

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Recently it was shown that when the resonance velocity of the wave-particle interaction exceeds the particle thermal velocity, Alfvén gap modes (TAE, EAE etc.) can be destabilized even in the absence of sources of the energetic ions (such as neutral beam injection etc.) [1]. The physics of this phenomenon is a strong increase of the destabilizing influence of the temperature gradient when the resonance velocity exceed the thermal velocity. In stellarators, this condition can be provided by non-axisymmetric resonances predicted in [2]. In the case of the temperature distribution with a large gradient at the periphery, the destabilized mode can channel the energy from the peripheral region to the inner region; in other words, power received by modes in unstable region can heat the plasma in the stable region located at smaller radii. It is found that the considered destabilizing mechanism could manifest itself and lead to the inward spatial channelling of the ion energy in a relatively narrow region of the plasma in recent experiments on the Wendelstein 7-X stellarator where high frequency oscillations were observed [3].

In this presentation, in addition to the results of Ref. [1], a more detailed study of the inward energy flux produced by the temperature-gradient driven instability will be shown.

Note that the inward spatial channelling can also provide the transfer of the energy of fusion produced alpha particles by means of fast magnetoacoustic waves with frequencies above the alpha gyrofrequency [4].

The considered instability may affect the plasma performance in W7-X and deserves further experimental and theoretical studies. The mode could also play a role in other stellarators, in particular in LHD, TJ-II, H-1, U-3M and others [5-8].

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1-02

MOMENTUM-SPACE ANALYSIS OF SUPRATHERMAL ELECTRONS GENERATION UNDER CONDITIONS OF GAS PUFFING DURING RUNAWAY TOKAMAK DISCHARGES

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The energy of disruption generated runaway electrons can reach as high as tens of mega-electron volt energy and they can cause a serious damage of plasma-facing-component surfaces in large tokamaks like International Thermonuclear Experimental Reactor [1]. At the same time, the quiescent runaway electron generation during the flat-top of DIII-D low density Ohmic discharges allows accurate measurement of all key important parameters to runaway electron excitation [2].

Using a test particle description (like [3]) that includes acceleration in the toroidal electric field and collisions with the plasma particles the generation of suprathermal electrons is analyzed under conditions of gas puffing. In presented modeling, the plasma parameter behavior close to the DIII-D quiescent runaway shot #152895 parameters is used. For this puffed discharge the growth and decay of high-frequency ECE signal was in disagreement with the HXR and synchrotron emission signals. Possibility of formation of the suprathermal electron population with $v_\perp >> v_\parallel$, which is trapped in a uniform magnetic field, is shown ($v_\parallel$ and $v_\perp$ are the velocities parallel and perpendicular to the magnetic field, respectively). The growth and decay of high-frequency ECE signal may be explained by occurrence of this suprathermal population.

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1-03

LOW FREQUENCY OSCILLATIONS IN U-2M CONDITINING RF DISCHARGES

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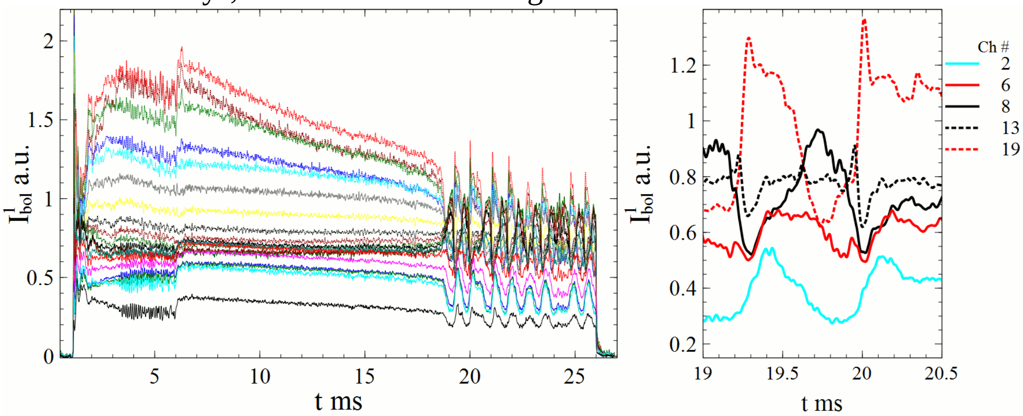
An appearance of various 1-20 kHz oscillations was observed in URAGAN-2M (U-2M). Two multichannel pinhole cameras were recently installed in U-2M for monitoring the oscillations of visible light emission from two positions in the same plasma cross-section. New electronics was designed and manufactured for measuring the plasma density, electron temperature and plasma potential profiles with high time resolution in cold, low density RF conditioning discharges via triple Langmuir probe technique. New measurements by modified diagnostics show, that the plasma beta is rather high in these discharges in spite of the low temperature and density: this is because of very low magnetic field B_0=0.01T. Variation of the magnetic configuration of U-2M substantially modifies the features of the oscillations in the plasma of such discharges. In addition to significant variation of the fluctuations amplitude, the modification of the oscillating modes type and frequency is also observed. Rotated *m=2* mode is transformed into the Sawtooth-like oscillations in different magnetic configurations. Clear phase inversion of the Sawtooth-like oscillations was observed both by horizontal and vertical bolometer arrays, as it is shown in the figure.



Time evolution of horizontal bolometer array signals. Phase inversion of the sawtooth-like oscillations is seen from central channels #6,8 and outer channels #2,19

Coherent oscillations are observed by bolometers, triple Langmuir probe and microwave interferometer in different toroidal cross-sections. Strong gradients of the radial electric field and electron temperature are observed in discharges with substantial oscillations only. These gradients can be caused by presence of rational magnetic surfaces in magnetic configurations with oscillations. The role of rational surfaces in the transport barrier formation accompanied by the sawtooth-like oscillations was discussed in the case of hot plasma of TJ-II [1]. Similar sawtooth-like oscillations were recently observed in W7-X discharges with rational surfaces. In spite of different conditions, i.e., low temperature and partially ionized plasma in RF conditioning discharges of U-2M in comparison with hot plasma of TJ-II and W7-X, a qualitative similarity of the oscillations behavior was observed. Strong dependence on the magnetic configuration indicates that observed phenomena can have similar roots in different plasma conditions.

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1-04

IN SITU QUANTIFICATION OF PLASMA FACING SURFACE CONDITIONS IN THE URAGAN-2M TORSATRON

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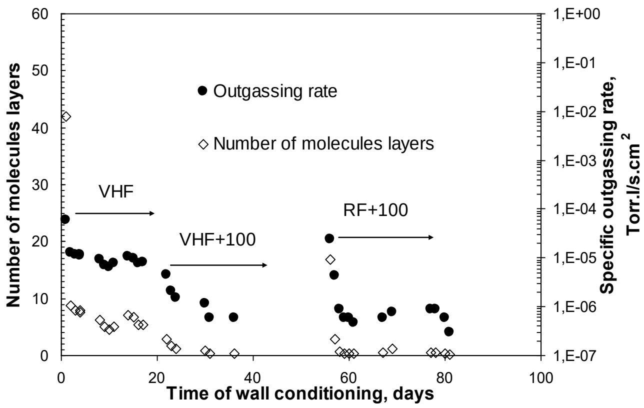
The thermal desorption method has been developed for diagnosing impurity level on Uragan-2M vacuum chamber surfaces *in situ*. The corresponding device consisting of thermo-desorption probe and a vacuum gauge was designed, manufactured and installed in the U-2M vacuum chamber, which gives possibility to register flows of gases desorbed from the 12KH18N10T stainless steel strip-like probe head during its pulsed heating up to temperature 250-300 ºC.

Using this method the investigations of outgassing rate were carried out and estimation of the number of molecules layers was done in the Uragan-2M torsatron *in situ* after RF plasma discharge cleaning in different regimes combined with pumping. It had been indicated that the VHF and RF discharge cleaning in low magnetic fields of 0.01-0.02 T are more effective than the regimes without magnetic field. After preliminary short time VHF/RF discharge cleaning and long time pumping out, the number of impurity molecules layers was decreased from ≈40 up to less than one layer (Figure).



Uragan-2M wall conditions: black circles correspond to SS probe specific outgassing rate at 300 ºC after VHF or RF discharge cleaning in H_2, N_2 or N_2+H_2 mixtures, rhombs correspond to number of molecules layers on the SS probe

Mass-spectrometric measurements have shown domination of H_2O (18 u), presence of CO_2 (44 u) and 28 u, as the main gases desorbed from the SS probe surface during its heating. Heavy hydrocarbon masses (58 u) were also registered.

The proposed method was also tested in the high temperature regime (400-700 ºC) to measure hydrogen outgassing (release) from the SS probe. It was observed the essential (one order of magnitude) increase of hydrogen release after two hours exposure by RF plasma discharges in the regular regime comparing with the regimes of RF wall conditioning. This means that the hydrogen content in the SS probe also increased. Note, that after long time discharge cleaning regimes the hydrogen retention in the SS probe was not essential. So, using thermal desorption probe method one can effectively monitor not only the surface conditions but also the hydrogen retention and release in the vacuum chamber wall material.

1-05

2-D ELECTRON SYSTEM IN THE RF-DISCHARGE PLASMA PART I. GENERAL OBSERVATIONS

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The peculiarity of RF discharges consists in the formation of positive-ion space charges close to the antenna surface. This effect adversely affects the RF plasma heating. The attempts to weaken or control the effect are hampered by difficulties of its diagnostics. The creation of two-dimensional electron systems (TDES) in the research of solids has led to striking results. This has stimulated the attempt to demonstrate the identity of the processes occurring in the near-antenna region of the RF discharge and in the TDES. The common characteristic feature of both the plasma and solids is the presence of free electrons. In a separate atom, the electrons are moving so that their energy levels have a discrete character, i.e., they get quantized. This opens ample opportunities for plasma spectroscopy. The free electron spectra of in solids (crystals) also determine their type and basic properties. As atoms group together in a solid, their electron shells get overlapped. Each energy level gives rise to level bands, i.e., the bands, the number of which equals the number of electrons in the crystal. The energy separation between the levels in the band is very small. The allowed energy bands are separated by forbidden bands. With increase in the energy, the allowed band width increases, while the forbidden band width decreases. In the crystal, the allowed bands may be filled wholly (insulator), partially (conductor) or may be perfectly free. The crystal, where an appreciable number of electrons fall within the empty band due to thermal excitation, is a semiconductor. It is evident that the type and properties of the solid are specified by the band structure, which is difficult for investigation in the bulky crystal.

The problem was solved using the methods of dimensional effects [1]. For this purpose, the crystal film was prepared, the thickness of which, d, was comparable with the de Broglie wavelength. The film is placed in the (x-y) plane normally to the electric field E. In the (x-y) plane, electrons move freely as in a bulky crystal. The energy of transverse motion along z takes on some selected values, determined by the film thickness d, i.e., it gets quantized. This results in a cardinal reconstruction of the electron spectrum. Apart from thin films and wires, it has appeared possible to create the TDES through electron localization in a certain space region, the potential well having the width of about the electron wavelength. These structures represent the capacitor with metal-metal plates, the semiconductor-metal, and the semiconductor-semiconductor. The 2D electron gas is formed near one of the capacitor plate surfaces by the electrostatic field. The possibility to control the electrons in the TDES has made it possible to investigate the band structure of solids, to create new elements for microelectronics, and to provide a convenient model system for investigating physical processes.

In RF discharges, the plasma itself forms space charges of particles along thereby forming the potential well near the antenna surface. This structure is supposed here to be similar to the TDES. In Part II of the work, consideration is given to the TDES existence media, generation conditions and possible methods of controlling the processes in the mentioned formations.

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1-06

2-D ELECTRON SYSTEM (TDES) IN THE RF-DISCHARGE PLASMA PART II. SIMILARITY OF TDES IN A SOLID AND IN THE RF DISCHARGE

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The realization of the TDES calls for the presence of free electrons in the medium. This property is intrinsic in metals, semimetals, semiconductors and plasma, although they have different free-electron densities. The TDES is formed in crystals to produce the 2D electron gas. The electron gas is identified as two-dimensional if the electrons exhibit two degrees of freedom in the plane, while their motion is forbidden or limited in the third dimension. Under this condition, the substance can possess the properties other than those in an ordinary crystal. The TDES can be realized in anisotropic media of crystals and plasma, in magnetic and electromagnetic fields, including the RF region used for plasma generation and heating in the stellarators U-3M and U-2M. In the TDES, electrons and holes can move in semiconductors, while electrons and ions can move in the plasma. Structurally, the TDES represent the capacitors with small spacings between the plates. The potential electric field on the surface of one of the plates creates and controls a thin layer of emitted electrons (potential well). The TDES, having the width d commensurate with the electron de Broglie wave length, produces the quantum dimensional effect, i.e., the dimensional quantization. The term "dimensional effect" implies the dependence of properties of the solid body on its geometrical dimensions, when at least one of the dimensions would become comparable with the characteristic physical quantity having the length dimension. It follows from this definition that the indispensable condition for manifestation of the dimensional effect is the presence of the TDES in the medium. At that, the crystal size is by no means related to the potential well size, and can be arbitrary large. In theory, the "dimensional effect" was first proposed in 1953 by the KIPT physicists I.M. Lifshits and A.M. Kosevich [1]. If however the diffusion length, the shielding distance or the mean free path is taken as the characteristic physical quantity, then classical dimensional effects are realized. These variants are possible in the U-3M and U-2M RF plasmas. The basis for the TDES formation is the plasma capacitor, which is formed by the antenna surface and the neighboring positive-ion space charge. The electrons are localized by the potential field and the potential barrier on the antenna surface. Similarly, in the TDES based on heterostructures, the potential electric field is created by positive ions of the dielectric. In the near-antenna region, the potential well width is generally smaller than the mean free path of the electron. Therefore, in the RF field the current may flow parallel to the interface region with the two-dimensional conductivity. In the RF discharge, the TDES is formed by the plasma itself (to keep quasi-neutrality). Unfortunately, the processes occurring in the TDES reduce the efficiency of plasma generation and heating. To control or make them weaker presents a problem, because they are specified by the plasma parameters n_e and T_e, and also by the amplitude and frequency of the applied RF voltage. The motivation of present work has been to use the effective TDES results for solids as applied to RF discharges.

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1-07

MODELING OF TIME BEHAVIOR OF H, H_2 NEUTRAL DENSITIES, AND H_α LINE INTENSITY IN THE RF PLASMA OF THE URAGAN-3M TORSARTRON

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The time evolution of the experimental atomic and molecular hydrogen density in the plasma confinement volume of the Uragan-3M torsatron has been one of the most important research topics. Among the variety of plasma diagnostic methods, emission spectroscopy of Balmer spectral lines H_α and H_β represents a passive, and therefore non-invasive, diagnostic tool with a simple and reliable setup. Nevertheless, for the correct interpretation of spectral line intensity, one must have the comprehensive computer modeling of time dependence of H and H_2 neutral densities. Previously [1], the results of the modeling of radial profiles of plasma ions and neutrals, using the numerical code KN1D, were presented for some specified moment of the RF pulse when plasma was produced and heated by RF power.

The further computer simulation shows that to model time-dependent functions associated with hydrogen plasma and neutrals, it is reasonable to solve a system of four differential equations [2] with the following variables: 1) the H^+ ion density, 2) the density of low-energy atoms (H_L), 3) the density of charge-exchange atoms (H_{CX}), and 4) the H atom population on the wall. In this system, each of the first three time-dependent functions is supposed to be uniform along a minor plasma radius at any time moment of the RF pulse.

Results of a new numerical analysis were presented for two different plasma production and heating conditions. The parameters of the first regime were as follows: the toroidal magnetic field $B_0 = 0.6$ T, hydrogen pressure prior to the discharge $p_0 = 1.2\times10^{-3}$ Pa, line-averaged plasma density $\bar{n}_e \leq 2\times10^{18}$ m^{-3}, and electron temperature $T_e \leq 0.5$ keV. The hydrogen breakdown was initiated using the Three-Half-Turn Antenna (THTA) with the anode voltage $U_2 = 5$ kV. After that, the plasma was sustained by the Frame Type Antenna (FTA) with the anode voltage $U_1 = 8$ kV. The second regime was provided with $B_0 = 0.72$ T, $p_0 = 1.1\times10^{-3}$ Pa, $\bar{n}_e \leq 1.2\times10^{18}$ m^{-3}, $T_e \leq 0.5$ keV, $U_2 = 6$ kV, and $U_1 = 7$ kV.

The electron temperature (key parameter) was evaluated with some degree of approximation. According to the time behavior of the ECE intensity, four unknown functions are changing in the equation system. The calculated electron density was fitted to the experimental function.

Other time-dependent functions were also calculated using the system of equations. It was found that the temporal dependence of H_L atom density decreases sharply to a constant level. The wall population with H atoms changes monotonically: decreases initially and then increases. The intensity of the H_α line has a qualitative similarity with the measured function. The contribution of H_L atoms to the H_α line intensity was found much higher than that of H_{CX} atoms.

The molecular pressure in the chamber was determined from the additional differential equation containing the molecular density function. The calculated molecular pressure decreases exponentially with time, what is in agreement with the measured data.

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1-08

MODELING OF DUAL-POLARIZATION INTERFEROMETRY IN STELLARATORS

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Ordinary wave interferometry is a well known and commonly used plasma diagnostics for fusion devices and plasma technology [1, 2]. The ordinary wave number depends only on plasma density in the case of perpendicular probing with respect to the main magnetic field. Thus, the ordinary wave phase shift is proportional to the line-integrated plasma density along the chord of probing for the wave frequency greater than plasma frequency. For the extraordinary wave perpendicular probing, the phase shift depends on plasma density and the confining magnetic field distributions. Since the magnetic field is known for stellarator/torsatron devices, additional information about plasma density profile may be inferred from the extraordinary wave phase shift measurements. For example, this may be the peakedness of the plasma density distribution $\bar{n}/n_0$, where n_0 is the plasma density on magnetic axis and $\bar{n}$ - averaged plasma density.

The dual polarization interferometer has been designed and installed in Uragan-2M at the cross-section where magnetic surfaces are vertically elongated. For data analysis, the set of phase shifts was calculated using real spatial dependence of the magnetic field and the following parameterization of plasma density, $n(\psi) = n_0\left(e^{\xi} - e^{\xi\psi}\right)/\left(e^{\xi} - 1\right)$. Here ψ is the flux surface label equals to 0 at the magnetic axis and equals to 1 at the last closed magnetic surface, ξ is profile peaking parameter. Calculated phase shifts were matched with experimental results in order to determine the central density and peaking parameter of the Uragan-2M plasma. Thus, rather simple and effective way of plasma density measurement has been implemented [3].

However, an extensive modeling of microwave propagation through the plasma in the sheared magnetic field should be provided for correct interpretation of data. For this purpose, the system of two bounded ordinary differential equations of the second order for the electric fields of the ordinary and extraordinary waves was solved numerically. The transfer matrix from launching to receiving waveguides was obtained in the wide range of plasma parameters. This gives the possibility to understand the results of already fulfilled measurements and to propose the optimized way for dual-polarization interferometry in stellarators.

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1-09

FAST ALGORITHM OF MAGNETIC SURFACES RECONSTRUCTION IN STELLARATORS

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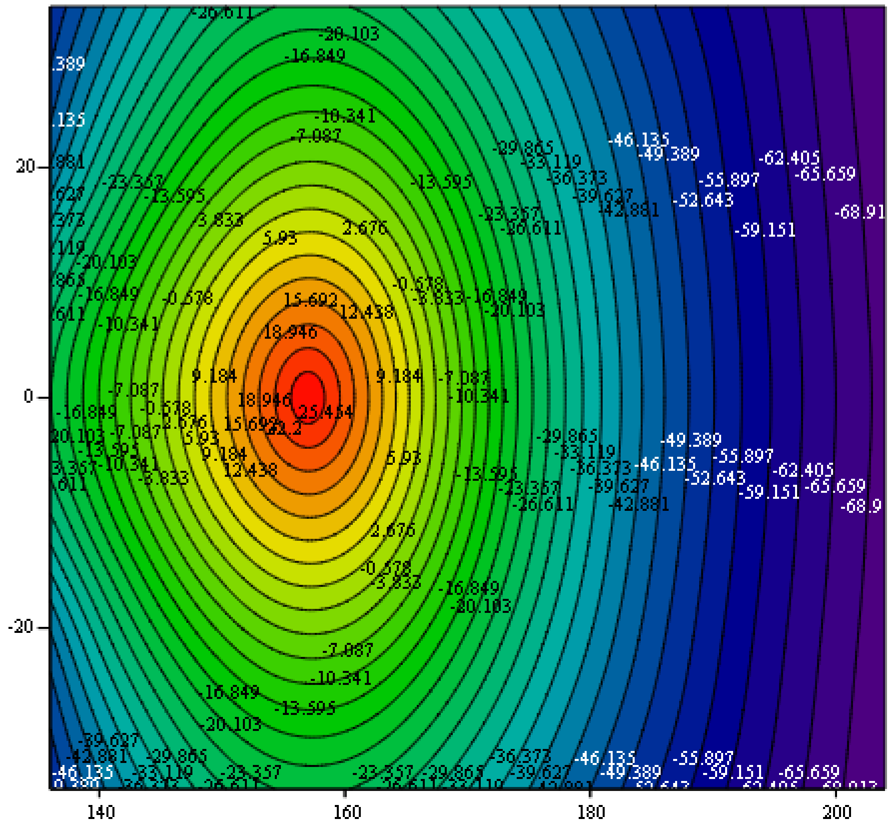
In this paper the algorithm of calculation of approximating function $\xi(R,\varphi,Z,\psi)$ is developed. Here (R,φ,Z) is cylindrical coordinate system connected to main axis of the torus and ψ is magnetic flux label (Figure). This function establishes the one-to-one correspondence between the real coordinate mesh with arbitrary step and magnetic flux label in the whole plasma volume. Such correspondence may be calculated with the predetermined accuracy. The calculation was carried out for Uragan-2M torsatron. But the developed algorithm may be applied to any stellarator. This approximation function is especially useful for fast connection of diagnostic data, which are known in real space coordinates, with magnetic surfaces where the plasma parameters (density, temperature etc.) supposed to be constant. Also, the approximating function allows realizing the real time magnetic configuration control due to extremely short time of calculations.



Reconstructed magnetic surfaces in the poloidal cross-section of Uragan-2M torsatron

1-10

THE MICRORELIEF STUDIES OF STAINLESS STEEL MIRRORS SPUTTERED WITH AR$^+$ IONS OF DIFFERENT ENERGY

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It was described in [1, 2] that ion sputtering of polycrystalline SS mirror specimens resulted in faster degradation of optical reflectance when ion energy increases: for an identical mean thickness of the eroded layer (measured by weight loss) the reflectance decreased with increasing ion energy. Due to the direct connection between reflectance and surface roughness, this fact is a clear indication on increase of difference between sputtering rates of metal grains with different orientation when increasing ion energy. In this presentation, we provide analysis of surface roughness which appears on the surface of SS mirror specimens after sputtering with Ar^+ ions of different energy.

Before the exposures, the specimens had a well-polished surface. Ions of Ar plasma were accelerated to a specimen (denoted as S1–S4) with kinetic energy E_i equal to 300 eV (S1), 600 eV (S2), 1000 eV (S3), or 1350 eV (S4). In order to optimize the comparison of the parameters of all specimens, the mean sputtered depth has to be equal for each specimen, and in the present study it was chosen as 2 μm. Two methods to process the data were applied.

For each specimen, the relief heights were measured along a rectangular serpentine with a total length of 18.7 mm. It was located on a digital microphotograph with a size of 480×280 μm ^{2}, obtained using an optical microscope. The AFM microphotograph with a size of 50×50 μm ^{2} provided an increased scale. Also, height profiles were obtained using a profilometer on a straight segment 4 mm in length.

The following results were found. The statistical distributions of irregularity heights for these specimens, $\Delta N/\Delta h$, have a slightly asymmetric, approximately Gaussian shape. With increasing energy E_i the distributions become much wider and lower, in other words, all heights increase. The roughness parameter (r. m. s. height of the irregularities) R_q increases with increasing energy E_i, taking the values 0.02, 0.16, 0.27, and 0.35 μm, correspondingly, for different ion energy. The wavelength distribution $\Delta N/\Delta\Lambda$ varies not significantly with increasing E_i. In this case, the mean period of a longitudinal wave $S_{\rm m}$ increases then decreases in the range of 11–15 μm.

The power spectral density $PSD(\Lambda)$ was calculated using the Fourier spectrum of height profile. It was found that with increasing energy $E_{\rm i}$ the PSD function increases and shifts noticeably toward the short-wavelength range. For example, the $PSD_{\rm S1}(\Lambda)$ function is very close to the wavelength axis, but the $PSD_{\rm S4}(\Lambda)$ function is substantially higher, especially its short-wavelength part, for $\Lambda \le 12$ μm. This part corresponds to micropores and microneedles that appeared only when ion energy was 1350 eV. They are not visible in the $\Delta N/\Delta\Lambda$ distributions and are clearly visible in the microphotograph of the specimen S4.

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1-11

EFFECT OF TOROIDAL MAGNETIC FIELD RIPPLE VALUE ON THE *l*=1, *m*=1 YAMATOR MAGNETIC SURFACES

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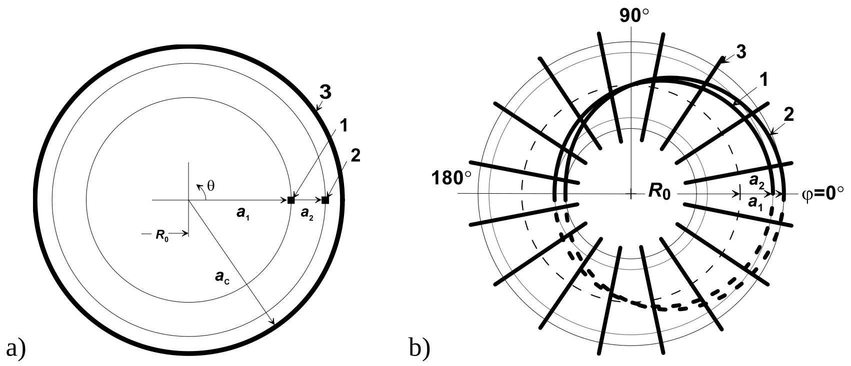
The stellarator-type magnetic system, named as a Yamator [1, 2], is interesting due to the opportunity of forming a toroidal closed magnetic surface configuration with a high value of the averaged magnetic well, $-U\sim0.1\div0.5$. However, the high numerically calculated parameter values have been obtained under condition that superposition of helical coil magnetic field and ideal axially symmetric toroidal magnetic field occurs. So, the calculations did not consider an inevitable appearance of the toroidal magnetic field ripples in the case of Yamator magnetic system practical realization and a possible effect of the toroidal magnetic field ripple values on the magnetic surface parameters. Ripple induced helical magnetic field violation follows from the analytical study results [3, p. 56].

In the present paper the numerical calculations were carried out on the l=1, m=1 Yamator magnetic field formed by superposition of helical coil magnetic field and rippled toroidal magnetic field generated by the system of N =16 circular discrete coils with radius a_c (Figure). In order to study the effect of toroidal magnetic field ripple value on the magnetic surface parameters the calculations were performed for several l=1, m=1 Yamator systems having different value of the toroidal magnetic field coil radius a_c. The final goal of the study is to define the bounds of coil radii a_c within the range of which the effect of toroidal magnetic field ripple value on the magnetic surface parameters can be neglected.



Poloidal cross-section (a) and top view (b) of the l=1, m=1 Yamator calculation model: 1, 2-helical coils, the helical coil currents are equal-in-magnitude and opposite-in-direction, 3-toroidal magnetic field circular discrete coils, θ is the poloidal angle, φ is the toroidal angle

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1-12

TORSATRON U-2M MAGNETIC SURFACES WITH ENHANCED MIRROR RATIO

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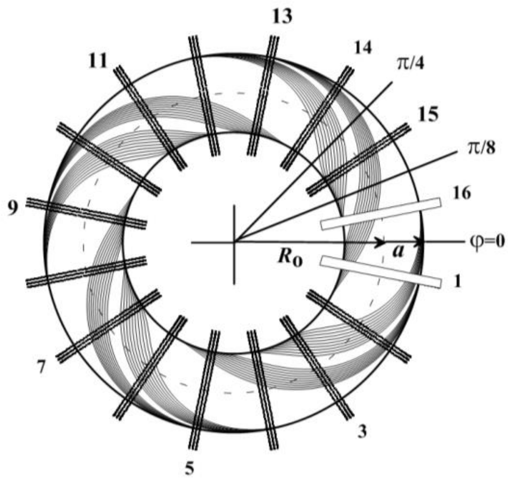
As a fusion neutron source for the sub-critical hybrid nuclear reactor [1] in the paper [2] has been proposed the magnetic system combination, including a stellarator-type and a mirror-type magnetic system. In the paper [3] a stellarator-mirror magnetic system based on the magnetic system of the torsatron *U*-2M [4] with the additional toroidal magnetic field coils was considered. The combined with stellarator-type magnetic system the mirror-type magnetic system was realized by switching off one of the additional toroidal magnetic field coils.

In this paper the magnetic field of the stellarator-mirror magnetic system is studied where the mirror-type part in *U*-2M is realized by switching off two adjacent additional toroidal magnetic field coils (Figure). Existence of closed magnetic surfaces with enhanced mirror ratio value and mirror region longitudinal size in the combined magnetic system model is demonstrated by the numerical calculations.



*Top view of the magnetic system of the l=2 torsatron U-*2M *calculation model. The positions of two adjacent switched off coils 1, 16 are indicated*

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1-13

A NUMERICAL MODEL OF RADIO-FREQUENCY WALL CONDITIONING FOR STEADY-STATE STELLARATORS

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A model of RF plasma production in stellarators in the ion cyclotron and electron-cyclotron frequency ranges is presented. This model will be used for numerical analysis of the plasma discharge for the vacuum chamber wall conditioning. As a basis for the whole code, the models for atomic gas [1] and for molecular hydrogen [2] are used, which were developed earlier. A newly developed model as well as the previous models includes the system of the particle and energy balance equations for the electrons and the boundary problem for the Maxwell's equations. New features of the model presented are account of molecular ions, H_2^+ and H_3^+, in the particle balance equations. The radio-frequency module of the code is modified accordingly. Neutral gas is assumed to consist of molecular and atomic hydrogen. In the balance of neutral gas, the hydrogen retention and recombination at the wall surface are taken into account.

A new module that calculates the second harmonic electron cyclotron heating in the case of weak wave damping is created and incorporated into the code.

The first calculations with the model are presented and discussed.

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1-14

SLOW WAVE PROPAGATION IN PLASMA WITH NON-UNIFORMITY NOT PERPENDICULAR TO THE MAGNETIC FIELD

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The slow wave plays an important role in certain scenarios of plasma heating and current drive, and also in wall conditioning discharge sustaining. Its field structure is studied well within one-dimensional model including the zone of lower hybrid resonance [1-3]. In the model it is assumed that the direction of plasma non-uniformity is perpendicular to the magnetic field. This is almost true for fusion machines because the plasma density is approximately constant at the magnetic surface. However, the magnetic field module has some variations, and the plasma dielectric tensor follows them. For such reason it is of interest to consider a case when the magnetic field is not perpendicular to plasma gradients.

In the report, 1D non-uniform plasma with tilted magnetic field is considered. The second order differential equation describing the slow wave is derived from the Maxwell's equations. The analysis of this equation reveals a singular point for the solutions. However, the point located aside of the lower hybrid resonance. The solutions obtained are also different. These solutions, location of the singular point and energy flux behavior are discussed in the report.

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1-15

POSITIVE-DEFINITE FORM OF TIME-HARMONIC MAXWELL'S EQUATIONS

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Time-harmonic Maxwell's equations are a subject for numerical treatment for analysis of the wave propagation in non-uniform plasma. In their original form, they contain sign-indefinite operators. This limits application of iterative procedures for their numerical solving.

In this presentation the following form of the Maxwell's equations is proposed for further numerical solving.

$$\nabla\times\nabla\times\mathbf{E} - ik_0(\hat{\varepsilon}^* + 1)\cdot\nabla\times\mathbf{H} + k_0^2\hat{\varepsilon}^*\cdot\hat{\varepsilon}\cdot\mathbf{E} = -\frac{4\pi i k_0}{c}\hat{\varepsilon}^*\cdot\mathbf{j}_{ext}$$

$$\nabla\times\nabla\times\mathbf{H} + ik_0\nabla\times(\hat{\varepsilon} + 1)\cdot\mathbf{E} + k_0^2\mathbf{H} = \frac{4\pi}{c}\nabla\times\mathbf{j}_{ext}\,.$$

Here **E** and **H** are the electric and magnetic field vectors, $k_0=\omega/c$, $\hat{\varepsilon}$ is the dielectric tensor, $(\hat{\varepsilon}^*)_{i,k} = (\hat{\varepsilon})^*_{k,i}$, $\mathbf{j}_{ext}$ is the driving (external) current. This system of equations contains positive-definite operator in the left-hand side. This feature, in principle, could be preserved after the discretization that results in a linear algebraic system of equations with positively-definite matrix.

It is necessary to note that the above system is degenerate. This feature is inherited from the original Maxwell's equations. Thus, a straightforward discretization may cause appearance of spurious solutions. A special technique derived in Ref. 1 could be applied for discretization to avoid this unwanted effect.

The above system of equations, being of higher order, needs more boundary conditions than the original one. For this purpose, the components of the original system could be used since they are differential equations of the first order.

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1-16

THREE-HALF-TURN ANTENNA PLASMA START-UP EXPERIMENTS

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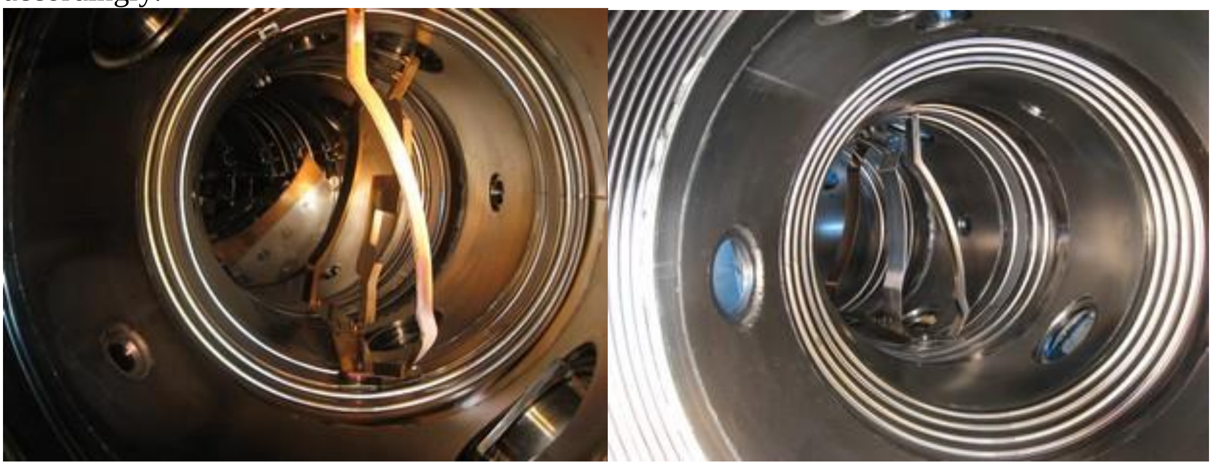
Three-Half-Turn (THT) antenna has 3 straps oriented perpendicular to the magnetic field lines. The THT antenna is fed through the central strap [1]. THT antennas is used for plasma heating in Uragan-3M and Uragan-2M. The research task was to study independent RF plasma creation with THT antenna in. both devices. Electron plasma density and temperature were measured with Langmuir probe, electron temperature was observed in real time with separate spectral lines, electron plasma density was measured in real time with microwave interferometer and multi-chord visible light diagnostics showed the shape and position of the plasma column. THT antennas are capable of creating dense plasma at decreased compared to regular regime magnetic fields, but with long idle time what is dangerous for antenna insulators because of high voltage at the antenna elements. Experimental conditions were changed through variation of magnetic field, pressure and RF generator parameters in order to find optimal regime of operation. The optimum magnetic field was 0.62-0.68 T at Uragan-3M and 0.37-0.38 T at Uragan-2M while standard field was 0.7-0.72 T and 0.4-0.42 T accordingly.



Modification of crankshaft antenna (left) into THT antenna (right)

THT antenna of Uragan-2M was crafted from crankshaft antenna by replacing middle crankshaft-shape strap with the straight one. While the crankshaft antenna could operate in the wide range of available at Uragan-2M magnetic fields, THT antenna required the decreased magnetic filed against regular regime and the narrow space of operation. A reason of this could be lower ability to excite the slow wave. Ability of THT antenna to create and heat plasma is presumably connected with presence of ion cyclotron zone inside of plasma column where the Alfvenic relay race occurs at low plasma densities.

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1-17

STRUCTURE OF MHD FLUCTUATIONS IN THE TORSATRON U-3M IN STEADY-STATE STAGE OF DISCHARGE

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In the U-3M torsatron in the investigated regime, the plasma was created and heated by the frame antenna at a frequency close to ion-cyclotron ($f_{RF} \leq 0.8\omega_{ci}/2\pi$, $B_\phi(0) \approx 0.7$ T). In this case, the regime of rare collisions was realized in the confinement volume of the plasma and a toroidal current I ≈ 2 kA was observed.

For registration of magnetic fluctuations in the confinement volume, a set of 15 magnetic sensors (Mirnov's coils) located along the azimuth around the plasma column in one of the poloidal cross sections was designed and installed. Magnetic sensors made it possible to record oscillations of a poloidal magnetic field with an amplitude of $\tilde{B} \geq 10^{-3}$ G in the frequency range 0.5...100 kHz. Number of magnetic sensors and their arrangement allowed to perform confident identification of magnetic perturbations with poloidal wave numbers up to 5 inclusive.

A study of the MHD plasma activity was conducted in the quasistationary stage of the high-frequency discharge [1], where the energy content and the longitudinal plasma current remain constant. It was found that the MHD fluctuations are nonstationary and have a structure with poloidal wave numbers m = 0...4. In the frequency spectrum of oscillations in the range from 0.5 to 50 kHz several frequency ranges are observed where the amplitude of the oscillations reaches the maximum values. For processing of non-stationary oscillations, a special technique was developed.

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1-18

MHD PLASMA ACTIVITY IN THE U-3M TORSATRON DURING THE RF CLEANING MODE WITH A MAGNETIC FIELD $B_\phi(0)$ = 0.02 T

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In the considered mode of cleaning, plasma was created and heated by the frame antenna at a frequency $f_{RF} \approx 8.6$ MHz, the magnitude of the constant magnetic field was B_ϕ (0) ≈0.02 T, so that the ion cyclotron frequency was much lower than the heating frequency. The average plasma density was $\bar{n} \sim 1\mathrm{x}10^{18}\ \mathrm{m}^{-3}$, electron temperature was $T_e \sim$ 10 eV, working gas pressure was 10^{-4} Torr [1].

Using a set of 15 magnetic sensors installed in one of the poloidal sections of the torus, fluctuations of the poloidal magnetic field were recorded [2].

It was found that in the investigated frequency range 0...100 kHz, the spectrum of fluctuations of the poloidal magnetic field has two characteristic frequencies f ≈ 6 kHz and f ≈ 49 kHz. The dynamics of the intensity of the magnetic plasma fluctuations for the investigated frequencies was also studied. The spectrum of poloidal modes of magnetic fluctuations is analyzed.

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1-19

FINDIF CODE SIMULATIONS OF OP-1.1 WENDELSTEIN 7-X DISCHARGES

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The finite difference, multi-fluid code Findif is being developed as a flexible tool for 3D plasma edge simulations of fusion devices. Computational meshes for Findif are based on field line tracing. The code is parallelisable but can be run on a PC. Wendelstein 7-X, the world's biggest stellarator, is a particularly suitable testbed for edge simulations. The machine is equipped with numerous diagnostics, some of them aimed at investigating edge conditions. Numerous simulation, using state-of-the-art code EMC3-EIRENE are performed for W7-X; so, there is no shortage of data for comparisons. During the OP-1.1 campaign W7-X was equipped with a set of 5 limiters (one per period) as plasma facing components. Relatively high temperature of plasma hitting limiters allows us to neglect neutral dynamics, which our code does not currently simulate.

In our work we present first results of 4-equation (T_i, T_e, n_i, v_i) simulations of steady state discharges. We work with fixed magnetic field and consider 4 cases: standard magnetic configuration with big 5/5 islands, high mirror configuration with 3 values of plasma β= 0%, 0.84%, 1.7%. We compare heat loads on the limiters.

1-20

EFFECT OF RECYCLING FOR PHYSICAL PARAMETERS OF REACTOR-STELLARATOR

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The results of calculations of a stellarator reactor are presented, in which the influence of recycling on its physical parameters is taken into account. In earlier work on calculating the parameters of the stellarator reactor, it was assumed that all plasma lost as a result of neoclassical diffusion goes to the divertor, and its replenishment is carried out by injection of fuel pellets [1-4]. Such an ideal work of the divertor, apparently, is impossible to realize. Some of the plasma, which leaves behind the last closed magnetic surface, will remain in the vacuum chamber without getting into the divertor. In addition, part of the particles will escape from the plasma as a result of recharging. The particles thus lost will return to the plasma, partially replenishing the losses. In this paper, an attempt is made to evaluate the effect of such a process on the physical parameters of the reactor. As a result of the calculations, a significant dependence of the reactor parameters on the fraction of particles participating in the recycling is shown. With an increase in this fraction, the density profiles and temperatures of the reactor plasma become flat with increasing gradients near the plasma boundary. The reactor power level is lowered and higher additional heating powers are required to enter the self-sustained combustion regime.

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1-21

AMPLIFICATION OF THE RUNAWAY ELECTRONS FLOW IN THE TORSATRON URAGAN-3M

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In this paper, we present in more detail from one which was done in [1]. The results and conditions of increasing the runaway electrons flow possibility, which appear from the toroidal electric field at the leading edge of the magnetic field pulse of plasma build-up at Uragan-3M experiments. Dependences of the intensity of runaway electrons flow from the pressure of the working gas and on the intensity of the magnetic field are investigated. Dependences of the runaway electron intensity flow from the power and duration of the microwave oscillator pulse, which stimulated the formation of plasma by primary runaway electrons are given. The optimal delay of the microwave pulse relative to the rump-up of the magnetic field pulse was determined.

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1-22

INFLUENCE OF INJECTION OF IMPULSE GAS AND FLUCTUATIONS OF THE MAGNETIC FIELD ON THE RUNAWAY ELECTRONS DYNAMICS IN THE TORSATRON URAGAN-3M

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The influence of the fast injection of the molecular hydrogen gas on the dynamics of runaway electrons was investigated. The measured plasma radiation (microwave and hard X-rays frequency range) was conducted during the ramp up and at stationary phase of the magnetic field pulse. The possibility of suppressing the flow of runaway electrons during of gas injection on the magnetic field pulse rump-up and its consequences is shown. The expected creation of a preliminary plasma during interaction of runaway electrons with injected gas was not observed.

The influence of fluctuations of the magnetic field on the parameters of the flow of runaway electrons is considered. Fluctuations were of a natural nature, determined by the features of the magnetic field pulse, and created artificially.

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1-23

MASS-SPECTROMETER DIAGNOSTICS ATTACHED TO CRYOGENIC NITROGEN TRAP

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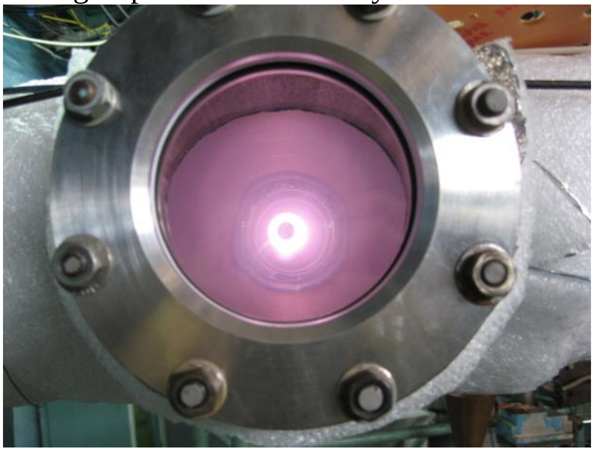
The mass-spectrometer diagnostics built at stellarator Uragan-2M for gas composition analysis is described. Mass-spectrum gas composition can be measured in two ways: with direct connection to Uragan-2M vacuum chamber and with connection to the diagnostic cryogenic trap [1] when it is warmed up. Highest possible precision measurements of mass-spectrum in stellarator Uragan-2M are possible when the wall conditions of the mass-spectrometer system are good enough not to distort measurements. Needed surface conditions were achieved through the sequence of procedures from washing to continuous conditioning RF discharge without the magnetic field [2]. Continuous RF discharge parameters: generator frequency is f=6…8 MHz, power is below 1 kW, working gas (hydrogen) pressure is about $1 \cdot 10^{-2}$ Torr. Two antenna types, rod and plate antennas, were used to ignite the discharge. Plasma discharge spread locally near antenna and its size increased proportionally to the input power. Such a wall conditioning improves considerably the wall conditions.



Continuous RF discharge without magnetic field in hydrogen inside vacuum branch

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1-24

CONCERNING SPACE DISTRIBUTION OF THE ION ENERGY IN U-3M

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The U-3M is equipped with two passive charge exchange (CX) neutral particle analyzers (NPA)[1,2] located in different toroidal cross-sections. In order to determine local CX flux source on the base of line-integrated data of the passive NPA inversion problem should be solved. Since two NPA are located in different toroidal cross-sections, 2D inversion methods are not applicable. We can use symmetry of the flux source as a simplification for dealing with 1D inversion problem instead. Correct solution of this problem is impossible due to the CX flux dependence on the concentrations of neutral hydrogen atoms and molecules. These concentrations in general are not a function of the magnetic surface, due to 3D geometry of U-3M [2]. Nonetheless this effect can be not so significant. In our work we assume that CX flux source is the function of the magnetic surface. We solve 1D inversion in two toroidal cross-sections under this assumption for similar plasma conditions. The local CX fluxes in the cross-sections "G-G" and "D-D" are calculated numerically on the base of experimental data. The U-3M magnetic surfaces have been approximated as a set of normalized plasma radius data in the grid covering this cross-sections. The local CX fluxes are determined as a function of the normalized radius. The line-integrated CX flux is calculated for every viewing area of each CX line-of-sight on the base of this local flux in the real geometry of the CX diagnostics. A fitting of the calculated line integrated CX flux in the cross-sections "G-G" and "D-D" profiles to the experimental profiles show that calculated local flux source profiles are rather similar in zero order approximations. Our calculations confirm previously published information about hollow CX fluxes profiles and hollow or flat ion temperature profile[1] in the low density frame antenna RF discharges of U-3M. This fact indicates that there is strong RF power deposition into ion component at the plasma periphery of U-3M.

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1-25

COMPUTER SIMULATION OF ELECTRIC FIELD EVOLUTION NEAR HF ANTENNA INSIDE MAGNETIZED PLASMA

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High frequency antennae are commonly applied as plasma heating devices for toroidal controlled fusion setups. Such antennae are typically positioned in a shape when the central wire is directed poloidally. That wire is usually bounded by side metallic walls to prevent the direct contact between the wire and hot plasma. Without such walls, plasma would form significant flows towards the wire along the magnetic field. This work is devoted to study the evolution of electric field potential in the area near such an antenna via the computer simulation in electrostatic approach.

2.5D hydrodynamic model (poloidal components were taken into account only for electrons' and ions velocities) was applied for 1-component Deuterium plasma in electrostatic approach. Equations' set for such a model was obtained in [1] and can be divided into three subsets, in particular – hydrodynamic equations for electron component, hydrodynamic equations for ion component and Poisson equation for electric field potential. In [1], that equations' set was significantly simplified and solved in diffusion approach. This work is devoted to numerical simulation for complete equations' set without any simplifications. Numerical model was built based on finite differences' method. From equations' set in finite differences, one can obtain recurrent formulae for electrons' and ions' velocities and densities in the next time step. Poisson Equation must be solved independently at each that step. For that purpose 2D matrix sweep method was applied. For all calculation described above, new software was developed with C++ programming language (Visual Studio 2013 environment). This software has a feature to apply various types of initial and boundary conditions.

Test simulation was carried out for the initial and boundary conditions similar to ones used in [1] for analytical calculations in diffusion approach. Those conditions include the Boltzmann-distributed ions' and electrons' streams towards the walls, HF oscillatory boundary condition for potential on wire and quasi-neutral boundary conditions for outside plasma. Also, densities of plasma components and their flows were considered continuous, as well as electric potential and radial component of electric field. Other important parameters was typical for controlled fusion setups: plasma concentration $2{\cdot}10^{18}$ m^{-3}, magnetic field 3 Tl, ion and electron temperatures were both 60 eV, heating field frequency and magnitude were $3{\cdot}10^{7}$ Hz and 20 kV respectively. Simulation results were obtained for initial 100 periods of HF electric field. Most of those results are very similar to ones obtained in [1] for diffusion approach. That results' coordination confirms the reliability of the developed simulation software.

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1-26

WALL CONDITIONING DISCHARGES DRIVEN BY T-SHAPED ANTENNA IN URAGAN-2M

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The new T-shaped unshielded antenna proposed by one of the authors (V.M.) was used for inner surfaces conditioning of Uragan-2M [1] chamber. The T-shaped antenna is a monopolar quarter-wave vibrator adjusted to the fitting of the vacuum chamber (16 cm diameter) and better matched with plasma resistance. It was used for the VHF discharge [2] with low density and low electron temperature plasma creation. As the method of chemical vacuum chamber wall conditioning [3] requires Franck-Condon ions. Finding the optimal regime for creation and maintaining continuous conditioning plasma discharge in small magnetic field and without it [4] was the main goal of the work. The most effective wall conditioning regime with magnetic field was run with B_0=100 Oe, $p_{H2}=1\cdot10^{-4}$ Torr. The optimal conditioning regime without magnetic field was found at p_{H2}=6 Torr. The plasma electron density and temperature and their spatial distribution were measured with movable the Langmuir probs and optical diagnostic. While the Langmuir probe measured the electron temperature precisely, the optical diagnostic allowed one to monitor the discharge. Both regimes were assessed and compared according to the nitrogen trap diagnostics and thermal desorption probe method [5]. The nitrogen trap [6] showed increased amount of condensate according to the amount of released gas during conditioning. The thermal desorption probe was heated to 300°C before and after the conditioning sessions to estimate the amount of deposited molecular layers on the surface of the Uragan-2M vacuum chamber walls.

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1-27

A SCENARIO OF PULSED ECRH WALL CONDITIONING IN HYDROGEN FOR THE WENDELSTEIN 7-X HELIAS

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A study of a chain of ultra-short pulsed Electron Cyclotron Resonance Heating (ECRH) discharges was proposed and started. The aim of the discharge chain is to improve wall conditioning in W7-X, basing on the results of the numerical modeling with 1D model [1]. The proposal employs wall conditioning in hydrogen and relies upon production of atomic hydrogen in plasma which interacts chemically with the impurities adsorbed on the chamber surface facing to plasma.

During two weeks in the beginning of the W7-X experimental campaign OP1.2b, successful discharges were done in accordance to the proposed scenario, with a single and four ECRH pulse start-ups with use of a pre-ionization plasma:

- A single ECRH pulse of 3 ms duration creates plasma of half density compared with preceding pulse ended 0.9 s before
- There are indications that the plasma is not fully ionized (optical lines behavior, half plasma density), and the atomic hydrogen generation is expected
- Plasma decay is quite fast. It is rather recombination-like than diffusive. This allows one to use high repetition rate (5 Hz)
- The H-alpha visible spectroscopy camera indicates volumetric plasma production during pulses
- A chain of 4 pulses accompanied with gas puff is successful. Such a chain may be a base for an Electron Cyclotron Wall Conditioning scenario.

The feasibility of the proposed scenario implementation seems to be realistic. A full elaboration of the optimal atomic hydrogen-based scenario for the wall conditioning using an ECRH driver in W7-X is planned.

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1-28

TRITIUM BREEDING CALCULATION IN A STELLARATOR BLANKET

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A main function a blanket of fusion machines [1] is turning the kinetic energy of fusion neutrons to the thermal energy of cooling liquid or gas. It also aimed to protect surrounding of neutron and gamma radiation. Besides, fusion needs tritium as a fuel. It is synthetic element which should be preferably produced at the place. In this case the tritium production should be integrated into the blanket.

In current blanket projects, tritium breeding ratio (TBR), the ratio of tritium production rate to the neutron production rate, is unsatisfactorily low, 1.1 – 1.2. The purpose of this study is to investigate a principal possibility of increase TBR within a stellarator blanket limited space. The MCNPX Monte-Carlo code has been used to model the neutron kinetics and to calculate tritium production.

The report presents a model of a stellarator blanket, calculation results for the neutron flux and spectrum at the different places at the blanket and tritium production at the zone filled by lithium. Different designs of the blanket are analyzed and compared.

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2-01

CHARACTERIZATION OF MACROSCOPIC EROSION OF CASTELLATED AND FLAT TUNGSTEN SURFACES UNDER ITER–LIKE TRANSIENT PLASMA LOADS

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Understanding of plasma-surface interaction (PSI) effects during the transient events in future fusion reactors requires dedicated R&D activity in plasma simulators used in close connection with material characterization facilities as well as with numerical modeling. This report is focused on the analysis of surface tension contribution to the erosion features of tungsten resolidified surfaces and resulting material response to large number of repetitive plasma impacts.

Experimental investigations of erosion processes on plane and castellated tungsten surfaces in conditions relevant to ITER ELMs have been performed within powerful quasi-stationary plasma accelerator QSPA Kh-50. The main parameters of hydrogen plasma streams were as follows: ion impact energy was about 0.4-0.6 keV, the maximum plasma pressure amounted to 0.32 MPa, and the stream diameter was equal to about 18 cm. The plasma pulse duration was equal to 0.25 ms. The surface energy load measured with a calorimeter was varied between the melting (0.6 MJ/m^2) and evaporation (1.1 MJ/m^2) thresholds.

Observations of plasma interactions with exposed W surfaces, analysis of dust particle dynamics and the droplets monitoring have been performed with a high-speed digital camera. Development of surface pattern and material modification in results of plasma exposures have been studied with optical and SEM microscopy, profilometry and XRD.

Repetitive plasma loads above the melting threshold led to formation of melted and resolidified surface layers. Networks both macro and intergranular cracks appeared on exposed surfaces. Cracks propagate to the bulk mainly transversely to the irradiated surface. The splashing of dust/liquid particles has been analyzed in the course of repetitive plasma pulses. It was revealed that mountains of displaced material at the edges of castellated units are primary source of the splashed droplets. The solid dust ejection dominates by cracking processes after the end of pulse and surface resolidification.

Due to the continuously growing crack width (from fraction till tens μm) with increasing number of pulses the initially uniform melt pool on the castellated units became disintegrated into a set of melt structures separated by cracks. As result, a number of ejected particles essentially decreased after first hundred plasma pulses. Further increase of repetitive plasma impacts (above 200) led to considerable qualitative changes of surface morphology. Each cell of the crack network is strongly subjected to the surface tension that minimizes melt pool area. After large number of exposures the progressive corrugation of the surface occurred due to the capillary effects on exposed W surfaces.

Results of simulation experiments for castellated targets and developed surface structures are compared with repetitive plasma exposures of flat tungsten surfaces. Important contribution of surface tension to the erosion processes under the ELM relevant repetitive loads and it influence on suppression of droplets splashing is discussed.

2-02

CLEANING OF METALLIC MIRRORS FROM CARBON-CONTAINING FILMS BY HYDROGEN PLASMA: NEW POSSIBILITIES FOR IN SITU MONITORING

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During experimental campaigns with plasma in Uragan-2M (2015 and 2016 years) several stainless steel (SS) mirror samples and two glass samples were exposed in different poloidal cross sections of the vacuum chamber. After experiments the reflectance (*R*) of SS samples in the wavelength 220-650 nm at normal incidence and transmission (*T*) of glass samples in the range 400-650 nm were measured. The results indicated on appearance of some deposit, what resulted in degradation of reflectance (SS samples) and transmission (glasses). The decrease of *R* varied between ~2.5% and ~32% (at λ=500 nm), depending on the location of mirrors in the vacuum vessel of U-2M. The deepest drop (32.4 %) was observed for the sample closest to the RF antenna used for plasma production. After taking off from the U-2M chamber, all samples were subjected to impact with low energy ions of hydrogen or deuterium plasma produced in conditions of electron cyclotron resonance (ECR) in the DCM-2 stand, what provided practically full *R* restoration for SS samples. The only exclusion was the sample placed nearby the RF antenna: in comparison to other samples much longer exposure to ions of D plasma with much higher energy was needed for full cleaning. This fact is an evident indication that the layer appeared on the surface of this sample contains some portion of metallic component.

The transmission of the glass sample was not restored even for 5 exposures (2.5 hours) in Ar and in D_2 plasmas, whereas the SS sample in its immediate vicinity was easily cleaned in one exposure in D_2 plasma. The reason of this could be modification of the uppermost glass layer.

To clear up the physical processes realizing when ions of D plasma impact on C-containing deposit, special experiments were provided at the DSM-2 stand. When exposing in DSM-2 the holder of samples was isolated from vacuum camera, what made possible to supply either positive or negative potential. The C-containing films on SS mirror-like samples (size 22x22 mm^2) were deposited in a special installation by using a non-self-sustained discharge that was exited in propane-butane mixture under a pressure of $4\cdot10^{-3}$ Torr.

The samples coated with C:H film were exposed to plasma ions through sapphire diaphragm with diameter 8 mm, thus there was possibility to have 4 exposures at different accelerating voltage for the same C film. Control of the removal efficiency of the C:H coating was carried out by optical and resistive methods.

It was found that cleaning of sample from C film can be almost equally effective either with negative sample voltage, when D_2^+ ions are accelerated, or with positive voltage that decelerates positive ions. This a not obvious result can be explained if: (i) the ion component of the ECR plasma in DSM-2 consists not only of positive D_2^+ ions but of negative D^- ions also, and (ii) the electrons with energy a few tens of eV can effectively break the C-C bonds of a C film, giving chance to form volatile hydro-carbon molecules, which are pumped out. In addition, small fraction of water vapor in vacuum vessel guaranties appearance of O^- ions, which can actively interact with C-film forming the volatile carbon oxide molecules. Thus, for successful cleaning of C-H film the direct contact of H^- or D^- plasma with the surface is needed.

Both these possibilities, (i) and (ii), of C-film erosion in D_2 ECR plasma can be proved by results of other authors in recent experiments with thin C films, what will be discussed in detail in the report.

2-03

FEATURES OF SURFACE MODIFICATION OF COPPER-BASED ALLOYS UNDER POWERFUL PLASMA EXPOSURES

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Copper-based alloys are widely used in heat transfer elements for electronics, nuclear fusion technology and many other areas du to their excellent thermal conductivity, strength and fatigue resistance. Such alloys, e.g. Cu-Cr-Zr, could be used as basis to construct heat sinks for first wall and divertor components of ITER. However, various changes of mechanical properties could be driven in copper alloys under the plasma exposures with extreme energy and particle loads.

The report presents experimental results on surface modifications and materials alloying under the plasma exposures. In particular, modification of thin multilayered coatings mixed with Cu substrate in a liquid phase under the plasma processing is analyzed.

Ti-Cr, Ti-Cr-Ti-Nb, Ti-Cr-Ti-Zr, Ti-Cr-Ti-ZrO multilayer PVD coatings have been deposited within a Bulat-type facility. Experiments on surface modification were carried out with a quasi-stationary plasma accelerator QSPA Kh-50. The main parameters of QSPA plasma streams were as follows: ion impact energy was about 0.4-0.6 keV, the maximum plasma pressure amounted to 0.32 MPa, and the stream diameter was equal to about 18 cm. The surface energy loads measured with a calorimeter achieved 0.6 MJ/m^2 and the pulse duration was 0.25 ms. Surface diagnostics included an optical and scanning electron microscopy, profilometry as well as microhardness, roughness and weight loss measurements.

Features of plasma alloying of Cu-based materials with Ti-Cr, Ti-Cr-Ti-Nb, Ti-Cr-Ti-Zr, Ti-Cr-Ti-ZrO have been studied in different regimes of exposures. It is shown that modified surface layer with homogeneous structure and thickness up to 10 μm has been formed in result of pulsed plasma treatment. Influence of plasma impacts on crack development for different copper alloys has been analyzed. Obtained results showed the favorable influence of alloying additions (Cr-Zr, Cr-Nb) on behavior of Cu-based materials under the high heat loads.

2-04

IMPLANTATION OF DEUTERIUM AND HELIUM IONS INTO TANTALUM-COATED COMPOSITE STRUCTURES

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Multilayered functional structures with vacuum-deposited coatings of tungsten or tantalum are considered as promising materials for use in plasma-contact devices in CTF installations. The possibility of their use to a large extent depends on their radiation resistance to the accumulation of own and impurity defects, such as particles of helium and isotopes hydrogen, which are formed as a result of the exposure of plasma beams. This problem is relevant, therefore recently [1-4] authors intensively studied it aimed to increase the radiation stability of the CTF devices by obtaining new materials with improved parameters using ion implantation techniques. In the work the processes of accumulation and thermal release of implanted deuterium and helium from tantalum coatings of multilayer composite structures by thermodesorption spectrometry were investigated.

Tantalum coatings of 1 μm and 1.5 μm thickness deposited by the magnetron sputtering of the Ta target in the Ar atmosphere on the substrate of stainless steel were irradiated with 10 keV D^+ (20 keV D_2^+) or 20 keV He^+ up to doses in interval $(0.1 – 1.2) \times 10^{18}$ cm^{-2} at the target temperatures in the range (290 – 670) K.

The spectra of thermal desorption of deuterium and helium from tantalum coatings of the composite structure (SSt + Ta (μm)) were investigated. The temperature intervals of the release of helium and deuterium in a vacuum, the predominant peaks of the thermodesorption of the implanted gases from the irradiated samples after the post irradiation heating were revealed; the coefficients of retention of helium and deuterium in the tantalum coating were determined. The influence of the D^+ and He^+ ions irradiation dose and the target temperature on the caption and release of implanted gases for the Ta coating were studied. A comparison with the results [1, 2] between the accumulation and thermal desorption of deuterium and helium in tungsten coatings was made. It was established that in tantalum coating as well as in tungsten one, concentration of accumulated deuterium was lower than concentration of helium, its capture coefficient was approximately one order lower. Helium accumulates almost in the same way for both coatings.

An assumption about the mechanisms of accumulation of deuterium and helium in Ta coatings irradiated with ions of these gases was made. The influence on the structural properties and radiation resistance of multilayer tantalum coating of functional structures was determined.

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2-05

ON RELATIVISTIC EFFECTS IN ELECTRON TRANSPORT IN THE BANANA REGIME

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In thermonuclear fusion reactors the characteristic temperatures of burning plasmas should reach 20-30 keV or higher. At such temperatures the bulk electrons in plasmas are in fact relativistic, so kinetics and transport physics for electrons should be generally described in the relativistic approach. In particular, calculations of neoclassical particle and heat fluxes for a fusion-relevant temperatures have to be carefully reconsidered starting from the relativistic drift-kinetic equation. At the same time, there is no need to build a completely new fully-relativistic neoclassical theory. For a fusion reactor physics it seems sufficient to account only the first order relativistic effects, which arise from the relativistic drift-kinetic equation and relativistic thermal equilibrium for electrons.

At the moment, practically all known numerical transport codes that are used for calculations of neoclassical transport in tokamaks and stellarators are non-relativistic, and thus it is instructive to obtain the final relativistic formulation in the form which can be incorporated directly into the existing transport codes. This approach was recently used to study the role of relativistic effects in stellarators [2]. Similarly, the aim of the present work is to update the standard procedure of calculating electron transport in the banana regime for an axisymmetric tokamak [1] by taking into account the relativistic effects for electrons. Our approach is based on the relativistic drift-kinetic equation and assumption that the local thermal equilibrium of electrons is described by the relativistic Maxwell-Jüttner distribution function. The results are expected to be suitable for implementation into the existing transport codes.

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2-06

TRITIUM BREEDING RATIO IN TOROIDAL FUSION BLANKET

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Tritium breeding is a critical point of a fusion reactor to be self-sustained. In current breeding scenarios the tritium breeding ratio (TBR) is only slightly higher than unity. Small TBR creates technical problems and makes fusion dependent on other nuclear technologies. Even small its increase would be highly favourable. Optimization conditions for nuclear reaction (n,2n) and usage of the transuranic elements is studied to increase TBR in conditions of limited space offered to a fusion blanket in stellarators. The study is performed numerically by modelling neutron kinetics and using Monte-Carlo codes, such as MCNPX.

2-07

EFFECTS OF WATER BATHING ON OPTICAL PROPERTIES OF METALLIC MIRROR SAMPLES

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Recently a quite detail experiments were provided with an aim "to understand the impact of accidental in-vessel coolant leaks on port plug optical samples" [1]. The authors of that report investigated the behavior of many mirror samples of different materials from several suppliers under impact of water steam and high temperature (≤250 °C), as imitation of the impact of accidental in-vessel coolant leaks on components of optical diagnostics in ITER.

In contrast, we are going to present the results on how the exposure of metal mirror samples in water of much lower temperature (100 °C and RT) or in water vapor (~100 °C) influences the optical properties of mirrors. Such data can be useful to predict the behavior of in-vessel mirrors of optical and laser plasma diagnostics in ITER in the case of water inrush event.

The experiments were provided with samples prepared from: single crystal Mo (100) and Mo (110), polycrystal W and ITER grade W, amorphous alloy Zr41.2Ti13.8Cu12.5Ni10Be22.5, and stainless steel. All samples were polished to a mirror-like quality and before the water test each of them was cleaned by a short exposure to ions of Ar or D plasma produced in conditions of electron cyclotron resonance (ECR) in a simple mirror-like magnetic device. The reflectance *R* in the wavelength 220-650 nm was measured just after cleaning, after water impact, and at the stage of reflectance restoration by successive exposing in ECR plasma. The change of the surface stage of all samples was controlled with optical microscope.

It was found out that exposure in water (or in water vapors) resulted in significant drop of reflectance, the most noticeably – for Mo mirror samples, in spite they have a single crystal structure. The degradation of R increased with increasing time of sample bathing and especially in the case of the water temperature 100 °C. The samples made of stainless steel and amorphous alloy proved to be the most resistant to water impact. The reflectance of all samples can be restored by exposing them in Ar or D_2 plasma produced in conditions of ECR discharge.

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2-08

EFFECTS OF IMPACT OF D_2 AND Ar PLASMA IONS ON MIRROR SAMPLES FABRICATED FROM AMORPHOUS ALLOYS

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The samples of two kinds of bulk metallic glasses (BMG) with different compositions, Zr48Cu36Al8Ag8 (grade 4) and Zr57Cu15.4Al10Ni12.6Nb5 (grade 5), were polished to mirror-like quality and, after measuring the initial reflectance at normal incidence, were subjected to impact of ions of deuterium or argon plasma with fixed energy (up to 600 eV) by supplying negative voltage to a sample holder. The main attention was paid to phenomenon on deuterium absorption that reveals as the weight gain after every exposure of samples in deuterium plasma. Other effects to study that become apparent when BMG samples were exposed in D plasma, were: change of reflectance, change of relief, change of sample shape.

At accelerating voltage below 120 eV, the amount of absorbed deuterium was found to rise linearly with increasing D ion fluence. The efficiency of absorption, i.e., the ratio of trapped deuterium atoms to the total fluence of D particles (supposing all ions are D_2^+) was in the range ~30% for both grades of BMG. For accelerating voltage exceeding 120 eV two opposite processes became to manifest themselves, i.e., deuterium uptake and sputtering of samples by ions of deuterium plasma, and with the ion energy >450 eV the sputtering process becomes to be predominant: the weight decreased after exposure in those conditions. The main reason of sputtering are ions of impurities in D plasma discharge, mainly, oxygen (several percent).

The absorption of deuterium causes a local increase in the volume of the near-surface layer, what is manifested in the bending of the sample in such a way that the side exposed to ions of deuterium plasma becomes convex. The curvature of the irradiated surface of the sample varies in proportion to the ion fluence and the amount of captured deuterium, what indicates on the localization of deuterium in a near-surface layer with the thickness weakly varying with time. The curvature is the consequence of the increase of the interatomic distance as follows from data of X-ray analysis, namely, from the position of the maximum on angular X-ray diagrams.

The exposure to D plasma ions of the opposite side of the bended sample resulted in its gradual straightening and bending in opposite direction, thus the initially convex side was becoming to be the concave one and vice versa. Important, that D accumulation, bending and straightening of the grade 5 samples do not influence behavior of their optical properties.

In the case of grade 4 samples, exposure in deuterium plasma lead to appearance of surface relief indicating that the amorphization of the cast is not complete. This fact, however, did not influence on the efficiency of D absorption and on bending or straightening of samples.

The rate of sputtering by Ar+ ions of grade 5 sample was measured factor two below the value published for the Zr, the metal component of alloy mostly resistant to sputtering [1, 2].

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2-09

EIGENVALUES AND EIGENFIELDS OF A CORRUGATED GYROTRON CAVITY WITH CONDUCTING WALLS

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Nowadays millimeter and submillimeter gyrotrons are subject of much interest due to widespread applications in spectroscopy, medical technologies, material processing, space research, security systems, etc. However, the best known and the main gyrotron application is electron-cyclotron heating of magnetically confined plasma in controlled thermonuclear fusion devices. In particular, more than twenty 170-GHz MW-class continuous wave gyrotrons are now under development worldwide for use in the heating system of the International Thermonuclear Experimental Reactor (ITER). Of special interest are gyrotrons operated at higher harmonics of cyclotron frequency because of the lower requirement on external magnetic field. The disadvantage of such gyrotrons is the competition of the operating gyrotron mode with the first (fundamental) cyclotron harmonic modes. This mode competition shortens the operating region of harmonic gyrotrons, reduces their efficiency and output power.

We consider the modified cylindrical gyrotron cavity with longitudinal wall corrugations. Such cavity has been proposed in [2] for use in harmonic gyrotrons. It affects distinctly the eigenvalues of cavity modes and thus can be used to suppress selectively the fundamental competing modes. The investigations in [2] have been performed on the basis of the approximate surface impedance model (SIM). In SIM, the corrugated walls are approximated by a smooth surface with averaged (effective) anisotropic impedance, which depends on the corrugation parameters. However, as was shown in [3], [4], SIM validity may fail for some of these parameters. The reason is noticeable coupling between Bloch harmonics of corrugated cavity. Additional effect can be related to the finite cavity conductivity, which was neglected in [4]. It leads to nonzero Ohmic losses in cavity walls [5].

In this study, the results of [4] have been extended to take into account the finite conductivity of cavity material. The eigenvalues, eigenfields and Ohmic losses of cavity modes have been calculated on the basis of full-wave approach. Their good convergence with respect to the number of Bloch harmonics has been demonstrated. It has been shown that the approximate surface impedance model is inadequate, when the number of corrugations is relatively small. This is because SIM ignores higher Bloch harmonics. It has been shown that effect of these harmonics on the total cavity fields diminishes with increasing number of corrugations. This process, however, is rather slow.

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3-01

FULLY RELATIVISTIC APPROACH TO THE THEORY OF SLOW AND PLASMA ECRF WAVES

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The theoretical study of the slow and plasma ECRF waves in magnetic traps requires accurate taking into account relativistic effects, connected with an increase in the mass of sufficiently fast electrons.

The ground for such a study is the exact evaluation of the fully relativistic plasma dielectric tensor for the conditions $\lambda = (k_\perp \rho_e)^2 \sim 1$ and $\lambda = (k_\perp \rho_e)^2 > 1$, where $k_\perp$ is the perpendicular wave number and ρ_e is the electron Larmor radius.

Such a problem for the case $N_{\parallel} = k_{\parallel} c / \omega < 1$, where $N_{\parallel}$ is longitudinal refractive index, was analytically resolved in the work [1].

The main purpose of the present paper is the further progress to resolve numerically this problem and analytically and numerically for the opposite case $N_{\parallel} > 1$.

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3-02

FLUCTUATIONS AND ION-ACOUSTIC WAVES IN COLLISIONAL DUSTY PLASMA: EFFECTS OF GRAIN CHARGING DYNAMICS

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The grains in a dusty plasma acquire electric charges due to absorption of electrons and ions i.e. grains are charged by the plasma currents. In the stationary state, the total current on the grain surface is equal to zero. The fluctuations of the charging currents lead to the fluctuations of the stationary grain charge. Moreover, the grain charges depend on electromagnetic field and give additional dielectric polarization of the medium.

In the present contribution the kinetic theory of electric field fluctuations in a dusty collisional plasma is formulated with due regard to the grain charging dynamics. The expressions for dielectric permittivity $\varepsilon(\mathbf{k},\omega)$ [1] and correlation functions $\langle\delta\rho_\alpha^2\rangle_{\mathbf{k}\omega}$ of electron ($\alpha = e$)

$$\langle\delta\rho_e^2\rangle_{\mathbf{k}\omega} = \left|1-\frac{\chi_e(\mathbf{k},\omega)}{\varepsilon(\mathbf{k},\omega)}\left(1+\frac{i\nu_{eg}}{\omega+i\nu_{\text{ch}}}\right)\right|^2 \langle\delta\rho_e^{(0)2}\rangle_{\mathbf{k}\omega} + \left|\frac{\chi_e(\mathbf{k},\omega)}{\varepsilon(\mathbf{k},\omega)}\left(1+\frac{i\nu_{ig}}{\omega+i\nu_{\text{ch}}}\right)\right|^2 \langle\delta\rho_i^{(0)2}\rangle_{\mathbf{k}\omega} \qquad (1)$$

and ion ($\alpha = i$) density are obtained with account to particle collisions within the Bhatnagar-Gross-Krook (BGK) model. Here $\chi_e(\mathbf{k},\omega)$ is the electron susceptibility, $\nu_{\alpha g}$ is the frequency of collisions between plasma particles and grains, $\nu_{\text{ch}} = \nu_{\text{ch}}^e + \nu_{\text{ch}}^i$ is the charging frequency (ν_{ch}^α is the derivative on the grain charge of the charging current, which is described by the Khrapak-Morfill interpolation formula [2]).

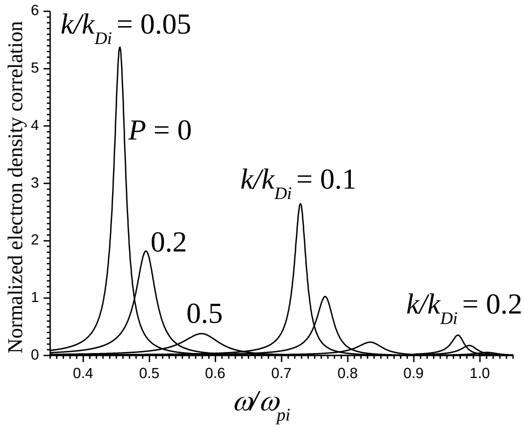

Fig. 1 Normalized electron density correlation $\langle\delta n_\alpha^2\rangle_{\mathbf{k}\omega}\omega_{pi}/n_i$ in nonisothermal ($\tau = 100$) argon plasma for $\nu_{in} = 0.02\omega_{pi}$, $ak_D = 0.15$, $k/k_{Di} = 0.05, 0.1, 0.2$ and $P = 0, 0.2, 0.5$.

The fluctuation spectra in strongly nonisothermal ($\tau = 100$) plasma computed from Eq. (1) are presented in Fig. 1. The positions and intensities of maxima depend on the wave number and coincide with the eigenfrequencies $\omega_{\mathbf{k}}$ of ion-acoustic waves in dusty plasma that are the solutions of dispersion equation $\varepsilon(\mathbf{k},\omega_{\mathbf{k}} + i\gamma_{\mathbf{k}}) = 0$ [1]. The presence of grains leads to the shift of fluctuation maxima toward higher frequency and to decrease of fluctuation intensity. The increase of the eigenfrequency is caused by the decrease of electron to ion density ratio $n_e/n_i = 1-P$, where $P = e_g n_g / e_i n_i$ is the Havnes parameter. The decrease of the fluctuation intensity and the increase of ion-acoustic waves damping are caused by the collisions of electrons and ions with grains and neutrals as well as by the grain charging dynamics.

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3-03

VELOCITY DISPERSION OF DUST PARTICLES CONFINED IN A SHEATH

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A behavior of dust particles immersed in plasma has been of considerable interest over the last three decades. One of the unusual effects observed in such a system is an anomalously high kinetic temperature of dust particles which significantly exceeds the temperature of the plasma environment. This effect was studied experimentally [1] and theoretically [2], and is the subject of our consideration.

In experiments dust particles are placed in a plasma layer where an electric field balances the force of gravity. This may be electric field of DC sheath, or ponderomotive force generated in RF sheath. Being in a sheath dust particles are not in a state of thermal equilibrium. Thus the more precise characteristic of particle motion is kinetic energy associated with incoherent motion or velocity dispersion that can be obtained from experimental velocity measurements [3].

A charge of a dust particle does not remain constant in time but fluctuates due to interaction with plasma environment. We consider the elementary mechanism of particle motion randomization in constant and alternating nonuniform electric fields due to fluctuations of their charge. The temporal variation of dusty particle velocity dispersion is found numerically. A dependence of the velocity dispersion on parameters of dust particles is discussed.

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3-04

CYCLOTRON WAVE-PARTICLE INTERACTIONS IN CURRENT-CARRYING PLASMAS

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Effective schemes of plasma heating in tokamaks can be realized by the collisionless wave dissipation in the range of ion-cyclotron and/or electron-cyclotron frequencies (fundamental cyclotron resonances: $\ell = 1$ for ions - ICR, $\ell = -1$ for electrons - ECR) and their harmonics $(|\ell| \geq 2)$. As is well known, the electromagnetic waves are always absorbed in equilibrium plasma models, e.g. with the maxwellian distribution functions of charged particles. However, the presence of energetic particles with non-equilibrium distributions can leads to plasma-wave instability observed as ion-cyclotron and electron-cyclotron emissions under the ICR and ECR plasma heating, respectively. Of course, other sources of instabilities may be resonant ions produced by neutral beam injection or by fusion-burn alpha particles. To estimate the damping/growth rates of electromagnetic waves in any plasma model we should know the conditions of resonant wave-particle interactions there. The corresponding resonant conditions can be derived automatically by solving the linearized Vlasov equation for perturbed distribution functions of plasma particles, accounting for the geometry of a confinement magnetic field. In this paper we discuss the cyclotron wave-particle interactions in the cylindrical current-carrying plasma (i.e. with a helical magnetic field) and in the two-dimensional (2D) axisymmetric toroidal plasma models for tokamaks with circular, elliptic and D-shaped cross-sections of the magnetic surfaces. It is shown that the Doppler shift at the cyclotron resonance conditions in the current-carrying plasmas is entirely different from ones for plasmas in uniform magnetic field: $k_{||}\upsilon_{||} = \omega - \ell\Omega_\alpha$, where $\ell = \pm1, \pm2, \ldots$ is the cyclotron harmonic number; Ω_α is the Larmor frequency of ions $(\alpha = i)$ and electrons $(\alpha = e)$; $k_{||} = \mathbf{kh} = k_z$ is the parallel wave-number relatively to confinement magnetic field $\mathbf{H}_0 = H_0\mathbf{e}_z$, $\mathbf{h} = \mathbf{H}_0 / H_0$. Another rough (but more adequate) 1D model of tokamaks is a magnetized current-carrying plasma cylinder with identical ends in the helical magnetic field, where the longitudinal ohmic current generates the poloidal magnetic field $\mathbf{H}_{0\theta} = H_{0\theta}\mathbf{e}_\theta$ in addition to the longitudinal $\mathbf{H}_{0z} = H_{0z}\mathbf{e}_z$. In this case the length of plasma cylinder is equal to $2\pi R_0$, where R_0 corresponds to the main tokamak radius. As a result, the stationary field $\mathbf{H}_0 = \mathbf{H}_{0\theta} + \mathbf{H}_{0z}$ becomes helical with substantial rotational transformation, allowing to take into account the so-called shear effects and the radial profiles of ohmic current by the radial dependence of plasma safety factor $q(r)$. The cyclotron resonance conditions in this case can be expressed as $(k_{||} + \ell\chi)\upsilon_{||} = \omega - \ell\Omega_\alpha$, where $k_{||} = \mathbf{kh} = \dfrac{m + nq}{R_0 q}$; m and n are the poloidal and toroidal wave-numbers, respectively, $\chi = \left(2 - \dfrac{r}{2q}\dfrac{dq}{dr}\right)/(R_0 q)$. The wave-particle resonance conditions in the 2D tokamak models are more complicated since there are involved (in addition to χ-corrections) the bounce-resonances ($p = 0,\ \pm1,\ \pm2,\ \ldots$) for untrapped $\dfrac{2\pi\upsilon}{R_0 q T_u}\left(p + nq + \ell\chi_u\right) = \omega - \ell\Omega_{0\alpha}\bar{g}_u$ and trapped $\dfrac{2\pi\upsilon}{R_0 q T_t}\, p = \omega - \ell\Omega_{c0}\bar{g}_t$ particles. Here $\Omega_{0\alpha}\bar{g}_u$ and $\Omega_{0\alpha}\bar{g}_t$ are the bounce-averaged cyclotron frequencies of untrapped (u) and trapped (t) particles: $g(r,\theta) = H_0(r,\theta)/H_0(0,0)$, $\upsilon = \sqrt{\upsilon_{||}^2 + \upsilon_\perp^2}$, T_u and T_t are corresponding to transit-time and bounce-period of u- and t-particles, respectively.

3-05

ENERGY DISSIPATION IN HELICON PLASMA AT THE NEAR FIELD OF AN ANTENNA

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As well known the helicon waves propagate in magnetized plasmas for frequencies between the ion and electron cyclotron frequencies and have been found to be very effective in creating high plasma densities both in linear and toroidal systems.

This report presents the results of computer simulation of energy dissipation in helicon plasma at near field of an antenna. Results are reported for a double-half-turn antenna, and comparison is made to a double-saddle-coil antenna which demonstrates the distinct inductive and helicon-wave modes.

The computer simulation revealed a significant wave-particle interaction in the near-field of the antenna that is less than half wavelengths from the antenna. Namely, in addition to the ohmic heating from the currents induced by the helicon wave, electrons can become trapped in the traveling helicon wave via the resonance condition given by $\omega - k_{\parallel} v_{\parallel} = 0$, where $k_{\parallel}$ and $v_{\parallel}$ are the wave vector and electron velocity, respectively, parallel to the axial magnetic field. Considerable attention has been paid to the ‘‘helicon jump’’ above which the plasma was assumed to be operating with helicon wave heating. A large increase in plasma density (n_0), coupled with decreases in plasma potential (V_p), and the electron temperature (T_e), have been computed across the jump, and a fundamental change in the EM-mode are shown.

Based on the RF wave-fields that exist in the plasma, three distinct modes of operation are considered which usually one labels as capacitive "E-mode", inductive "H-mode" and helicon-wave mode "W-mode". Presence of two abrupt changes in plasma-density profiles, "jumps", is confirmed by computer simulation. The first jump occurs at the E–H mode transition, and the second at the H–W mode transition.

3-06

PRTICLE SUBENSEMBLES IN RANDOM FIELD WITH FINITE CORRELATION TIME

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We study particle transport in random electric field across uniform magnetic field. Our analytical approach is based on the microscopic description of particle motion, and accounts for particle trapping effects [1, 2], finite Larmor radius effects [3, 4] and arbitrary correlation times. Recently we generalized our approach for a frozen random field to account for particle subensembles by initial random potential [5]. It recovers the results of direct numerical simulation more accurately.

Here we apply the approach with subensembles to various finite Larmor radius and finite correlation times of random field. The dependence of mean square displacement and kurtosis in subensembles of particles on correlation time is calculated. We compare particle dynamics in different subensembles for various correlation times. The results of analytical approximation are checked by direct numerical simulation. The role of particle subensembles is discussed.

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3-07

RADIATION FROM PLASMA DUE TO PARAMETRIC EXCITATION OF CONVECTIVE CELLS

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The process of plasma radiation is studied when the transformation of an longitudinal Langmuir wave into the transverse electromagnetic wave occurs. The transformation takes place on turbulent plasma fluctuations in the presence of upper hybrid pump wave parametric instability. We consider the parametric decay of such wave into the daughter upper hybrid wave and modified convective cells. It is shown that the main contribution to the correlator of electron density which defines the value of transformation coefficient is given by low-frequency plasma oscillations (convective cells).

Notice must be taken that convective modes arise in magnetized plasma with a small ratio of the plasma pressure to the magnetic pressure, and can occur in the ionospheric plasma.

The transformation coefficient is calculated. We demonstrate the dominant role of the pump wave term which is essentially depend on the pump wave amplitude and frequency.
For typical ionospheric plasma parameters in the F layer at about 250 km, we show that the pump wave term can exceed by several orders of magnitude the analogous one for the case of stable plasma (the parametric instability is absent) when the level of plasma density fluctuations is determined by the thermal noise.

The intensity of transverse waves radiation from turbulent plasma is calculated and its dependence on convective cells frequency and damping rate is obtained

3-08

PROPERTIES OF CHARGED PARTICLE MOTION EQUATIONS IN CROSSED FIELDS AND LARMOR'S THEOREM

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The Larmor theorem is known in electrodynamics, according to which "in the nonrelativistic case, the behavior of a system of charges all having the same e/m, performing a finite motion in a centrally symmetric electric field $\vec{E}$ and in a weak uniform magnetic field $\vec{H}$, is equivalent to the behavior of the same system of charges in the same electric field in a coordinate system rotating uniformly with the angular velocity $\vec{\omega}_{rot} = (e/2mc)\vec{H}$ "[1].

In present report charged particle motion equations in crossed fields in the laboratory and in rotating coordinate systems are compared. A homogeneous magnetic field is assumed to be arbitrary, not necessarily weak, as it is assumed in Larmor's theorem. The radial electric field has a spherical or cylindrical symmetry, an arbitrary dependence on the radius.

1. The comparison shows that in the coordinate system rotating at a given frequency ω_{rot}, the equation of motion in fields E, H in a plane transverse to the magnetic field looks like the equation of motion in the laboratory frame in crossed fields E', H', that are equal:

$$\omega'_c \equiv 2\omega_{rot} + \omega_c, \qquad eE'/(mr) \equiv \omega_{rot}^2 + \omega_c\omega_{rot} + eE/(mr) \tag{1}$$

($\omega'_c = eH'/(mc)$). This conclusion is valid in the most general case: for arbitrary rotation frequency ω_{rot}, fields E, H, for a finite and infinite particle motion along the radius. The quantities E, E' and H, H' can be of different signs.

2. The invariant of the motion equation under rotation transformation is found: $I = -\Omega^2/4$ ($\Omega^2 \equiv \omega_c^2 - 4eE(r)/(mr)$, $\omega_c = eH/(mc)$), so $\omega_c^2 - 4eE/(mr) = \omega_c'^2 - 4eE'/(mr)$.

3. The problem statement, such as that considered by Larmor, is considered. There are found the frequency of rotation ω_{rot} and the condition, under which the particle motion equation in crossed fields E_1, H_1 in the laboratory frame coincides with the motion equation in fields E_2, H_2 in a rotating frame. A coincidence is possible only if the invariant I_1 in the fields E_1, H_1 coincides with the invariant I_2 in the fields E_2, H_2. This result can be considered as a generalization of Larmor's theorem. Using it, one can determine the solution of motion equation of one particle in fields E_2, H_2 by the known solution in fields E_1, H_1, and also determine the characteristics of ensemble of particles. In this way in present report from known expressions in a negative field there are determined: the equilibrium distribution function of background gas ions f_0 and corresponding density distribution $n_i(r)$, the "hydrodynamic" rotational frequency $\omega_i(r)$, the ion nonlocal contribution to the dispersion equation of oscillations of non-neutral plasma placed in a positive electric field $\delta\varepsilon_i$. The obtained expressions coincide with the expressions found by direct calculations in [2].

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3-09

GROUP ANALYSIS OF CHARGED PARTICLE MOTION EQUATIONS IN CROSSED FIELDS

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The transformation of charged particle motion equation in crossed homogeneous magnetic and radial electric fields under transition from a laboratory frame to a rotating one is considered in the paper [1]. It is shown that in a rotating frame the motion equation in fields E, H in a plane transverse to a magnetic field looks like the motion equation in fields E', H' in the laboratory frame. The quantities E', H' equal

$$\omega_c' \equiv 2\omega_{rot} + \omega_c , \qquad eE'(r)/(mr) \equiv \omega_{rot}^2 + \omega_c\omega_{rot} + eE(r)/(mr), \qquad (2)$$

($\omega_c' = eH'/(mc)$). This is a consequence of the linearity of the rotation transformation (it is an equivalence transformation [2]), the homogeneity of the magnetic field and the symmetry of the electric field.

It was found heuristically in [1] that under rotation transformation the quantity $I = -\Omega^2/4$ ($\Omega^2 \equiv \omega_c^2 - 4eE(r)/(mr)$, $\omega_c = eH/(mc)$ – cyclotron frequency) remains invariant, i.e. $\omega_c^2 - 4eE(r)/(mr) = \omega_c'^2 - 4eE'(r)/(mr)$.

It is easy to see that the transformation (1) is a one-parameter group (with a parameter $a = \omega_{rot}$) in the plane of variables $x \equiv eE(r)/(mr)$, $y \equiv \omega_c$. This allows us to apply the Lee method of group analysis [2] to the search for invariants of the rotation transformation (1). This method is the only general method that allows solving analytically nonlinear differential equations. The group analysis method did not find proper application in the theory of non-neutral plasma, although new powerful methods of group analysis have been developed and are awaiting application. Among the mathematicians, interest in group analysis of particle motion equations in electromagnetic fields (see, for example, [3, 4]) and other plasma physics equations (hydrodynamic, kinetic), continues in recent years. The results of their investigation are strongly "mathematized". This does not allow lay readers to analyze, to understand and to use them in practice.

In present report, the generator X of the transformation group (1) is constructed and the rotation transformation invariant I is found by a standard procedure – by solving the equation $XI = 0$ [2], but not heuristically, as it was done in [1].

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3-10

MODELLING OF THE ELECTROMAGNETIC SURFACE WAVES PROPAGATION ON THE INTERFACE BETWEEN THE LEFT-HANDED METAMATERIAL AND THE DISSIPATIVE DIELECTRIC

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There are large numbers of experimental and theoretical studies of the metamaterials already have been done and currently carry out in the world laboratories. Such metamaterials possess many unique physical properties that are not found in natural materials, such as: simultaneously negative both permittivity and permeability, reverse Doppler and Cherenkov effects, etc. Such properties will open the possibilities to create new devices [1]. It was considered previously a number of planar waveguide structures that contain the left-handed metamaterials, mainly without losses [2, 3].

In our recent paper [4] it was demonstrated the possibility of full loss compensation for the surface electromagnetic wave at the boundary between the dielectric with losses and the isotropic left handed material with gain.

In the present work it was studied the planar waveguide structure in which the left-handed metameterial with gain is cladding by the slab of high-permittivity dissipative dielectric material.

The dispersion equation and the spatial field distributions of surface electromagnetic eigenwaves of such waveguide structures were studied analytically and numerically.

The results of this work can be useful for the process modeling and creating of novel devices based on metamaterials for biology and medicine.

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3-11

LIMITS OF APPLICABILITY OF THE WEAKLY-RELATIVISTIC APPLICATION IN THEORY OF PLASMA WAVES

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Presently, the theoretical study of ECR frequency waves in the laboratory thermonuclear plasmas is performed as a rule in the frame of the weakly relativistic approximation, when the longitudinal (to magnetic field direction) spatial dispersion of plasma is expressed in the terms of the weakly-relativistic plasma dispersion functions (PDFs)

$$F_{q+3/2}(z,a) = \frac{e^{-a}}{(\sqrt{a})^{q+1/2}} \int_0^\infty du \, \frac{(\sqrt{u})^{q+1/2} e^{-u} I_{q+1/2}(2\sqrt{au})}{u+z-a}, \qquad (1)$$

where q is the number of the electron cyclotron harmonic under observation, $a = \mu N_{\parallel}^2/2$, $\mu = (c/V_{Te})^2$, c is the speed of light in the vacuum, V_{Te} is the thermal velocity of electrons, $N_{\parallel} = k_{\parallel}c/\omega$ is the longitudinal refractive index of plasma [1].

Applicability limits of such approximation are not clear enough, since ones could be exactly defined only by the means of somewhat limit transition on the base of the exact fully relativistic approach.

The main scope of the present work is the definition of applicability limits of the weakly-relativistic approximation in the theory of plasma waves on the base of limit transition in expressions for the exact fully relativistic PDFs [2].

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3-12

DISCRETIZED COLLISION OPERATOR FOR SIMULATIONS OF FUSION NON-MAXWELLIAN PLASMA RELAXATION

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The plasma observed in modern fusion devices very often exhibits strongly non-Maxwellian distribution. This is the result of magnetic field lines reconnection with formation of magnetic resonant structures like magnetic islands and stochastic layers. Along with that, the plasma heating by means of neutral beam injection (NBI) and ion/electron cyclotron resonance frequency (ICRF/ECRF) heating induce the non-Maxwellian fast ions, which interact with bulk and thermal ions. This phenomenon significantly modifies the characteristics of plasma in general that is clearly observed on fusion device Tokamak JET [1, 2]. The variety of numerical techniques to simulate the transition from Maxwellian to non-Maxwellian distribution is developed [3 - 5]. In order to get the comprehensive description of plasmas one should take care of plasma particles interaction, i.e. Coulomb collisions in non-Maxwellian environment. The crucial point is the fact that the approach to describe the non-Maxwellian plasma relaxation through collisions should be introduced. That could be done via discretized collision operator developed for the test particle tracing approach. This operator was introduced in the paper [6] for the pitch-angle scattering and the energy slowing down and scattering. Later it was extended to different plasma species [7] and its validity to trace heavy impurities in fusion plasmas was shown in [8]. The significant constraint put in this operator is the Maxwellian distribution of the background plasmas.

The objective of our work is to extend the applicability of the discretized collision operator to non-Maxwellian plasma. Starting from the Fokker-Planck collision operator, which includes Rosenbluth potentials, we derive new expressions for the discretized operator of a general Monte Carlo equivalent form $F_n = F_o + (d\langle F\rangle/\mathrm{dt})\tau \pm \sqrt{(d\sigma_F^2/\mathrm{dt})\tau}$ in terms of expectation value and standard deviation including an arbitrary shape of distribution function for bulk plasma.

The operator is used to simulate slowing down of fusion product fractions likeα-particles, protons and deuterium ions on background plasma particles. The initial distribution functions for each test fraction are chosen highly peaked with the mean energies 3.52MeV for alphas, 3.02MeV and 14.7MeV for protons and 9.5MeV for deuterons. Under these conditions the bulk plasma is assumed to have δ-function distribution and the criteria of use of operator under mentioned conditions is presented. The applicability of the operator to reproduce the time scale for fusion products slowing down in plasmas is shown.

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3-13

ELECTROMAGNETIC MODEL OF GAS DISCHARGE IN LONG TUBE OF SLIGHTLY VARYING RADIUS

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The modern technologies require plasma sources with the desired plasma density value and uniformity in axial direction [1]. A number of analytical and numerical models exert to make predictions of axial distribution of plasma parameters in discharges that occur in discharge chambers with different structure. The fact that the wave that sustains rather long discharges in narrow tubes is the eigen wave of the discharge structure is the characteristic feature of such discharges. So, one of the approaches to describe stationary plasma density distribution in rather long discharges is so called electromagnetic model, which consists of the detailed equations that described the wave propagation and the model equation that describes the discharge features [2]. This model was widely used previously to describe the axial structure of stationary state gas discharge in rather long discharge chambers [3]. The previous studies have shown that the slight variation of the waveguide radius along the discharge is one of the possible mechanisms of controlling the axial distribution of plasma density [4]. The aim of this work is to investigate the influence of variable radius of metal waveguides on the properties of the discharge that is sustained by symmetric and dipolar modes. The choice of these modes was stipulated by its availability for discharge sustaining [1, 2].

It was considered the diffusion regime of the discharge in rather long discharge structure. The studied wave propagates along the waveguide that consists of plasma column, which is enclosed by the cylindrical metal wall. The vacuum gap separates the plasma column from waveguide metal enclosure. External steady magnetic field is directed along the axis of the structure. Plasma was considered in the hydrodynamic approach as a cold, weakly absorbing media with constant effective collisional frequency. The model that describes the discharge consists of the system of Maxwell equations for the wave, the energy balance equation along the discharge and the model equation that connects wave power absorbed per unit length of discharge with local plasma density [2]. It was supposed that all geometric, plasma and wave parameters slightly vary in axial direction, so the WKB approach can be used to obtain the solution of the equations [5].

With the help of this model the influence of the external magnetic field value on the axial structure of gas discharge in slightly tapered and slightly divergent metal waveguides was studied. The carrying out modeling has shown the difference of plasma density axial distribution for the cases of waveguide with constant and varying radius.

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4-01

EFFECT OF PLASMA-OPTICAL SYSTEM ON CHARACTERISTICS OF LOW ENERGY DENSE ION PLASMA FLOW

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The presented report considers features of plasma produced by MEVVA kind source and propagated through a cylindrical electrostatic plasma-optical lens. Plasmadynamical features of streaming high density flows, optical emission spectra and the charge state distribution depending on different experimental conditions were studied.

The vacuum arc sources, like MEVVA, for production high-current (ampere scale), moderate energy (1 ÷ 100 keV) heavy metal ion beams with different species are known and well explored The cylindrical electrostatic plasma lens (PL), based on the fundamental plasma optical principles, is well-explored tool for focusing and manipulating kind ion beams, where the concern of beam space charged compensation is critical [1]. The combination of these tools in one device looks a very attractive. The attachment of PL in a volume of MEVVA source creates new possibility for manipulating a low energy ion plasma flow propagating towards to substrate (deposition option) or to emission grid (plasma source option).

The focusing of the low energy dense plasma flow with PL use is observed. The effect exists for the case when the center lens electrode was biased to positive, negative and floating potentials. We believe that for the case of floating potential, focusing is due to the establishment of a self-consistent mode in the volume of the lens. The measurements showed the formation of a self-sustained positive potential of about 10 V on the central lens electrode upon transport of the plasma stream [2]. The value of the negative potential on the central electrode of the lens was -500V (actual potential was -400 V). In this case, the focusing effect may be associated with the formation of fast electrons due to the action of ions on the inner surface of the central electrode of the lens. These electrons, together with slow plasma electrons, can accumulate on the axis and provide the focusing of ions due to the polarization effect. In the case where the applied positive potential was +500 V (actual potential was approximately +50 V), the central electrode served as the second anode for the MEVVA source and the plasma-optical focusing effect in this case is not so strong.

Presence of fast electrons in the PL volume in case of applied negative potential at the central electrode was confirmed by means of optical emission spectroscopy. Significant intensity growth of the plasma emission lines of both copper atoms and single charged copper ions in the plasma with negative potential increase was recorded. Optical and electron microscopy of deposited films with and without PL use, demonstrated a positive effect of the PL on reducing the number of microdebris in the flow.

For testing ion charge state distribution by magnetic sector analyzer, the combined system was transformed into an ion source with emission grid and accel-decel ion optical system to provide information about the ion beam with extraction voltage 15 kV. At that the current of the extracted ion beam and the currents of Cu ions with charge 1+ to 4+ significantly increase with application of negative potential and magnetic field.

The proposed system can be used to devise effective plasma sources of heavy metal ions and electrons, and is also attractive for high productivity technological equipment using pure plasma flow for the synthesis of fine coatings and thin films.

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4-02

CONTROL OF THE COMPRESSION ZONE POSITION IN PLASMA STREAMS GENERATED BY MPC

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Numerous studies of self-compressed high-density plasma flows are owing to need for exploring the fundamental principles of plasma physics, due to prospects for development of lithography oriented applications and necessity of studying the salient features of plasma surface interaction, etc [1-2]. Through significant quantity of the previous investigations, it was established that compressed plasma stream parameters and compression zone position are strongly influenced by the electromagnetic force distribution [2]. Therefore, this paper is devoted to analysis and investigation of the magnetohydrodynamic characteristics of plasma streams generated by a magnetoplasma compressor (MPC) and control of a compression zone position.

The distributions of electric currents were measured using a set of magnetic probes in different modes of MPC operation with residual gas. The MPC channel is formed by cylindrical rod-type anode with outer diameter of 8 cm and conical solid cathode with the outer diameter of 3 cm. MPC is installed into the vacuum chamber with diameter of 40 cm and length of 200 cm. Nitrogen (P = 0.3 and 0.6 Torr), helium (P = 2 and 10 Torr), and argon (P = 1 Torr) were used as working gases. The plasma stream velocity was measured by the time-of-flight method of a plasma stream between two electric probes. The average statistical error of the probe measurements was 10–15 %. The main part of present experiments was performed at voltage up to 20 kV, the maximum value of discharge current was 400 kA.

In that connection, the results of measurements identified that for helium (2 Torr) both toroidal vortices and magnetic field displacement from the near-axis region are observed, then, the change of the electric current direction occurred. It is also can be observed by decreasing the initial pressure of helium from 10 to 2 Torr, but in this case, the current direction changes much earlier. The velocity measurements reveal that duration of the plasma stream generation in the mode with helium (P = 10 Torr) decreases for 1.5-2.5 times compared to the other modes. The modes with nitrogen (P = 0.6 Torr) and (P = 0.3 Torr) showed that the electric current flows to 25-35 cm from the central electrode, with the current vortices and further displacement of a magnetic field at a distance of 6 cm from the central electrode output. Currents expand to 10–35 cm from MPC output, depending on the MPC operating regime. The total value of current in a plasma stream outside of the MPC channel is up to 120 kA. The electric currents flowing in the plasma stream possess a complex spatial structure (toroidal and fan-shaped current configurations). The research has brought a better understanding of how distributions of electric currents can influence the control mechanism of the compression zone spatial position.

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4-03

NONDESTRUCTIVE CONTACT OF A CATHODE WITH PLASMA IN CROSSED FIELDS

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The interaction of plasma with a conducting surface with a potential negative with respect to the plasma usually leads to the destruction of the surface and contamination of the plasma by the surface material. There are two main mechanisms of destruction. The first mechanism is the cathode sputtering of the surface by ions from the plasma. The second mechanism is the formation of emission centers. It is so-called cathode spots. This second mechanism produces more serious destruction, including the separation of relatively large particles of material. To prevent these processes, the potential difference should be reduced. This can be done by introducing a charge (current) into the plasma, because the plasma is charged positively relative to the wall due to the higher mobility of the electrons.

Since the middle of the last century, the effect of self-sustained secondary electron-electron emission in crossed fields in a vacuum is known. At about the same time, it is known about the phenomenon of emission at a current density of hundreds of amperes per square centimeter, which is observed when a diffuse (glow) discharge is excited in a hollow cathode. There is an opinion (I.I. Bakaleynik 1970) that the effect of a hollow cathode is associated with self-sustaining secondary electron-electron emission or a dynatron effect. However, in a conventional hollow cathode discharge with a moderate current density, the cathode drop or the potential difference between the plasma and the wall (cathode) remains a rather high as hundreds of volts. At this potential drop cathode sputtering occurs quite intensively.

Later, at the turn of the century, many experiment results were published, including experiments involving the author in whom emission with a high current density was observed. In such experiments, the destruction of the cathode is indistinguishable, the cathode voltage drop is less than one hundred volts, and the discharge is diffuse, i.e. cathode spots do not arise.

In the publications, the mechanism of emission in such diffuse discharges is usually not considered in detail. There are also suggestions about the main role of ion currents from the plasma. Meanwhile, the value of the ion current, as is known from the theory of plasma probes, is much smaller than the electron current. If we calculate the limiting value of the ion current from the data on plasma parameters, then it turns out to be much less than actually observed current. Energetically impossible are the process of secondary electron-electron emission from data on its coefficient and the energy of incidence obtained at low current densities. It remains to be assumed that with increasing current density, the secondary emission coefficient increases substantially. Confirmation of this assumption can serve as observation of a significant emission of electrons when the electron system of conductors is excited by a strong current or powerful (laser) light radiation.

The photographs of the cathodes obtained after exploitation in the crossed fields for strong and moderate current densities are presented. At moderate current densities (units of amperes per square centimeter), strips of arc erosion are visible. If the current density reaches hundreds of amperes from a square centimeter the strips is not noticeable. The transition from low-current emission to high-current emission (in the absence of a current-limiting resistor in the storage capacitor circuit) occurs very rapidly. It makes according to the time less than one hundredths of a microsecond. Fast processes are characteristic for the electron component of the plasma and the conductor. This serves as an indirect proof that these processes are related to the electron subsystems of the plasma and the conductor.

Thus, taking into account this mechanism, it is possible to protect the walls of the chamber from destruction, and plasma from contamination. In addition, it is possible to introduce a current into the plasma and to produce its heating.

4-04

SPECTROSCOPY OF THE PLASMA STREAMS GENERATED BY QUASI-STATIONARY ACCELERATOR QSPA-M

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Quasi-stationary plasma accelerators (QSPA) have been used for studies of plasma surface interaction issues relevant to fusion reactor for long time. The QSPA-M is quasi-stationary plasma accelerator of new generation with external magnetic field [1]. A new level of plasma stream parameters and its wide variation could be achieved in new QSPA-M device. Careful optimization of the operational regimes of the plasma accelerator's functional components and plasma dynamics in the magnetic system of QSPA-M device should be performed for the necessary level of plasma parameters achievement and their effective variation.

Thus, spectroscopy studies of plasma stream dynamics within and without external magnetic field were carried out. Investigations of plasma surface interaction were performed also. Experiments have been carried out with follow working parameters: discharge voltage up to 10 kV, discharge current achieved 400 kA and plasma pulse duration exceeded 100 μs. The hydrogen was used as working gas. The external longitudinal magnetic field linearly increased along the direction of the plasma propagation and reached maximal value of 0.8 T at the distance of 1.65 m from the end of outer electrode. All spectroscopic measurements were performed in region of maximal magnetic field.

Spectral measurements were carried out using compact spectrometer SL-40 in wavelength range of 200-700 nm. The plasma electron density was estimated using Stark broadening of H_β spectral line profiles. The dynamics of radiation intensity of plasma and impurities in free plasma streams were evaluated. An analysis of near-surface plasma layers characteristics during plasma-material interaction has been performed also. Distributions of plasma density along z-axis at different distances from the target were reconstructed. It was found that maximum plasma electron density reached $N_e = 2 \times 10^{15}$ cm^{-3} in free plasma stream (without magnetic field). Plasma density is increased four times to $N_e = 8 \times 10^{15}$ cm^{-3} under magnetic field influence. The growth of plasma density in shielding layers discussed also.

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4-05

EROSION PROPERTIES OF TUNGSTEN AND WTa5 ALLOY EXPOSED TO REPETITIVE QSPA PLASMA LOADS BELOW MELTING THRESHOLD

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Lifetime of Plasma Facing Materials (PFM) is critical issue for successful implementation of fusion reactor project. Tungsten is chosen as main plasma facing material for ITER and DEMO divertor design due to advantageous properties: high thermal conductivity, high temperature strength and stability, high recrystallization temperature and high spattering threshold for hydrogen. The one of the most important issues for simulation experiments at the fusion-reactor relevant conditions are studies of properties of different tungsten grades under a large number of plasma exposures.

Surface pattern, damage and structure of pure tungsten and tungsten-tantalum alloy WTa5 targets have been analyzed in condition of preheating to 200 °C, 300 °C and at room temperature (RT). Plasma loads up to 400 hydrogen pulses below the melting threshold (0.6 MJ/m^2) have been performed with a quasi-stationary plasma accelerator QSPA Kh-50. The plasma pulse shape is triangular, pulse duration 0.25 ms. The ion impact energy is about 0.4 keV. Maximum plasma pressure is 0.32 MPa, and the stream diameter 18 cm.

Surface analysis of exposed samples was carried out with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscope (SEM) JEOL JSM-6390. Pprecise measurements of the surface roughness with the Hommelwerke tester T500 were also performed. X-ray diffraction (XRD) has been used to study structure, sub-structure and stress state of targets.

Large number of repetitive plasma loads below the melting threshold led to the clear degradation of thermo-mechanical properties of the affected surface layers on tungsten. Network of cracks appeared on exposed surfaces. Cracks propagate to the bulk mainly transversely and parallel to the irradiated surface. The melting onset of edge of cracks is observed whereas other surface remains non-melted. Melted edges eject the nm particles. Such small particles are able to be melted even for rather small heat loads below the surface melting threshold.

4-06

MILLSTEIN-RUNGE-KUTTA ALGORITHM FOR MONTE CARLO SIMULATION OF TWO-DIMENSIONAL POLOIDAL NEOCLASSICAL DIFFUSION

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Based on the theory of diffusion Markov processes, the system of stochastic drift equations of motion of charged particles in a toroidal plasma corresponding to the drift theory with Coulomb collisions in general form is considered. For an isotropic plasma in an axially symmetric magnetic field, a system of equations for kinetic energy, a pitch-parameter and a classical two-dimensional diffusion of particles in the poloidal cross-section of a plasma cord is formulated. Such a system correctly considers the drift of trapped and circulating particles and the radial Brownian motion, which leads to the effects of neoclassical diffusion. The 1st-order Millstein-type algorithm for numerical integration of these equations is presented. This algorithm does not require calculation of derivatives for kinetic coefficients, i.e. belongs to the Runge-Kutta class. The algorithm also eliminates the need to calculate the repeated Ito continual integrals in the simulation of two-dimensional poloidal diffusion, and therefore can serve as a convenient basis for simulating enhanced neoclassical plasma diffusion by the Monte Carlo method, avoiding the analytical models of "banana" trajectories of particles in toroidal plasma. Based on these theoretical considerations the numerical code was developed. Herein we present the results of numerical simulations for 2D spatial diffusive motion of fast ions in tokamak obtained with a proposed algorithm. It is demonstrated that this algorithm may be effectively applied also for the calculation of fast ion loss poloidal distribution over the first wall in tokamaks.

4-07

ION INDUCED STRUCTURES DEVELOPMENT ON TEXTURIZED TUNGSTEN SURFACE UNDER STEADY-STATE ION BOMBARDMENT

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Polished polycrystalline Plansee tungsten (W) sample with purity 99.99 wt% and 0.75 mm thickness has been exposed to intense argon (Ar) ion beam with average energy of 2 keV and etched through in the centre. As a result, castle-like structures with strong asymmetry and with the height of >200 μm have been formed. Structures can be observed by naked eyes and with scanning-electron microscopy (SEM). It has been revealed, that the structures have been formed not immediately, but at the later stages of irradiation. Primary factors favouring the formation for the structures are relaxation of the surface stresses and activated surface mobility of atoms [1].

The scheme of Hall-effect thruster with wide acceleration zone [2], ballistic and magnetic beam focusing is proposed. Magnetic field distribution in reversed magnetic focusing system and trajectories of hydrogen ions with energy of 800 eV in inhomogeneous magnetic field are calculated, optimal values of current [3] in magnetic field coils are determined. Technical documentation on source manufacturing is completed and further experimental testing is planned.

Key words: Hall-effect thruster (HET), tungsten, surface morphology, ion-induced structures, stresses, relaxation, activated surface mobility.

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4-08

INFLUENCE OF DIFFERENT TYPES OF HYDROGEN TREATMENT ON HYDROGEN RETENTION AND RELEASE FROM 12X18H10T STEEL

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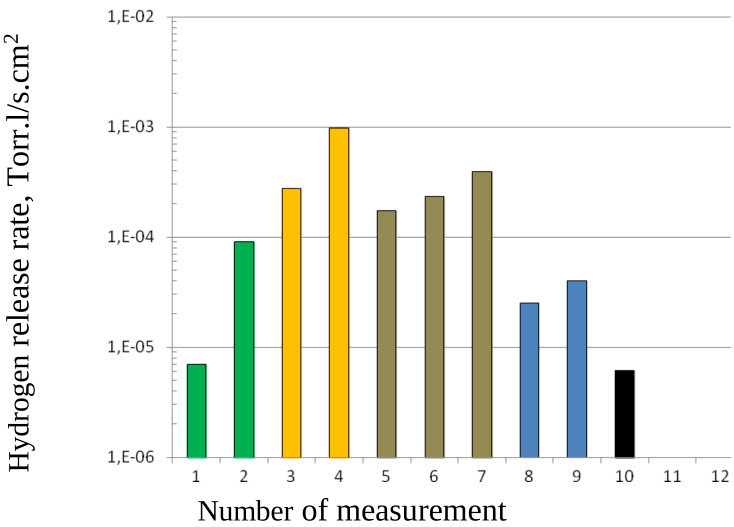
The influence was examined of plasma treatment on hydrogen retention and release from 12X18H10T stainless steel (SS). Hydrogen treatment of the SS samples was carried out with impact of different plasmas: of VHF/RF pulse discharges during wall conditioning in the Uragan-2M torsatron, with RF pulse plasma heating regime in Uragan-2M, with steady state plasma of magnetron type discharges in DSM-1 device (ions energy of 0,7keV and fluence $6 \cdot 10^{24}$ ion/m^2), with pulse plasma in the plasma accelerator QSPA Kh-50 (surface heat load of 0.6 MJ/m^2 and fluence $5 \cdot 10^{24}$ m^{-2}). Also, for comparison, saturation in molecular hydrogen gas at the low pressure of ~10^{-2} Torr was used at room temperature. It enables to compare the results received for different samples. The measurements were carried out with thermal desorption method [1] with mass-spectrometry involvement. The values of the hydrogen release rate for various methods of sample treatment are shown in Figure.



Rates of hydrogen release from ss samples at 500 ℃: 1-after 4 hours RF discharge cleaning vacuum chamber of U-2M, 2 – after 2 hours exposure RF heating regime in U-2M, 3-4 – hydrogen saturation in glow discharge in DSM-1 device, 5-7 – hydrogen plasma treatment in QSPA Kh-50, 8-9 – after 24 hours exposure in molecular hydrogen gas at the pressure of ~10^{-2} Torr, room temperature, 10- specific hydrogen release rate from SS samples after 1 hour heating at the temperature of 700 ℃

The kinetics of hydrogen interaction with stainless steel is discussed.

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4-09

ANOMALOUS DIFFUSION OF PLASMA IN THE LOWER HYBRID CAVITIES OBSERVED IN THE TERRESTRIAL IONOSPHERE

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In the plasma of terrestrial ionosphere the axially symmetric regions elongated along the geomagnetic field are observed, which are characterized by a lower density of plasma in comparison with the environment as well as an increased level of oscillations in the range of a lower hybrid frequency [1]. Such regions called the lower hybrid cavities (LHC), another name is the lower hybrid solitary structures (LHSS), have transverse dimensions from tens to hundreds of meters. Registration of LHC is carried out by satellites and sounding rockets, which occurs randomly. Because of the relatively small transverse dimensions of LHC and the high velocities of the spacecraft, the time of measurement is up to tens of milliseconds. However during this time the cavity does not change significantly, which indicates that LHC is sufficiently stable formation. Although there are a number of works on the explanation of this phenomenon [1], the mechanisms for occurrence of LHC, as well as their stability, are not completely clear. There are also no estimates of the time of their existence and the explanations of their disappearance.

This report is devoted to the problem of disappearance of LHC. As a possible mechanism for the disappearance of LHC we consider the anomalous diffusion of inhomogeneous plasma across the magnetic field. It is known that in magnetized plasma the excitation of various instabilities due to the radial inhomogeneity of the plasma density is possible. One of them is the drift lower hybrid instability due to which an increased level of low hybrid oscillations in the LHC is believed to occur. In addition, it is possible the excitation of a drift instability with a frequency much less than the ion cyclotron frequency, which can lead to the lower frequency drift turbulence of plasma. In turn, due to the drift turbulence, an anomalous diffusion of plasma across the magnetic field occurs, which should lead to the filling of the LHC with plasma and its disappearance. Since the cavities have axial symmetry, then an analysis of the development of turbulence as well as quasilinear processes in plasma of LHC in the present work is considered on the basis of the model of small-scale cylindrical waves [2]. We considered the linear as well as the nonlinear stages of drift instability for cavities conditions, found the level of turbulence in the LHC, and also obtained the diffusion coefficient of plasma. We also estimated the lifetime of the cavity, which can be more or about 1 second.

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4-10

INFLUENCE OF MOVABLE B_4C-LIMITER ON CHARACTERISTICS OF RF DISCHARGE PLASMA IN THE URAGAN-2M TORSATRON

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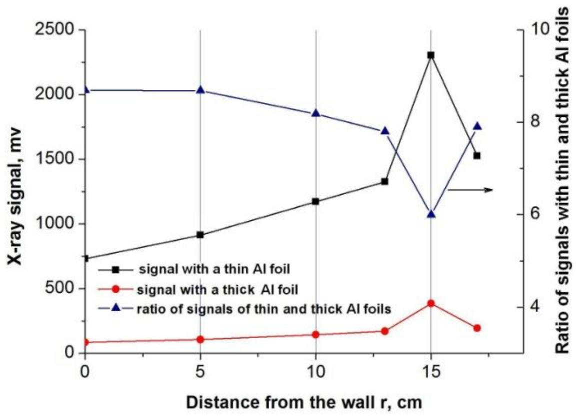
A new variant of the movable B_4C-limiter has been designed, manufactured and installed in the Uragan-2M torsatron. The influence of the limiter position relative to the minor axis was investigated on plasma parameters in the regime of plasma heating in pulsed RF discharge.

The Langmuir probes located at the plasma edge have shown the essential dependence (decrease) of ion saturation current when the limiter is positioned closer to the center. Mostly strong effect is observed for the probe located 2 cm from the wall 1.5 m away from the limiter. The fact of signal decrease from the probe located in the plasma column cross-section different from those of the limiter, means plasma column cutoff layer by layer with limiter motion to the minor axis.

Spectroscopic measurements have shown no essential influence of limiter plate repositioning on the H_α line intensity. The CIII line intensity essentially decreases and OV line increases under limiter positioning at the distance of 15 cm from the wall. Soft X-ray signals appreciably increase at the same time (Figure). This can be explained by input of sputtered boron carbide into plasma or increase of plasma temperature. But the absence of the noticeable change in the plasma density suggests possible electron temperature increase. Additional experiments, including spectroscopic measurements of boron release into the plasma during the discharge, could shed some light on the question.



Soft X-ray signals for thick (circles) and thin (squeres) Al foils versus limiter position

A strong macro damage of one of the plates was observed after limiter exposure to plasma. The cracking in the nearest surface bulk of boron carbide as the result of local abrupt overheating could be the reason for such damage. Most likely, such macro damage was formed when the limiter was placed at the nearest distance from the plasma column axis (17 cm). The second B_4C plate on another side of the limiter head part has no visible macro damages. The measured values of B_4C erosion rate during three work campaigns allows to expect that the procedure of so called "solid target boronization" on the significant part of the U-2M torsatron vacuum chamber could be possible with the using of B_4C limiter.

4-11

SPECTROSCOPIC STUDIES OF TUNGSTEN SAMPLES EXPOSED TO INTENSE DEUTERIUM AND ARGON PLASMA STREAMS

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The use of tungsten (W) as the main plasma facing component (PFC) was proposed for fusion reactors many years ago. Since that time many ideas and experiments have been performed. Tungsten has unique physical properties as the PFC; it is a refractory metal with a high melting point and it has an adequate thermal conductivity at a room temperature, although it is a relatively brittle material. In a comparison with other PFC (i.e. beryllium and carbon) tungsten can be significantly activated by the neutron irradiation. These properties have motivated intense research on tungsten properties and behavior, but many questions have still remained unsolved. Therefore, our recent experiments have been focused on spectroscopic studies of tungsten properties under its irradiation by intense plasma streams.

Several samples made of pure W or (90 %W + 10 %Cu) have been exposed to deuterium and argon plasma streams generated by the IBIS multi-rod plasma injector at different experimental conditions. Those samples were located at a distance of 20 cm from the IBIS molybdenum electrodes outlets. The optical emission spectroscopy (OES) measurements have been carried out as a function of a plasma-stream energy density. A significant influence of that energy on features of the erosion of the irradiated samples surfaces has been observed for deuterium- as well as argon-discharges. The studies of the dynamics of spectral lines emitted from the evaporated target material were performed by means of a Mechelle®900 optical spectroscope, which has a high temporal resolution (1 ns). It allowed the influence of the plasma-stream energy density on erosion properties of the tungsten samples to be determined. The plasma electron density was estimated on the basis of the Stark broadening of the D_β and D_α spectral lines in a deuterium-plasma stream propagating freely (i.e. without any target), as well as near the tungsten surface.

Results of a surface analysis of the tungsten samples after their irradiation by pulsed plasma-ion streams, and the influence of those streams on physical and mechanical properties of the irradiated samples, are discussed. A relationship of the structure and properties of the modified surfaces with parameters of the incident plasma-streams is also analyzed.

4-12

DISCHARGE CHARACTERISTICS IN THE MPC CHANNEL IN PRESENCE OF EXTERNAL LONGITUDINAL MAGNETIC FIELD

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Quasi-steady-state self-compressed plasma flow was discovered theoretically [1-2] and observed experimentally [3]. The main principle of quasi-steady-state plasma flows is a transition to the mode of operation when discharge current is carried by ions in the profile channel. In this mode of operation current carrying ions should be injected from anode (outer electrode) surface into accelerating channel to support discharge current and compensate potential jump, and then absorbed by cathode (inner electrode) surface. Additional injection of ions from anode side to support discharge current resulted in increasing of total mass flow rate. Increasing total mass flow rate leads to decreasing of plasma stream velocity.

The one way to avoid potential jump formation in the near anode region is to add the external longitudinal magnetic field. In this case the ions instead of being moved from anode surface to fast they rotate around axis and are kept in the near anode volume. Thus, the potential jump will be compensated. In theoretical and numerous numerical investigations [1-4] the feasibility of the trans-sonic quasi-steady-state plasma flow without potential jump formation was shown.

The experiments were performed in MPC facility [5]. The MPC channel is formed by cylindrical road-type anode with outer diameter of 8 cm and conical solid cathode with the outer diameter 3 cm. MPC is installed into the vacuum chamber with diameter 40 cm and length 200 cm. The main part of present experiments was performed at voltage up to 20 kV, the maximum value of discharge current was 400 kA. The solenoid with inner diameter 15 cm and with length 17 cm produced external longitudinal magnetic field in the MPC channel with strength 0.05-0.25 T in the entrance of MPC channel that decreased in two times at the channel output.

The influence of the external longitudinal magnetic field on the electrotechnical characteristics of discharge in MPC and main plasma stream parameters will be discussed.

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4-13

PULSED ELECTROMAGNETIC GAS VALVES FOR HIGH-CURRENT PLASMA ACCELERATORS

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Powerful plasma accelerators are used in various branches of modern science. In particular, powerful quasi-stationary plasma accelerators are used for the simulation of transient events in the International Thermonuclear Experimental Reactor ITER, such as current disruptions and ELMs. Energy density in the plasma streams generated by such accelerators can be varied in a wide range (0.1...10) MJ/m^2 at pulse duration to 0.3 ms [1]. To achieve ITER relevant parameters in generated plasma streams, the working gas quantity fed into accelerating channel should be carefully monitored. This requires development of appropriate systems of injection of the working substance.

To achieve such parameters, high-speed pulse injectors of working gas into the accelerating channel has been developed in IPP NSC KIPT. Novel gas valves of electrodynamic type have been designed on the base of injectors with increased mass flow of working gas [2, 3].

The paper describes design features of the gas injectors for working gas supply in the accelerating channel using parallel to the axis injection into the accelerating channel.

The results of the gas-dynamic studies of designed injectors are presented. In particular, dependence of the working gas dynamics on the pressure under the cap locking valve has been investigated. It is shown that amount of injected working gas is strongly influenced by electric current magnitude in the control coil. The developed gas injectors allow effective variation the working gas flow parameters in wide range. Maximal mass flow through the valve achieved 78 cm^3 H atm per pulse.

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5-01

CHERENKOV RADIATION OF THE LASER PULSE IN DIELECTRIC WAVEGUIDE

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The process .of excitation of cherenkov electromagnetic field by the short laser pulse in dielectric waveguide has been investigated. The dielectric waveguide is homogeneous dielectric cylinder. The side of dielectric cylinder covered by perfectly conducting film. Along axis of the waveguide circular polarized laser pulse is propagated. Nonlinear electric polarization of the isotropic dielectric medium and, accordingly, polarization charges and currents, induced ponderomotive force of the laser pulse, are determined. Spatial-temporal structure of wakefield in the dielectric waveguide is obtained and investigated. It is shown, that exited field consists of potential polarity electric field and a set of radial electromagnetic harmonics of dielectric waveguide. Polarization field is due by nonlinear polarization of the media, induced potential component of ponderomotive force. Polarization electric field includes in itself bipolar solitary pulse, located in the region of the laser pulse, and monochromatic wakefield wave of frequency of polarization oscillations of the dielectric media. Nonlinear polarization, the induced by vortex part of ponderomotive force, is responsible for excitation of a set of electromagnetic radial modes. Each radial mode consists of bipolar solitary pulse and monochromatic eigen electromagnetic wakefield wave of the dielectric waveguide. Expressions for amplitudes of wakefield waves are investigated.

5-02

INCREASE OF EFFICIENCY OF ACCELERATION OF THE TEST ELECTRON BUNCH BY SEQUENCE OF ELECTRON BUNCHES IN THE DIELECTRIC RESONATOR

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Results of numerical simulation of acceleration of test bunch by sequence of relativistic electron bunches in the cylindrical dielectric resonator with resonance frequency 300 GHz are presented (outer diameter was 1.2 mm, internal 1 mm, quartz was a dielectric, resonator was 5 mm length, diameter of electron bunches was 0.9 mm, their energy was 5 GeV). If the distance between bunches of sequence equals to the wavelength of electromagnetic field in structure and the test bunch follows the last bunch of sequence, the step growth of energy of the accelerated test bunch with increasing of number of sequence of driver bunches is observed. At that number of bunches creating the step height (defining increase of energy of test bunch) is significantly less than number of bunches determining its length (when energy of test bunch does not change). To reduce the step length we analyzed influence of multiple increase in distance between bunches of driver sequence with the invariable bunches duration on acceleration of test bunch. At the 2nd and 4th-fold increases in distance on the curve dependence of energy of the accelerated test bunch as functions of number of driver bunches sequence the duration of steps decreases, and at the 8th multiple increase in distance between bunches of driver sequence dependence becomes almost linear. Thus, we have shown that to avoid case when the increase in number of diver bunches does not lead to growth of energy of test bunch, it is necessary to inject bunches with the repetition period multiple 8 and more of inverse resonance frequency of structure.

5-03

PARAMETERS OF TWO-CHANNEL FIVE-ZONE DIELECTRIC STRUCTURE FOR EXPERIMENTS ON WAKE ACCELERATION IN KIPT

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The results of the computations of the parameters of a two-channel five-zone rectangular dielectric structure for the purpose of experimental test of the basic principles of using such structures for wake acceleration are presented. Multi-zone dielectric structures make it possible to obtain a transformer ratio greater than 2, which provides a large energy of accelerated particles. The five-zone two-channel dielectric structure consists of two adjacent vacuum channels (one for the drive bunch, the other for the accelerated bunches) surrounded by dielectric slabs. The entire structure is placed in a rectangular metal waveguide.

As a dielectric material, Teflon was chosen (the dielectric constant is 2.05). As calculations have shown, when using such a dielectric, as a rectangular dielectric waveguide, it is necessary to choose a waveguide R_{13} with transverse dimensions of 180x85 mm. The dielectric structure will be excited by electron bunches injected from the "Almaz-2" accelerator. Electron energy of bunches is equal to 4.5 MeV, the bunch repetition frequency could vary from 2802 to 2805 MHz. To ensure Cerenkov s synchronism between the electrons of bunches and eigenmodes of a structure at selected bunch electron energy one must select a certain thickness of dielectric plates. For the working mode, LSM_{31} was chosen with a frequency of 5606.5 MHz (second harmonic of the bunching frequency) with a symmetrical transverse distribution of the longitudinal electric field in both channels. Thus the thickness of the plates should be equal to 9.28 mm (leftmost slab), 14. 69 (central slab) and 5.41 mm (rightmost one). The width of the vacuum channels is 21.4 mm (accelerating channel) and 129.18 mm (for the drive bunches, adjacent to the rightmost plate).

Numerical computations of the excitation of the selected dielectric structure by a single bunch showed that such a structure can provide a transformation coefficient of ~ 8. If the charge of a single bunch is 0.32 nC , then the accelerating field is 1 keV / m . The train of the drive bunches will essentially increase this value of the accelerating gradient.

The work also investigated the tolerances for the parameters of a two-channel wakefield dielectric structure that affect the value of the transformation coefficient and the accelerating gradient, namely the tolerances for the deviation of the permittivity from the given , tolerances on the dimensions of dielectric plates and vacuum channels.

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5-04

EXCITATION OF WAKEFIELD BY A LASER PULSE IN A METALLIC-DENSITY ELECTRON PLASMA

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With newly available compact laser technology [1] one can produce 100 PW-class laser pulses with a single-cycle duration on the femtosecond timescale. With a fs intense laser one can produce a coherent X-ray pulse that is also compressed, well into the hard X-ray regime. T.Tajima suggested [2] utilizing these coherent X-rays to drive the acceleration of particles. Such X-rays are focusable far beyond the diffraction limit of the original laser wavelength and when injected into a crystal it interacts with a metallic-density electron plasma ideally suited for laser wakefield acceleration [2]. At the laser acceleration of self-injected electron bunches by plasma wakefield field (LPWA) it is important to accelerate bunches up to the high energy. Also in [3-10] it has shown that at certain conditions in blowout regime the laser wakefield acceleration by plasma wakefield with time is replaced by a combined joint LPWA acceleration and beam-plasma wakefield acceleration. In this paper laser wakefield acceleration in a plasma of metallic density, the maximum accelerating gradient in such a new medium, the charge of accelerated electron bunch, the transition to the regime of joint laser wakefield acceleration and beam-plasma wakefield acceleration are investigated by numerical simulation.

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5-05

QUASI-STATIONARY MODE OF THE BEAM BLASMA DISCHARGE

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For the beam-plasma discharge (BPD) applications (e.g., plasma technologies for films` deposition) it is necessary to estimate the parameters of the stationary mode of this discharge.

The previous results of BPD simulation in a two-dimensional electrostatic model [1] demonstrated the peculiarities of the initial stage of the discharge. However, the quasi-stationary mode of BPD was not achieved. In this report the results of two-dimensional electrostatic modelling via PIC method [2] for BPD development were provided. Discharge development was studied from initially non-ionised helium to quasi-stationary stage when the intensity of ionization processes is balanced by the recombination processes. Dependence of the stationary parameters on the system properties (beam current, beam energy and gas pressure) was obtained and discussed. The spatial distributions of the densities of beam and background electrons, of the electrostatic potential and plasma temperatures are obtained.

A quasi-stationary discharge mode accompanied by a periodic excitation of the beam plasma instability was demonstrated.

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5-06

IGNITION OF THE BEAM-PLASMA DISCHARGE FOR VARIOUS PARAMETERS OF THE SYSTEM

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Study of the beam-plasma discharge (BPD) is interesting for the formation of dense plasmas for technological applications, interpretation of artificial beam-plasma experiments in the ionosphere etc. Considering complexity of the processes accompanying BPD in the real geometry, computer simulation should be used for its study [1-3]. The aim of this work is the simulation of the initial stage of the BPD in 2D geometry in the initially non-ionised helium.

Previous results of the beam-plasma discharge simulation in a two-dimensional electrostatic model [2] prove the key role of plasma-beam instability in the heating of the background plasma and support of the discharge. However, processes of formation of the initial background plasma are not yet fully clear, including conditions of the plasma accumulation due to ionization of a neutral gas by an electron beam, focusing of the initially divergent beam and development of beam-plasma instability.

Using computer simulation for 2D electrostatic model, dynamics of the stripped electron beam in the initially neutral gas for different parameters of the system was studied.

Heating of the background plasma electrons by the space charge field and effect of this phenomenon on the overall ionization rate of the neutral gas at the initial stages of the plasma-beam discharge development is discussed. Theoretical estimation for the characteristic time of the beam transversal compression for different values of gas pressure, beam current and accelerating voltage was found. Development of the beam-plasma instability on the beam motion in the background plasma formed by the impact ionization of a neutral gas was demonstrated. The spatial distributions of the background plasma electrons` temperature for different time points were obtained. Various mechanisms of the background gas ionization were compared. The key role of the beam-plasma instability in ionization of neutral gas at the later stages of simulation was demonstrated.

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5-07

NONLINEAR SATURATION OF THE WAKE WAVE EXCITED BY THE SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES

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Wake waves excitation in plasma via electron beams and bunches is of interest as a way to construct the new generation of electrons` accelerators [1-3]. Computer simulation (including PIC method) is one of the main methods to study these effects [3-4].

For wake field accelerator construction it is necessary to obtain maximal magnitude of the wake wave. Such wave can be excited by the sequence of the short relativistic electron bunches. But the wave magnitude is restricted due to the relativistic effects [1-2].

This report is devoted to the study of nonlinear effects that move to the saturation of the wake wave excited by the sequence of the short relativistic electron bunches. . We used the modernized simulation package described in [4] and based on the PIC method.

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5-08

INFLUENCE OF ELECTRON-ION AND ELECTRON-NEITRAL COLLISIONS ON THE BEAM-PLASMA DISCHARGE DEVELOPMENT

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Study of the beam-plasma discharge (BPD) is interesting for the formation of dense plasmas for technological applications, high frequency field generation etc. [1-2]. Considering complexity of the processes accompanying BPD in the real geometry, it is impossible to provide the exact analytical description, therefore, computer modelling is often used [3].

The beam-plasma discharge is provided by heating of the electron gas via high-frequency field produced by the beam-plasma instability. Electrons` scattering on the heavy particles plays an important role in this process. In the experiment [1], ignition of a beam-plasma discharge was observed in a very wide range of neutral gas pressures ($5\cdot10^{-3}$ - $5\cdot10^{-1}$ Torr). Depending on the working pressure, elastic collisions with neutrals or Coulomb collisions can play the main role.

The particle-in-cell (PIC) method is one of the most common methods for BPD modelling. However, in the common implementation of this method the phenomenon of Coulomb scattering is not taken into account, since the charge distribution on the distances smaller then cell size is approximated very roughly [4]. Correct simulation of the Coulomb scattering requires the determination of all the forces acting between electrons and ions within one cell, that results in significant reduction of the PIC method productivity.

In this report, the contribution of different scattering mechanisms as a function of pressure is considered. An efficient algorithm for calculating the Coulomb scattering by the Monte Carlo method is proposed. An algorithm for Coulomb scattering by the method of full computing of the pairwise interactions of particles within the cell is proposed. The productivity of various methods for simulation of the Coulomb interactions and the accuracy of these methods are discussed. The temperature distributions of the background plasma electrons for different time moments as a function of the gas pressure are obtained using various methods for Coulomb collisions` approximation. Our PLS package [5] is used for simulation.

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5-09

OPTIMAL RESONANT ASYMPTOTICS OF WAKEFIELD EXCITATION IN PLASMA BY NON-RESONANT SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES

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Resonant wakefield excitation by a long sequence of relativistic electron bunches is difficult because it is difficult to support homogeneous and stationary plasma in experiment [1]. In [2] the mechanism is found of resonant plasma wakefield excitation by a nonresonant sequence of short electron bunches. The frequency synchronization results by defocusing of those bunches which fall into a wrong phase with respect to the plasma - frequency wave. In this material results are presented on 2.5D numeral simulation by 2d3v code LCODE [3] of resonant asymptotics of wakefield excitation in plasma by non-resonant sequence of relativistic electron bunches. Under resonant asymptotics we mean the excitation of the wakefield with the maximum growth rate, when the non-resonant sequence has already self-cleared so that the interaction of the excited wakefield with the bunch electrons in the acceleration phases is negligible. Then the wakefield grows with steps. Optimum parameters are investigated at which the amplitude of the excited wakefield in the regime of resonant asymptotics is the largest.

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5-10

INVESTIGATION OF THE POSSIBILITY OF THE ENERGY TRANSMISSION TO IONS OF PLASMA BY OSCILLATIONS OF LARGE AMPLITUDE IN A MAGNETIC TRAP

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The results of a theoretical and experimental study of the possibilities of effective heating of the ionic component of plasma in a plasma trap are presented. The heating mechanism is the decay of a high-frequency wave, which is introduced into a trap from a magnetron, to low-frequency waves whose characteristics are largely determined by the ionic component of the plasma. It is important that such decay is modified decay, which is always chaotic. As a result of this decay, low-frequency waves are produced, the dynamics of which are also chaotic. These waves can effectively transmit their energy to plasma ions.

Theoretical studies have shown the existence of an anomalously low threshold for the appearance of regimes with dynamic chaos in the plasma trap when low-frequency waves are excited. A cascade of chaotic decays is also described; as a result these cascades the several low-frequency ("ion") plasma branches are excited. The efficiency of ion heating in the field of such waves is estimated.

In the experiment, the processes of decay of an external high-frequency wave, which is introduced into a magnetic trap, into high-frequency and Langmuir waves (the waves with participation of the electron subsystem of plasma) are investigated. It is shown that such decays arise at field strengths of tens of kV/cm. This generates a group of high-energy plasma electrons and high-frequency bursts associated with these electrons. The dynamics of these electrons and their distribution function are studied. The physical picture of the interaction of high-frequency waves with the electronic component of the plasma is qualitatively described. It is also shown that, at much lower field strengths, fluxes of the ion component of the plasma are observed. The energy of these ions exceeds the energy of the equilibrium particles. Estimates show that the heating of these ions can be caused namely by the process of the decay of an external high frequency wave into low-frequency branches of plasma oscillations. There is good enough qualitative agreement of the results observed in the experiment with theoretical estimates.

5-11

A QUALITATIVE APPROACH TO EXPLAINING THE MECHANISM OF ION ACCELERATION BY AN ELECTRON BEAM IN PLASMA

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Acceleration of ions in a vacuum electric discharge, accompanied by the generation of an electron beam, was occasionally observed from the 30s of the last century. Significant progress has been made in next experiments. The experiments related in large part to activities of A. A. Plyutto with co-workers. Despite the improvement of this approach to the problem of collective acceleration in the experiment, even a satisfactory qualitative theory of this phenomenon has not yet been created. The acceleration observed by Plutto in the longitudinal magnetic field indicates that the effect is most likely not connected with the transverse motion. This allows us to consider the acceleration process as one-dimensional. This approach greatly simplifies both the theoretical analysis and numerical modeling.

Here we consider qualitative considerations in the framework of a one-dimensional model without taking into account pair collisions. A high-current beam, when injected into plasma, generates, in general, a wide spectrum of oscillations. This is mainly electronic (electrostatic) oscillations. The excitation of low-frequency oscillations associated with the motion of the ions can be neglected. The beam, giving energy to the electrons of the plasma, slows down. When the momentum is conserved, the plasma electrons must be accelerated. Because of the initial neutrality of the beam-plasma system, a region depleted of electrons is formed behind the beam front. On the contrary, when the beam slows down, the limiting current decreases and a virtual cathode forms at the beam front. A contribution to the creation of a virtual cathode can additionally be made by plasma electrons accelerated by the beam. The ions from the electron-depleted region are mutually repulsed; they enter the potential well of the virtual cathode. The edge of the potential well, the opposite of the motion of the cathode begins to neutralize and move in the direction of the beam motion. In this case, the ions must continue to accelerate, until the ionic clot reaches the anode. To implement the proposed scheme, the plasma density should be limited both from above and from below. The most natural limitation from above is the limitation of a model that does not take in account of collisions, which at high plasma densities is inapplicable. On the other hand, if the ions become too much, a heavy ionic clot will have a low rate of acceleration. This situation is not beneficial for high energy. This also limits the plasma density from above. The lower limit for the plasma density is associated with a small number of ions trapped by the virtual cathode. This reduces the current of accelerated ions. In addition, this can reduce the speed of the virtual cathode. Thus, the acceleration rate will also decrease. The upper limit of the ion energy will be correspond ion velocity that is equal to an electron beam velocity. It can be assumed that the optimum density of the plasma will be close to the beam density. At least this will be true in a logarithmic scale. Such a low density is rather difficult to sustainably maintain in experiments. Apparently this is the reason for the poor repeatability of a number of experiments on ion acceleration. The proposed model makes it possible to explain some other features of the acceleration process. In particular, it explains the directly proportional dependence of the ion energy on its mass.

Statement of the problem associated with the newly detected singularity at transition a magnetron gun in plasma mode with high current.

5-12

ACCELERATION OF ELECTRONS IN WAVEGUIDE-DIELECTRIC RESONATOR WHEN DEVELOPING OF AUTO-MODULATION

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Nowadays, work is intensively being carried out to study new methods of accelerating charged particles. Advanced wake-field accelerators are excited electron bunches or their sequence in waveguides with dielectric slowing down structures.

We have experimentally shown a significant acceleration of a part of the electron bunches upon excitation of the self-modulation regime in a resonator with a dielectric plug and an internal feedback loop. Auto-modulation mode occurs as the beam current increases or the feedback depth increases. In our case, for the development of auto-modulation, the beam current in a pulse of duration 2 μs should be greater 0.4 A.

After the injection of the beam begins, the system accumulates a field. Due to the presence of the beam, the phase and amplitude of the accumulated field change in such a way that the initial position of the injected bunches on the phase plane changes and a small part of the bunches can move from the wake-wave slowing down phase to the accelerating one. In an experiment when developing the self-modulation regime, a part of the electron bunches of the beam obtains an energy gain of ~ 1.2 MeV, which corresponds to an accelerating field of ~7 MV/ m.

5-13

CHERENKOV RADIATION OF THE ELECTRON BUNCH IN DIELECTRIC MEDIA WITH FREQUENCY DISPERSION

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Dielectric permeability of condensed media has frequency dispersion. Taking into account this frequency dispersion at passing of charged particles through dielectric media leads to appearance of polarization losses, which is comparable or exceeds Cherenkov losses. Frequency dispersion will exercise substantial influence on process of wakefield excitation by the relativistic electron bunches in dielectric media. In present report Cherenkov wakefield value and its structure, exited by electron bunch in the cylindrical dielectric waveguide with taking into account the frequency dispersion of dielectric permeability are obtained and investigated. It is shown, that the total Cerenkov wakefield consist of the potential polarization field and electromagnetic field, which is a sum of excited radial modes of the dielectric waveguide. The polarization electric field consists of bipolar solitary pulse, located in the region of the electron bunch, and monochromatic wakefield wave of frequency of polarization oscillations of the dielectric media. The frequency dispersion exercises substantial influence also on the picture of excitation of electromagnetic wakefield waves of the dielectric waveguide. It turns out, that a radiation takes place at all values of the dielectric waveguide parameters (static dielectric permeability, radius of the waveguide) and bunch energy. The frequency spectra of Cherenkov radiation have been determined. The expression for electromagnetic wakefield, which is a set of the radial modes, is obtained and investigated. Each radial mode includes in itself located in the region of electron bunch, bipolar solitary pulse and electromagnetic wakefield wave, which propagates behind the electron bunch.

5-14

DISPERSION PROPERTIES OF THE DIELECTRIC WAVEGUIDE REQUIRED FOR ELECTRON ACCELERATION BY THE LASER PULSE WAKEFIELD

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Cherenkov electromagnetic radiation as a wakefield can be excited in a slowing down medium not only by a relativistic electron bunch but by a short laser pulse too. For laser power of PW-level excited wakefields are so intensive that particle acceleration by using such wakefields is related to the advanced methods of high gradient acceleration. We considered the dispersion properties of waveguide partly filled with dielectric which are required to accelerate electrons by wakefield, excited in dielectric waveguide by a laser pulse. Phase velocity of the excited wakefield is coincided with group velocity of the laser wave packet, which is less than speed of light. Therefore for realization of effective acceleration of relativistic electrons it is necessary to provide such conditions that group velocity should be close to speed of light. This requirement can be attained at partly filling waveguide with dielectric. In present report for realization these conditions two dielectric waveguides are considered. First dielectric waveguide is perfectly conductive tube (cylindrical mirror) in which there is thin dielectric layer near lateral wall. Second dielectric structure is dielectric coaxial line, which includes in itself same mirror and located near axis homogeneous dielectric cylinder. It is shown, that in such systems transversal dielectric inhomogeneity will only weekly changes discrete transverse wave numbers of eigen waves of the waveguide. In result phase and group velocities are weekly depend on the degree of filling of waveguide with dielectric.

5-15

QUASI-HARMONIC RF OSCILLATIONS IN A GYROTROPIC NONLINEAR TRANSMISSION LINE

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The paper considers formation of quasi-monochromatic radio frequency oscillations under the influence of a short carrier-free pulse of electric current, in the transmission line of doubly connected cross-section partially filled with a magnetized ferrite. The frequencies and amplitudes of the oscillations are determined by dispersive and non-linear properties of the structure which are, in their turn, governed by the geometry and size of the line proper, and the spatial structure of the ferromagnetic material with its intrinsic dispersion. The dependences shown by the oscillation parameters in physical experiments are reproduced and analyzed via numerical simulation within models which account separately for different physical properties of the material and the structure.

5-16

TWO MECHANISMS OF RESONANCE OVERLAPPING IN EXCITATION OF AZIMUTHAL SURFACE WAVES BY ROTATING RELATIVISTIC ELECTRON BEAMS

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In this report, two physics mechanisms are investigated to reach the conditions of resonance overlapping in plasma electronics devices based on electron beam excitation of surface type electromagnetic waves of extraordinary polarization propagating across an external d-c magnetic field in cylindrical metallic waveguides [1]. The regime of resonance overlapping is of interest for practical applications since it provides better matching of the beam to the plasma waveguide during the beam excitation of electromagnetic waves.

One of the mechanisms is known already for Cartesian geometry. It consists of increasing the beam particle density in the narrow gap between plasma column and waveguide wall within which the electrons move such that the growth rate becomes of the order or greater than the distance between the nearest resonance frequencies. In this case we assume that all the electrons of the flow contribute to wave excitation. The gap which separates the plasma column from the metal wall is so narrow that there is no place for two or more resonant electron layers with different harmonic number S. Therefore the modes with different S have to compete.

The other mechanism is natural for cylindrical beam-plasma structures only. It consists in widening the gap within which the electron flow of low particle density rotates such that more than one resonant electron orbit appears to belong to the gap. In this case the width Δr of the layer within which electrons of the flow are in resonance with the wave is assumed to be less than that of the gap $(b-a)$ between the plasma column and metal wall, $\Delta r \ll b-a$. This mechanism does not relate to mode competition.

For both these mechanisms, just increasing the number of electrons which take part in wave excitation is the physics reason of the resonance overlapping. But the first one looks like more preferable due to its higher efficiency: in this case all the electrons of the beam take part in the excitation, and the ASW growth rate $\mathrm{Im}(\omega)$ increases with the beam particle density n_b as $\mathrm{Im}(\omega)\propto n_b^{1/3}$. The second mechanism runs such that a small part of electrons of the beam transfers its energy to the ASW. These are only those whose orbit radii are close to the resonant values determined by the resonant condition

$$\omega = \omega_0 + \delta\omega = S|\omega_e|\gamma^{-1} + \delta\omega. \qquad (1)$$

In (1), S is a natural number, ω_0 is the eigenfrequency of the ASW in the absence of a beam, and $\delta\omega$ is the frequency correction, which is caused by the beam-plasma interaction, $|\delta\omega| \ll \omega_0$. In this case the ASW growth rate is naturally lower, $\mathrm{Im}(\omega)\propto n_b^{1/2}$. Nevertheless, the second mechanism is demonstrated to take place for the first time in [1]. It is of interest for the general theory of beam-plasma interaction in cylindrical geometry and can be applied in plasma electronics devices. This mechanism can also be observed in Cartesian geometry (in plane plasma waveguides) when a velocity shear is allowed in a direction normal to the interface.

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5-17

EXCITATION OF HIGHER RADIAL MODES OF AZIMUTHAL SURFACE WAVES IN THE ELECTRON CYCLOTRON FREQUENCY RANGE BY ROTATING RELATIVISTIC FLOW OF ELECTRONS IN CYLINDRICAL WAVE-GUIDES PARTIALLY FILLED BY PLASMAS

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The report confirms the prediction that application of the first radial mode, l=1, of Low Frequency (LF) Azimuthal Surface Waves (ASWs) can provide higher frequency of the generated electromagnetic waves while keeping the same order of the growth rate as for the zero-th radial mode, l=0, [1]. However, application of higher modes than the first radial mode does not seem to be reasonable. Transition from l=1 to l=2 only allows to increase the wave frequency by a factor which is close to one. But to get this moderate result one has to accept that the growth rate decreases by two orders. Comprehensive numerical analysis shows that higher growth rates are reachable for denser electron flow, stronger stationary external magnetic field B_0, and wider layer where the electrons rotate.

The increase of the growth rate with increasing electron flow density is clear from a general point of view. The dependence of the peak value of the LF ASW growth rate versus the electron flow density in the case of a wide layer where the considered electrons rotate, $\mathrm{Im}(\omega)\propto n_b^{1/2}$, differs from that of a narrow layer, $\mathrm{Im}(\omega)\propto n_b^{1/3}$, considered earlier. This controversy is explained by the difference in the initial assumptions of the models. Earlier it was assumed that the layer where the electrons rotate is narrow enough to provide simultaneous reaching the resonance

$$\omega = \omega_0 + \delta\omega = S|\omega_e|\gamma^{-1} + \delta\omega, \quad (1)$$

(in (1), S is a natural number, ω_0 is the eigenfrequency of the ASW in the absence of a beam, and $\delta\omega$ is the frequency correction, which is caused by the beam-plasma interaction, $|\delta\omega| << \omega_0$) for all the electrons of the beam. In this report we consider the layer to be much wider than the radial range where the resonant electrons rotate.

The increase of the LF ASW growth rate with the stationary external magnetic field can be explained as follows. The stronger B_0 is, the less the harmonic number S of the resonance (1) is. The increase of the LF ASW growth rate with the width of the layer where the electrons rotate is not linear. We do not study the possibility to excite the LF ASWs with negative azimuthal wave numbers, m<0, since their direction of propagation is opposite to that of electron rotation in the stationary axial magnetic field so that they cannot be excited by the electron flow.

The results obtained here are of interest for developing new sources of electromagnetic radiation [2] in GHz frequency range, in nano-physics and in medical physics [3].

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<u>5-18</u>

TRANSITION BETWEEN BEAM-PLASMA AND BEAM-DISSIPATIVE INSTABILITY REGIMES IN THE INTERACTION OF RELATIVISTIC LARGE LARMOR ORBIT ELECTRON BEAMS AND AZIMUTHAL SURFACE WAVES ABOVE THE UPPER-HYBRID FREQUENCY IN COAXIAL PLASMA WAVEGUIDES

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The initial stage of Azimuthal Surface Waves (ASW) excitation in coaxial plasmas above the upper-hybrid frequency (HF range) caused by their interaction with electron flows rotating along large Larmor orbits was studied [1] taking dissipation into account. Dissipation cannot be neglected in many practical applications like plasmas in metals and semiconductors. Also in gaseous plasmas, its influence can be important. The frequency range studied here is higher than that of the electron cyclotron frequency region studied earlier in [2], which explains the actuality of the present study since practical applications need electromagnetic waves with shorter wavelengths. Possible applications of ASWs are expected in the areas of plasma electronic devices, plasma-antenna systems, nano-technologies, and plasma production for various applications.

The dependence of the growth rates on the beam particle density n_b and on the collision frequency ν is expected to be as follows:

$$\mathrm{Im}(\omega) \propto n_b^x \nu^y. \tag{1}$$

The beam-plasma instability is well-known to be characterized by x =1/3 and y =0 [3], while in the case of beam-dissipative instability, x =1/2 and y = –1/2 [4].

The lower the maximum value of an HF ASW growth rate is, the stronger is its decrease caused by dissipation. No qualitative difference is found in the impact of dissipation on HF ASW excitation in coaxial plasma-filled waveguides with an internal electron beam as compared to that with an external electron beam. No super relativistic velocities of electron beams are needed to excite HF ASWs in the structures considered.

The influence of dissipation on HF ASW excitation significantly differs from that in the case of low-frequency (LF) ASWs [2]. The character of the dependence of the HF ASW growth rate on such physical properties of the beam-plasma coaxial structure as beam particle density and plasma collision frequency does not demonstrate any rapid transition from the regime of beam-plasma instability to that of beam-dissipative instability. The exponents x and y in (1) which characterize the dependences of the HF ASW growth rate on the beam particle density and collision frequency vary smoothly. That is why in the general case one cannot speak about a pure beam-plasma or a pure beam-dissipative instability.

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5-19

HIGH-CURRENT RELATIVISTIC ELECTRON BEAM FOCUSING IN PLASMA

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Different types of charged particle beam envelope equations in a plasma are widely used to analyze (qualitative) beam behavior under various operating conditions, in particular, during transportation of an ion or electron beam to a target, or an accelerating (slowing) structure [1-3]. The report presents a qualitative analysis of the envelope equation for a high-current relativistic electron beam propagating in a plasma in an external uniform magnetic field. In the paraxial approximation ($|v_r|,|v_\theta| << v_z$, $v_{r,\theta,z}$ - velocities), the envelope equation can be presented in a Hamiltonian form $H(r,\dot{r}) = \dot{r}^2/2 + U_{eff}(r)$ with an effective potential $U_{eff}(r) = \alpha r^2 - \chi \ln(r) + \delta / r^2$, where r is a beam radius, $\alpha = (\Omega / 2\gamma_o)^2/2$, $\Omega = eB_o/mc$, B_o - external magnetic field, γ_o - relativistic factor, m - electron mass, c - speed of light, $\chi = 2c^2(I/I_{AL})\left[1 - f_e - \beta_o^2(1 - f_m)\right]$, $I_{AL} = \beta_o\gamma_o mc^3/e$, $\beta_o = v_z/c$, I - beam current, f_e - charge neutralization coefficient, f_m - current neutralization factor, $\delta = (P_\theta/\gamma_o m)^2/2$, $P_\theta = m\gamma_o r v_\theta + m\Omega r^2/2$ is the conserved angular momentum. This allows fully analyze the behavior of the beam envelope as a function of the beam current, beam energy, plasma density and plasma conductivity, as well as on the external magnetic field and the initial beam angular momentum. There are four basic modes of beam evolution depending on the problem parameters: periodic beam radius oscillations (linear or nonlinear), unlimited growth of the beam radius, conservation of the beam radius in the process of its propagation in the plasma, and the pinch mode, when at some distance from the injection site the beam is compressed into a point. Beam pinching in a plasma (for the case B_o = 0, P_θ = 0) occurs at length $\sim c\beta_o r_o \sqrt{\pi / |2\chi|}$, r_o - initial beam radius. This length can be effectively controlled by plasma density and conductivity. For beams with I ~ 20 kA, W ~ 750 keV [4], r_o ~ 1 cm, f_e = 1, and f_m << 1 pinching length ~ 1 cm. For pinching length << 1 cm, the paraxial approximation may not be applicable. In this case, it is necessary to solve numerically a complete system of equations that describes the beam envelope in a plasma, or use the particle-in-cell codes to simulate beam behaviour in a plasma. Both types of simulations have shown that the pinch length can be effectively controlled by using the plasma density and its conductivity.

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5-20

SELF-ACCELERATION OF ELECTRONS IN DIODE WITH PLASMA CATHODE. II RELATIVISTIC CASE

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The nonlinear effect of electron flow self-acceleration during diode gap filling was considered earlier in [1]. Electron flow self-acceleration is caused by repulsive influence of electrons moving after the flow front on electrons taking the lead. In [1] the electron energy increase on an order of magnitude as compared to the energy of single electron gained in the attached electric field was shown. This energy increases from a few tens to hundreds of keV.

Four electrodynamic areas appear in a diode with plasma cathode when voltage step $\varphi_0(t)=\varphi_0^{\max}\left[1-\exp(-\alpha t)\right]$ with sharp front (pulse rise time $1/\alpha$) is applied to it: (0; b_1) – ions, (b_1; b_2) – plasma, (b_2; b_3) – electrons, (b_3; l) – vacuum (for t=0: b_1=0, b_3= b_2) (Fig. 1). In current investigation the electron motion is studied under the relativistic approach for each area of the diode gap. Expressions for the fields, potentials, densities and speeds of electron flow are received and joining of these solutions is conducted at the borders of areas.

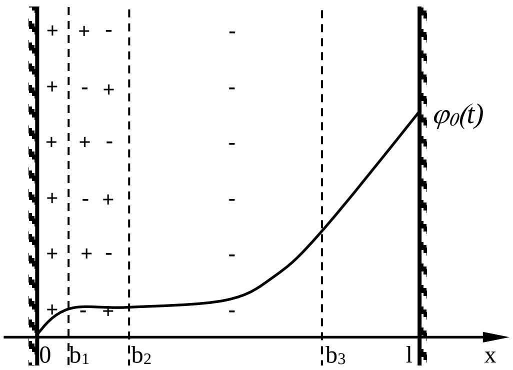

Fig. 1. Scheme of the electrical diode with a plasma cathode

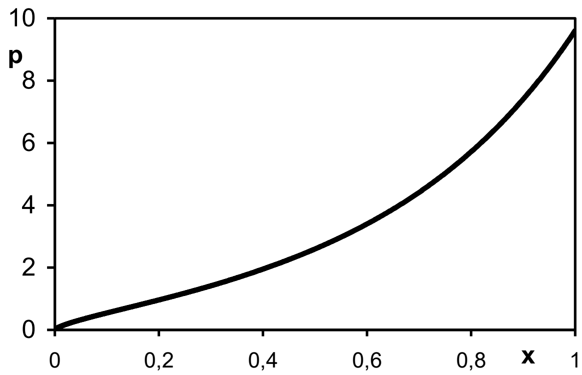

Fig. 2. Momentum of electrons of flow front. *p* measures in $m_{e0}c$

The results can be illustrated by dependence of momentum that electrons gained passing through the diode gap (Fig. 2), when $\varphi_0^{\max}\sim 1kV$ and $l=1sm$. Kinetic energy of electrons is related to their momentum by the relation $E=m_{e0}c^2\sqrt{1+p^2}$, where m_{e0} – electron rest mass, *c* – light speed. It is possible to draw conclusion that electrons which reach the anode can gain energy in a few MeV.

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5-21

ELECTROMAGNETIC SURFACE WAVE EXCITATION AND ENERGY TRANSPORT ALONG A PLANE PLASMA BOUNDARY

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Plasma theory reported that eigen electromagnetic waves of surface type can propagate along the surfaces which bound plasma or separate the plasmas of different densities [1]. The waves of this type are widely used in processes of etching, polishing and cleaning [2, 3], but these technologies are based mostly on the experimental observations and their analytical description is still required to optimize the processes.

The well known analytics issue a range of the wave vector values for surface waves on the vacuum-plasma boundary [1]. The conclusion of this analysis is that surface wave eigenvector in this case is larger than the vacuum wave vector. As a result, surface waves of this type cannot be excited by the electromagnetic wave which hits a plasma surface from vacuum. Fortunately the surface wave theory is developed already for metal waveguides. It indicates that in a plane structure metal-vacuum-plasma the wave vector of the surface wave can be less than the vacuum wave vector. The effect is achieved when the surface wave penetration depth in vacuum is less (or the same order) than a width of vacuum layer between the metal plate and plasma boundary. The idea of our research is to use the metal plate as an antenna with surface current. The waveguide structure can effectively transfer energy along the plasma boundary (inside plasma) only by the wave of single length calculated from the dispersion relation. The space periodicity which is required to excite the wave can be provided by the surface current on metal plate.

The problems to be discussed on the way to the experimental setup are following. First, the distance between the metal plate and plasma can not be arbitrary. For large distances the surface wave can not be excited. For small distances the problem is very sensitive to possible shifting in the antenna position. The optimal distances should be defined. Second, the surface wave penetration depth defines a width of power transferring channel in plasmas. But energy is transferred along the plasma boundary both in vacuum and plasma subspaces. The ratio of energies in these media is calculated. Another important characteristic of energy transferring is normal (to the boundary) energy density. Just this value is interesting for the solids processing. And, finally, a speed of energy transfer along the boundary is also important for the technological processes.

The considered problem supposes an existence of two different types of the electromagnetic waves. First one is traveling wave (in vacuum) which is launched by the antenna and reflected many times between metal and plasma boundaries. And second one is the excited eigen wave of the surface type in plasma. An initial stage of the surface wave excitation requires a consideration of the transient processes. And, most probably, it can be done by direct numerical simulations only. The numerical analysis can also issue a distribution of the electromagnetic energy between traveling and surface waves. The results of our research give data for direct numerical study of the problem.

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5-22

INVESTIGATION OF PLASMA PARAMETERS AT INJECTION OF ADDITIONAL IMPULSE CAPACITY

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When burnt oxide nuclear fuel (UO_2) in spent nuclear fuel (SNF), a significant amount of multicomponent compounds is formed [1]. When such a substance is transferred to plasma, a considerable part of the energy will be spent not on the ionization of the working substance, but on the dissociation and excitation of vibrational and rotational levels of molecules and atoms. To estimate the energy expenditure for dissociation and excitation of levels, in the first approximation, it is possible with the help of gas-discharge plasma.

The work is carried out with molecular gases Ar, CO_2, CH_4, N_2. The formation of plasma occurred in a plasma source with an incandescent cathode at an energy deposition in the range of 700-1500 W in a stationary mode. Under these conditions, no formation of an atomic plasma was observed, only a molecular plasma was observed. A further increase in the input power in a stationary mode is not possible due to a violation of the thermal regime and subsequent destruction of the plasma source. The increasing of the input energy is possible only in the pulsed mode. For this we used a pulsed source with the following parameters: C = 6.6 mF, U = 400 V.

In this paper the plasma parameters were investigated at a pulsed discharge applied to a stationary discharge.

Optical measurements were made in the stationary and pulsed operation modes of the plasma source. Dissociation of the working gas and a change in the component composition of the plasma were observed.

The plasma parameters were study using probe measurements.

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5-23

FEATURES OF THE SPECTRA OF NONLINEAR OSCILLATORS IN REGIMES WITH DYNAMIC CHAOS

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It is known that regimes with dynamic chaos are characteristic practically for all nonlinear oscillatory systems. Especially these regimes are characteristic for plasma systems. Indeed, in the well-studied processes such as wave-particle interaction and processes of the wave-wave interaction with sufficiently large amplitude of waves the local instability develops. The dynamics of particles and waves at this becomes chaotic. On the one hand, this leads to a significant complication of the dynamics itself, and, in general, to the complication of its study. On the other hand, the appearance of chaotic dynamics makes it possible to use well-developed methods of statistical physics to study the dynamics of particles and fields. However, at present the use of the algorithm of this analysis is not in all cases quite correct. Algorithm of the analysis is that after use of one of criteria of appearance of the regimes with dynamic chaos it is practically always supposed that dynamics is analogous to the delta correlated dynamics with white noise. The spectra of such processes are continuous.

However, analysis of regimes with dynamic chaos shows that the spectra of such processes can differ considerably from continuous spectra. Moreover, for some values of the parameters they can be quite narrow. In this case, the algorithm used for analyzing such regimes has to be changed. In our investigations, the Chirikov criterion was used as criterion of arising of the local instability. Wave-particle interaction processes and wave-wave interaction processes were investigated. Particular attention was paid to the analysis of particle dynamics at cyclotron resonances. It was found that the spectra of the studied regimes considerably depend on the used parameters. Moreover, the criteria themselves give only a threshold of appearance of the regimes with dynamic chaos. However, from kind of these criteria it is impossible to conclude about characters of the spectra of dynamics of the studied systems. It can turn out that in regions of parameters with dynamical chaos there can be regions with sufficiently regular dynamics. The spectra in this case are rather narrow or linear. It is also found that at cyclotron resonances there can be regimes at which the highest moments are greater, than the second moments (dispersion). In this case, the analysis of the dynamics of the studied system can't be carried out by equations of the Einstein-Fokker-Planck type. Only the second moments these equations are taken into account. To describe the dynamics of such systems, kinetic equations that take into account the higher moments are necessary. Particular examples of such equations are given.

6-01

FEATURES OF ATMOSPHERIC PRESSURE DISCHARGES WITH A TRANSVERSE COMPONENT OF THE VELOCITY OF GAS FLOW TO THE CURRENT CHANNEL

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Low-temperature plasma is used in various fields of science and technology. There are many designs of plasma generators with different types of discharges. However, unsolved problem of creating powerful industrial atmospheric pressure plasma-chemical systems with long-term time of work that could generate wide-aperture flow of plasma still exists. Duration of work of the plasma generators is usually limited by electrodes erosion. The rotating gliding discharge may be a promising source of atmospheric pressure plasma that satisfy above requirements. The interest to such system appeared because it allows to obtain non-equilibrium atmospheric pressure plasma with large cross section (tens of cm^2). The atmospheric pressure discharges were studied in work. The rotating gliding discharge and the discharge in transversal air flow were compared. The rotating gliding discharge system is an axially symmetric system of electrodes: the central electrode and peripheral electrodes separated by fluoroplastic insulator. Fluoroplastic insulator has a cavity and channels are directed to the cavity tangentially to form a vortex flow of plasma-forming gas. The system is based on discharge in transversal air flow consists of two cylindrical electrodes. The ends of the electrodes were a rounded shape. Electrodes were inclination towards each-other at an angle of approximately 120°. Gas flow was applied perpendicular to the discharge. Video observation of the discharge burning was conducted. The current and voltage oscillograms of the discharges were measured.

During study of a direct current rotating gliding discharge, an analogy of this discharge with a direct current transverse discharge was found:

1. For atmospheric pressure transverse discharges there is no mode of direct current when direct current source is used. Current and voltage modulation occurs sawtooth signal.
2. The current channel is characterized by jump-like changes in the location of the binding to the electrodes. The jump time is significantly less than the time of the permanent binding location. Constancy of time between jumps is not observed.
3. The main mechanism of the sawtooth modulation is the oscillating nature of the change in the length of the current channel with a practically constant period at intervals of constant binding.
4. Diameter of current channels at atmospheric pressure in both discharges is about 1 mm.
5. For discharges with transverse component of the velocity of gas flow to the current channel is shown a different mechanism of electrodes erosion than for arc discharge.

6-02

CONDITIONS FOR ION-PLASMA DEPOSITION OF NUCLEAR FUEL IN THE PLASMA MASS FILTER

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The conditions necessary for collection of fuel ions in the plasma mass filter[1], which is being developed at present for the separation of nuclear fuel (NF) and fission product (FP) ions are considered. Calculations of the trajectories for molecular NF and FP ions in a plasma rotating in crossed electric and magnetic fields show the necessity of a variable component for radial electric field to separate spatially molecular ions of actinide and lanthanide oxides.This leads to an increase of the fuel ion energy, which is calculated to be more than 500 eV at ejection into the wall of the chamber for the given initial parameters. The deposition area for NF ions is ~10^4 cm^2, thatresults in high specific heat at a level of~ 30 W/cm^2. Estimated calculations have shown that at a setup productivity of ~ 2 g/s of the working mixture, the growth rate of the deposited fuel layer will be at a level of 0.6 mm/h. Following from thevalue of thermal conductivity for the uranium dioxide layer of ~$2.5 \cdot 10^{-2}$ W/cm·s at 1500 ^{0}C, deposition of the fuel ions would be carried out at high temperatureswithdecrease ofthe condensation coefficient and increase of thesputtering coefficient. Therefore, reducing the energy of the deposited ions is an important task.For this purpose it is proposed to enlargea deposition surface in ~ 20 timesbyformation of a buffer region for fuel ions collection('a pocket'). To suppress the high energy of the deposited ions, it is possible to use various methods, in particular [2, 3].

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6-03

EXPERIMENTAL INVESTIGATION OF ARC COLUMN EXPANSION GENERATED BY HIGH-ENERGY SPARK IGNITION SYSTEM

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Pulsed arc discharge is widely used as a reliable ignition source of lean fuel-air mixtures. Ignition reliability depends on a size of high-temperature region. We use a special spark ignition system where the total ignition energy achieves one Joule to generate pulsed arc. It has to note that the total spark energy of traditional automotive ignition systems is up to 50-200 mJ. The designed system initially generates a high-voltage pulse by a pulsed transformer that leads to a spark breakdown. Then the system produces a current pulse by a capacitor connected in series with secondary winding of the transformer. Due to significant growth of the discharge current we have an arc formation.

We used a single turn high current transformer as the pulsed transformer. The turns ration was 90. It was used Hitachi Metals F1AH1122 transformer core. Wire diameter of the secondary winding was 1 mm. The coil secondary resistance was 124.5 mΩ. Capacitance of the capacitor was variable and equalled 1 μF, 1.5 μF, and 3.3 μF to change the total discharge energy. The capacitor was charged to an initial voltage 600 V.

We used a high-speed digital camera MS70K to investigate an arc column expansion generated by the designed system. A recoding speed was from 15,000 fps to 38,600 fps. The discharge was generated in atmospheric pressure air. The spark gap length was about 5 mm. Discharge current and arc voltage were measured. Amplitude and form of discharge current were varied by changing of a schematic diagram of the discharge circuit and circuit parameters. Influence of a discharge current pulse form on the arc column expansion was determined by correlation of the arc images with the discharge current. The velocity of the column expansion was estimated. The energy input in pulsed arc was calculated as the time integral of the electric power. A resistor of pulsed arc was estimated using experimental results of voltage and current time histories.

It was found out that a maximal radius of the arc column generated by the designed system equals from 4 mm to 8 mm depending on the discharge current pulse form. An average velocity of the pulsed arc expansion was about the speed of sound. Duration of the high-voltage pulse was up to 1 μs. Amplitude of the voltage pulse exceeded 20 kV. Duration of the current pulse was from 100 μs to 200 μs. The arc amplitude was above 100 A.

The obtained results can be used to improve features of the automotive ignition systems.

6-04

KINETICS OF PROCESSES IN AIR PLASMA DISCHARGES AT ATMOSPHERIC PRESSURE IN THE TRANSVERSE FLOW OF GAS

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Today, discharges in gas flows transverse to the current channel are of particular interest. Since these discharges can generate large-aperture high-pressure non-equilibrium plasma streams for hybrid plasma catalysis of high-scale transformation of substances (sliding and rotational sliding discharges), and low-power plasma flows for small electron energies for plasmomedicine (micro discharge in vortex flow of gas). This paper is devoted to the consideration of the kinetics of a number of processes in the air plasma of similar discharges: the population of the oscillatory levels of oxygen and nitrogen molecules and the formation of nitrogen oxides.

The studies were performed using numerical simulation based on the codes of ZDPlasKin and Bolsig+ [1] under typical conditions for the discharge plasma in the reduced electric field
(20 ÷ 40 Td). The list of possible processes consisted of the elementary processes of the interaction of electrons with N_2, O_2 [2] and N, O, NO, NO_2, O_3 [4]; chemical reactions involving N_2 [3], O_2 [5]; with the participation of N_2O, NO_2, NO_3, N_2O_5, N_2O^+, NO_2^+, N_2O^-, NO_2^-, NO_3^-. The list of possible processes was supplemented by processes involving H_2O, H, OH taking into account the air humidity.

The dependences of the change in the composition of the gas flow intersecting the region with constant temperature and electric field were obtained from the calculations for the time interval of $10^{-8} \div 1$ s with a time increment of 10^{-8} s. The time dependence analysis for N_2^* (v = 0 ÷ 8) and O_2^* (v = 0 ÷ 4) found that the distribution of populations of oscillatingly excited levels along the excitation energies corresponds to the Boltzmann's law. The determined from emission spectra temperatures of excited vibrational levels of the plasma components coincides with the calculated ones within the limits of the error.Analysis of time dependences for nitrogen oxides showed that the main ones are NO and N_2O.

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6-05

DYNAMICS OF MACROPARTICLE IN A WEAKLY COLLISIONAL PLASMA

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Cathodic arc deposition is a recognized technique for the formation thin films and coatings for a variety applications [1]. The macroparticles (MPs) contamination is a major disadvantage of the cathodic arc [2]. The significant MP fraction in the plasma flow worsens the coating parameters, and it is the critical problem of cathodic arc deposition. Most of the theoretical studies on the MP dynamics in the collisional plasma have been carried out assuming that plasma consists of electrons and singly charged gas ions, with a uniform background neutral gas [3,4]. However, this model is not appropriate to describe the MP immersed in cathodic arc. The vacuum arc sources generate highly ionized metal plasma with multiply charged ions [5]. The increase in gas pressure causes a slow decrease of metal ion charge states, and a simultaneous increase in gas ion fraction. Keidar et. al. [6] proposed model of the MP behavior in cathodic arc, which takes into account the increase in gas ion fraction due to non-resonant charge exchange between the singly charged metal ions and gas atoms. However, the constant MP charge has been used in this study.

In the present work, the metal plasma-gas interaction in cathodic arc operated in the nitrogen gas atmosphere is analyzed. The metal plasma interacts with a background gas through charge exchange collisions. Collisions between energetic metal ions and background gas molecules result in a decrease of the kinetic energy of the metal ions and the average ion charge state. We propose the one-dimensional stationary fluid model which describes the ion slowing down in the interelectrode region of the cathodic arcs. The main forces acting on MP as well as the charging of MP in the weakly collisional plasma are studied. It was found that the collisions increase the negative charge of MP. The ion drag force decreases with the collisions, while the neutral drag force increases. The ion drag force is purely determined by the collection of metal ions.

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6-06

PVD COATINGS FOR MEDICAL DEVICE APPLICATIONS: A BRIEF REVIEW

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Physical vapor deposition (PVD) has become widely used to deposit wear-resistant thin-film coatings on a variety of medical devices, including orthopedic implants, vascular grafts, pacemakers, surgical instruments, orthodontic appliances and dental instruments. The value of PVD technology rests in its ability to modify the surface properties of a device without changing the underlying material properties and biomechanical functionality. In accordance with ISO 10993-1 guidelines for materials that experience short-term body contact TiN, ZrN, TiAlN, AlTiN are acceptable for external and internal medical devices that contact bone, skin tissue or blood. PVD coatings on medical devices must also be compatible with the sterilization process and resist corrosion that can be caused by steam and chemical autoclaving.

In the paper, ion-plasma vacuum arc deposition technique in combination with assisting RF field was used for synthesis of Zr, ZrN, Ti, TiN bioinert nanostructured coatings on stainless steel substrates (including surgical and dental instruments, plates for osteosinthesis) as well as on flexible medical polyurethane used for vascular grafts material. The developed technology provided low-temperature coatings synthesis, minimizes discharge breakdown decreasing formation of macroparticles (MPs) and allowed to deposit coatings with high hardness and enhanced corrosion resistance characteristics. Structure examinations –X-ray fluorescent analysis (XRF), X-ray diffraction analysis (XRD), and scanning electron microscopy (SEM) with microanalysis (EDX), transmission electron microscopy (TEM), nanoidentation method – were performed to study phase and elemental composition, surface morphology, microstructure and mechanical characteristics of the obtained coatings. Such coatings provided improved instrument performance, decreases friction and improves wear resistance, and also provided barrier layer for various solutions and environmental exposures.

6-07

ELECTRODYNAMIC ACCELERATOR OF PLASMA RING IN THE ATMOSPHERIC PRESSURE AIR

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A lifetime extension of plasma in the atmospheric pressure air without energy supporting by an external source has a scientific interest. An internal energy source of a plasma formation can allow increasing in the plasma lifetime probably. We used an electrodynamic accelerator to accumulate energy of a magnetic field in a plasma ring generated in the atmospheric pressure air.

We designed a special electrodynamic accelerator. Electrical wire explosion was used to generate plasma in the air. An initial form of an exploding wire corresponded to a ring. Thus we obtained a ring electrical conducting region. The wire ring was coaxially positioned near an inductor. The inductor was connected with a capacitor via a switch. The switch was turned on simultaneously as the ring conducting region was formed to accelerate the plasma ring. During acceleration the dynamic energy exchange happens between the capacitor, the inductor, and the ring due to magnetic and electric coupling. The plasma acceleration causes a reduction in a mutual inductance of the inductor and the ring. We try to achieve the fast reduction when a ring current is maximal to store energy of a magnetic field in the plasma ring.

A simplified numerical model of the accelerator was developed to find out conditions when the energy of magnetic field store in the ring. We used differential equations of transient process in electrical circuits including magnetic coupling of the inductor and the ring. It was calculated that the conditions appears if a fast reduction of the mutual inductance happens at a fist or third quarter period of discharge in an inductor loop.

We designed the experimental setup of the accelerator. A total capacitance of the capacitor was variable and equalled 3 μF and 75 μF. The capacitor was charged to a voltage from 20 kV to 30 kV. The ring exploding wire acceleration was investigated using infrared and video cameras. We observed the moving of lighting region from the inductor. We plan to measure a current of the ring loop in future investigation.

6-08

PLASMA OF ARC DISCHARGE BETWEEN MELTING Cu AND Ni ELECTRODES

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Plasma of free-burning electric discharge at arc current of 30 A between asymmetric one-component Cu and Ni electrodes was investigated by optical emission spectroscopy. Radial distributions of temperature and electron density were determined in the average cross section of arc column.

Plasma composition was calculated on the base of experimentally obtained temperatures and electron densities as initial data in the assumption of local thermodynamical equilibrium. It was found that a cathode surface plays the predominated role as a source of metal vapors in discharge plasma.

The proposed technique can be used for estimation of the erosion properties of different contact materials.

6-09

USING OF ELECTRON CYCLOTRON RESONANCE DISCHARGE IN ION BEAM SPUTTERING SYSTEMS FOR SPACE CHARGE COMPENSATION

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A common characteristic of all beam-plasma systems is the separation of ions and electrons due to acceleration of the ionized substance. The main feature of low and medium energy ion-beam systems, which are mainly used in vacuum-plasma technologies, is that the impact ionization of molecules and atoms of the residual gas by an ion beam in the transport region is insignificant and, as a consequence, there are no electrons that can neutralize the space charge of the ion beam. As a result, the electric fields of the space and surfaces charges created by the beam interfere with the efficient transport of ion beams under low gas pressure conditions and lead to expansion, deceleration and even beam locking in a case if virtual emitter is formed.

In this paper, we consider the possibility of using a magnetic mirror in the output slot of ion source with a closed electron drift to generating of additional gas discharge using the electron-cyclotron resonance effect (plasma cathode-compensator) to obtain charge and current compensation of the ion beam space charge.

In order to form a plasma electron cathode source, it is necessary to provide conditions for the electron cyclotron resonance discharge in the annular slot of the accelerator magnetic circuit. To create maximum intensity of the microwave electric field in the region of the annular slot of the magnetic circuits capacitive type antennas are usually used. These can be disks or rings located concentrically to the output slot of the ion source. In our experiments a disk water-cooled holder for the sputtered target as a microwave antenna has been used. To adjust the microwave generator to the antenna and plasma load, a microwave applicator based on a coaxial-waveguide transition with tuning plungers has been designed.

The first experiments (physical start-up of the system) showed that an additional microwave discharge generated in the region of the annular slot when the microwave power is applied. Changing of the discharge shape glowing corresponds to a changing of the magnetic profile in the output slot when the current in the magnetic system changes. An additional plasma source of electrons provides the maintenance and intensification of the gas discharge in the accelerator with an anode layer, as well as the charge and current neutralization of the ion beam by the electrons.

6-10

PLASMA OF UNDERWATER ELECTRIC DISCHARGES WITH METAL VAPORS

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Plasma of underwater electric discharges between metal granules or electrodes is investigated in this study. Temperature and electron density as plasma parameters are determined by optical emission spectroscopy. The Boltzmann plot techniques in the assumption of local thermodynamic equilibrium was used in the measurement of temperature in the discharge gap. Intensities of some spectral lines of metal vapour elements were chosen in this technique. The electron density is determined from width of spectral lines, emitted by hydrogen and/or metal atom, broadened by Stark mechanism.

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6-11

THE PROPERTIES OF ARGON-ACETYLENE DUSTY PLASMA

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The properties of an Ar/C_2H_2 dusty plasma (ion, electron and neutral particle densities, electron temperature and dust charge) are studied numerically using a volume-averaged model. It is investigated how the properties depend on the electron and dust particle densities, the dust particle size and the shape of electron energy distribution function. It is shown that the densities of most hydrocarbon ions are smaller in the plasma with large dust density n_d comparing with the case of low n_d, while the argon ion density is larger in the former case. The ion density differences are found to be due to larger electron temperature and smaller electron density in the plasma with large dust density. It is also found that the acetylene density is larger in the case when the effect of dust particles on plasma properties is small as compared with that when the dust density and size are sufficiently large to modify plasma properties. The main processes affecting the loss and production of different ions and neutral species in the plasma are also determined. It is obtained that dust particles affect essentially the ion densities in the plasma as well as the density of atomic hydrogen. Numerical calculations also showed that argon atoms in excited states affect the production of $C_2H_2^+$, $C_4H_2^+$, C_2H and H as well as the loss of C_2H_2, C_4H_2 and H_2. The loss of C_2H^- anions in the plasma is found to be mainly due to the anions' collisions with positive ions and atomic hydrogen. The results of calculations are compared with available experimental data and found to be in a good qualitative agreement.

6-12

NON-SELF-SUSTAINED ARC DISCHARGE IN VAPORS OF CONSTRUCTIONAL MATERIALS OF NUCLEAR POWER ENGINEERING

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It is not always possible to use the discharge in the vapors of the cathode material, since the physical processes in the discharge are such that it leads to the presence of the droplets of the cathode material in plasma flow[1-2]. Recently, interest in the possibilities of a non-self-sustained arc discharge in vapors of anode material has increased considerably. This interest is stimulated by studies which prove the possibility of creating a highly ionized plasma stream of various materials without any drops by a given type of electrical discharge. Increases of the corresponding interest in it are explained that this type of discharge can also be effectively used to develop sources of ions of various solid-state materials for accelerators and other needs. The non-self-sustained arc discharge in the vapor of the anode material is characterized by a diffuse attachment of discharge on the anode and evaporation of the working material from a wide zone. Experiments show that the mode of local evaporation of the working material from the surface of the anode in this type of discharge is practically absent [3-5].

The paper presents the results of experimental studies of the conditions of ignition and burning for non-self-sustained arc discharges in nickel and tantalum vapors. The investigations were carried out with the aim of developing new methods for efficient generation of plasma-free and highly ionized plasma flows of structural materials of nuclear power engineering. In the experiments, the minimum power required to obtaining a sufficient vapor pressure of working material and ignition of vacuum arc discharges was obtained. The values of the minimum discharge power in the conditions of their stable burning were also determined, the current-voltage characteristics of the discharges in vacuum and under conditions of gas input into the vacuum chamber were studied. It is shown that the created plasma streams can be used to deposit the films not only on metallic and semiconductor films, but also on dielectric substrates. The paper also presents data indicating that the discharge in the vapor of the anode material is capable of providing a film deposition rate comparable to that of a vacuum cathode arc.

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6-13

BEHAVIOR OF MOLYBDENUM TARGET IN CONDITION OF IRRADIATION BY THE HIGH CURRENT RELATIVISTIC ELECTRON BEAM

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The success of the practical implementation of new projects of nuclear power plants is largely determined by the availability of materials that can be operated under the influence of extreme values of ionizing radiation, high temperatures, pressure, and corrosive media. In this connection, it is important to carry out test studies of the change in the properties of materials when they are irradiated with concentrated energy flows whose energy parameters are comparable with those characteristic of nuclear power plants. For these purposes, as a rule, various sources of plasma are used, studying the problem of erosion of the materials of the first wall of thermonuclear reactors resulting from current failure. At the same time, in such studies, there are effects that seem promising, from the standpoint of creating independent technologies. Such areas include, for example, the modification of the properties of materials as a result of the action of plasma flows and also the generation of vacuum ultraviolet radiation for photolithographic purposes. Thus, there are two directions for using concentrated energy fluxes: it is a test effect involving obtaining information about the ability of a material to retain its characteristics and technological influences aimed at modifying the properties of a material or obtaining a secondary radiation flux of the required spectral range. Considering the questions of material science for the implementation of thermonuclear fusion facilities and technologically oriented issues, one should point out that one of the ways to initiate a thermonuclear fusion reaction was to consider a high-current relativistic electron beams (HCEB). In connection with this method of initiating a thermonuclear fusion reaction, it is also necessary to create radiation-resistant reactor chambers. Since among the candidate materials of the first wall of the reactor, metals are generally considered to be refractory, it seems relevant to investigate the behavior of molybdenum specimens under the action of the HCEB.

Irradiation was carried out at the accelerator TEMP-A NSC Kharkov Institute of Physics and Technology. Electron beam parameters: electron energy 350 keV, beam current 2 kA, pulse duration 5 μs. intervals between pulses of the order of 5 minutes, cathode diameter of 50 mm. Molybdenum plates with a thickness of the order of 0.5 mm were used as targets. Microstructural studies were carried out with a scanning electron microscope JEOL-840. The thermograms of the surfaces were analyzed by a Fluke 32 thermographic camera.

The mechanisms of the beam effect on the target are analyzed. The instantaneous introduction of energy into the target, causes the heating of the target, which leads to the generation of stresses due to the thermoelastic effect. Ablation of molten matter generates a reactive recoil momentum.

Specific features of the microstructure of the target in the region of the melting effect of the beam and in the region of thermal action are determined. They are compared with the initial structure. It is established that as a result of surface remelting by the beam, a more continuous structure is formed, for which the presence of pores and also the elongation of the grains in the direction of the surface is characteristic. The initial structure of the target has a stratified structure. On the surface, as a result of irradiation, swollen blister-like blisters and craters are formed. An estimation of the change in optical properties in the infrared range is made, it is shown that the emissivity coefficient of the surface changes due to irradiation.

6-14

CONVERSION OF CARBON DIOXIDE IN LOW-PRESSURE PLASMA

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One of the most serious problems facing humanity is climate change due to excessive levels of greenhouse gases, particularly CO_2, so its conversion into fuel and valuable chemical raw materials is one of the most effective ways of simultaneously solving the environmental and energy problems.

The present paper reports the results of experimental study of efficiency of carbon dioxide conversion to CO and O_2 in gas-discharge plasma at low and medium gas pressure. The inductively coupled plasma source operates at 13.56 MHz in the RF power range 5-500 W. Pure CO_2 is fed into the plasma while the internal composition of atomic and molecular species is estimated using optical emission spectroscopy, and the output gas composition is measured by a mass spectrometer. CO_2 pressure was changed in the range of 1-200 mTorr.

Using the mass spectrometry method, the dependencies of the conversion rate and the energy efficiency of carbon dioxide conversion in plasma on the gas pressure and the power deposited in the discharge was measured. The maximum achieved conversion rate is 82%, the energy conversion efficiency is up to 50 %.

Using a Langmuir probe, the dependencies of plasma density and electron temperature on the gas pressure and input power has been measured. It is shown that the maximum conversion rate is achieved at the lowest pressures (down to 1 mTorr) and at the highest pressures of the researched range (up to 200 mTorr) while at intermediate pressures the conversion rate has a minimum. This could be explained by assumption that at the low pressure when the electron temperature is more then 5 eV, the carbon dioxide molecule dissociation occurs after electron impact, while at low pressure when the electron temperature is about 2 eV, cascade excitation of molecular vibrational levels plays the main role.

6-15

COLLISIONAL AND COLLISIONLESS PLASMA SHEATHES IN BOUNDLESS GAS MEDIUM

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The dynamics of the spreading of the low pressure gas discharge plasma under the continually acting ionization sources in the boundless gas medium was investigated numerically. For this purpose the combined drift-diffusion model was created, which involves ambipolar diffusion equations in the plasma region and drift equations for the moving plasma sheath. Electrons was assumed to be maxwellian. Both collisional and collisionless sheathes was considered. We found that the ion density profile undergoes the discontinuity in the case of the collisional sheath, which explained by the collisions governed ions velocity distribution. The sheath velocity is find to be equal to Bohm velocity in the collisionless case and is reduced by the drag force due to the collisions. Temporary and space dependencies of the ion velocity, ion and electron density, electron temperature and ambipolar field are obtained.

6-16

PLASMA-CATALYTIC REFORMING OF RICH ETHANOL-AIR MIXTURES

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Interest in the conversion of renewable hydrocarbon raw materials into the feedstock suitable as a crude oil replacement for chemical industry increased with the global shift towards sustainability at the start of the 21st century. Despite important advantages, conversion of renewable raw materials into value-added chemicals has complications, which stem from the complexity and variety of their composition. The most well-developed are indirect approaches, which first convert renewable raw materials into the mixture of H_2 and CO, syngas, mainly via the gasification process. Produced syngas is then used in methanol or Fischer-Tropsch synthesis to obtain the desired chemicals. Unfortunately, this pathway of renewable raw materials conversion requires high energy input and provides low product yields.

Among the alternative processes that show great potential in this area is plasma technology. Low-temperature non-thermal plasma has the advantage of being able to activate chemical processes by producing electrons, excited atoms, and molecules, instead of initiating the reactions via heating of the reactor. In addition, plasma has already been successfully used to produce syngas from renewable raw materials. Considering this, several recent studies examined the prospect of value-added chemicals synthesis from light hydrocarbons using plasma [1] or plasma-like conditions in rich flames [2].

This work focuses on the experimental investigation of the synthesis of value-added chemicals and raw materials from renewable liquid hydrocarbon using plasma-catalytic approach to the activation of chemical reactions. The study was conducted using a chemical reactor connected to plasma source based on the rotating gliding discharge. Ethanol was used as a model hydrocarbon and oxygen in the atmospheric air was used as an oxidant. Total airflow was divided into two separate flows, one mixed with the ethanol and injected into the reactor, the other one supplied as a working gas into a plasma source. As per plasma-catalytic approach, plasma operated as a source of activated oxidant. The ratios between the introduced ethanol and oxygen were 1:1, 2:1, 3:1 and 4:1, which correspond to rich mixtures with fuel-air equivalence ratios of 3, 6, 9 and 12, respectively. During the study, input air flow was 12.5 $l\ min^{-1}$, which at 2:1 ratio between introduced ethanol and oxygen corresponded to the stoichiometry of ethanol partial oxidation reaction. The products of ethanol conversion were cooled down after they left the reactor. Condensed liquid conversion products were separated from gaseous products. Obtained gas was sampled for analysis. All surplus gas was disposed of by combustion.

The temperatures at the top and bottom of the reactor during the conversion were monitored by the thermocouples. Optical emission spectra were used to determine the vibrational and rotational temperatures of hydroxyl (OH) in different zones of the reactor. Products of the conversion were investigated using gas chromatography and analyzed.

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6-17

PHOTOMETRIC DIAGNOSTICS OF PLASMA OF PLANAR CAPACITIVE RF DISCHARGE IN ARGON AT 1 ATM PRESSURE

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Non-thermal plasma of atmospheric pressure discharges attracts significant attention of researches due to the prospects of its technological applications. Such discharges do not require bulky and expensive vacuum equipment. Among different atmospheric pressure discharges one can distinguish radio-frequency (RF) discharges with dielectric barriers which allow to introduce high specific power (>100 W/cm^3) into the plasma that results in reaching high concentrations of active species.

Electron temperature is one of the most important plasma parameters since it determines efficiency of active species in the plasma, kinetics and rates of the plasma-chemical reactions. Determining electron temperature in atmospheric pressure RF discharge plasma is complicated due to small system dimensions and difficulties of probe uses. Thus, the use of plasma emission spectroscopy for such diagnostics is attractive due to the advantages of its non-perturbing nature and high precision of the measurements.

One of the most simple and attractive methods of determining electron temperature spatial distribution in atmospheric pressure RF discharge plasma is based on detection of bremsstrahlung emission occurred at interaction of electrons with neutral atoms of working gas. Electron-atom bremsstrahlung emission is dominating source of the spectrum continuum emission from non-thermal atmospheric pressure plasma in a wide wavelength range.

This work presents the results of photometric studies of electron-atom bremsstrahlung emission continuum of capacitive RF discharge plasma in atmospheric pressure argon by means of CANON EOS 350D digital camera in ≈400÷600 nm spectrum range. Time-averaged spatial distributions of electron temperature in the discharge gap are obtained and tendencies of their variation at RF discharge transition from low-current mode to high-current one are determined. The comparison between computer simulation of RF discharge and experimental results is also presented.

6-18

HARDWARE-SOFTWARE COMPLEX FOR AUTOMATED CONTROL AND MONITORING OF THE VACUUM SYSTEM OF THE COATING SETUP "BULAT–6"

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The software and hardware complex, created in the Institute of Plasma Physics of the NSC KIPT, is designed for automated monitoring and monitoring of the vacuum system of the Bulat-6 coating setup. Its use makes it possible to automate the process of obtaining and maintaining the required vacuum in the installation. The complex ensures the stability of coating processes in various modes.

The complex is built on the basis of the software-logic controller (PLC) type EASY XLogic ELC – 22. In addition to the controller, the complex includes expansion modules for input and output of analog and digital signals relay modules for controlling the nodes and aggregates of the Bulat-6 installation. To control the vacuum process and display the current volumes and the status of the system nodes, the touch panel Touch screen Samkoon SK-70AS is used. The complex has extensive communication capabilities. With the help of an appropriate expansion module, it is possible to connect to an Ethernet network. This is necessary to create a complete operational process control system using the PC at the top level.

The Samkoon SK-70AS touch panel is also connected to the ELC-22 controller via an Ethernet port using a network switchboard. The exchange of commands and data between the PLC and the expansion modules of the complex is carried out via Modbus RTU protocol.

The original software was developed in accordance with the concept of unified control units of the setup in the language of FBD and in the development and visualization environment of SKWorkshop. Developed program can be corrected as soon as possible in accordance with changes in the algorithm.

The Samkoon SK-70AS touch panel displays an interactive mnemonic diagram of the vacuum system.

It shows a vacuum chamber, fore-vacuum and diffusion pumps, a fore-vacuum line, valves, sensors and devices for vacuum measurement, which are necessary for automated control. A mnemonic diagram with built-in elements provides control of the nodes of the vacuum system and displays their state. Also, the current vacuum values in the necessary nodes are displayed on it. This system provides high cognition, facilitating the perception of the displayed elements of adjustment, control and maintenance within the specified limits of technological parameters.

Despite its low cost, the automated complex based on the XLogic PLC demonstrated reliable operation during the tuning and debugging phases.

Due to its low cost, the XLogic software-logic controller has become an excellent alternative to expensive similar equipment of well-known brands such as Simens and others.

6-19

DEVELOPMENT OF AN AUTOMATED RADIATION CONTROL SYSTEM BASED ON SEMICONDUCTOR IONIZING RADIATION DETECTORS

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This paper describes an automated radiation monitoring system developed at the Institute of Plasma Physics of the NSC KIPT on the basis of semiconductor detectors of ionizing radiation. It is designed to measure and control the level of ionizing radiation during applied research on promising areas of controlled thermonuclear fusion.

On powerful experimental physical installations, magnetic plasma confinement systems are used. Removing the pulsed electromagnetic field (the magnitude of the current in the helical winding is about 16 000 A) is accompanied by a rapidly decrease of the current in the windings. This leads to uncontrolled dash of electric fields, which, in turn, provokes hard X-ray radiation.

Since the process of ionization radiation occurs rapidly enough, it becomes necessary to develop a special automated radiation monitoring device that allows measurements of the intensity of ionizing radiation in real time.

For these purposes, a prototype of the X-Meter 002 ionizing radiation meter was developed. It includes a high-frequency analog signal pre-processing part with a thermal stabilization unit, a microprocessor controller for recording X-ray intensity and controlling the instrument. The analog part of the device consists of a remote probe with an ionizing radiation detector, an amplifier and an analog signal generator.

As the ionizing radiation sensor in this work, a volumetric semiconductor detector developed at the NSC KIPT based on the CdZnTe connection is used, its dimensions are 5x5x2 mm. The pulse duration of the equipment for detecting hard ionizing radiation is of the order of 5 μs.

To quickly register a large amount of data and implement the required functions of the developed device at low costs, it seems optimal to use a powerful microprocessor controller. In the presented device one of the most modern high-performance 32-bit microcontrollers is used - the integrated microcontroller PIC32MX795F512H with a clock frequency of the processor 80 MHz, the amount of data memory is 128 KB and 1 million 10-bit analog-digital transformations per second.

The developed software is a package of programs for controlling the device, recording data and transferring them to the local network. The program is written in C32 to work in the MPLAB X environment running under Windows operating system.. The registered experimental data via a serial interface RS-232 (COM-port) is transferred to the computer of the local network for further processing. Visualization of the obtained results is carried out with the help of the package Origin 9, which allows to plot the graphs immediately after processing the experimental data.

Developed at the Institute of Plasma Physics of the NSC KIPT, an inexpensive device of available components based on a high-speed integrated microcontroller for controlling ionizing radiation makes it possible to monitor the intensity of electromagnetic radiation in the experimental zone.

6-20

EFFECT OF THE EXTERNAL MAGNETIC FIELD ON THE DYNAMICS AND POWER OF THE SELF-SUSTAINED PLASMA-BEAM DISCHARGE

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A key feature of the self-sustained plasma-beam discharge (SPBD) is the possibility of obtaining the large levels of pulsed power inputted into the discharge [1]. The main mechanism of power input into the discharge is the interaction of powerful electron beam with dense plasma in the local discharge region. The electron beam generation occurs in a double electric layer of space charge (DL). Systems, based on SPBD, can be used for intense energy flows impact on the different nature solids surface when creating new structural materials. Also, under certain conditions, in such systems it is possible to generate the powerful directional radiation in the extreme ultraviolet range from plasma of multiply ionized atoms [2]. At present the methods for increasing the efficiency of pulse power input into the discharge are being searched.

One of the effective methods for increasing the power inputted into the discharge is the use of an external magnetic field. Such possibility of power increasing is investigated in this work using a high-current pulsed plasma diode of low pressure. The diode feature is the working surface limitation of the high-voltage electrode. This facilitates the DL formation near the electrode of an inversion point, which arises from the magnetic fluxes bifurcation. Part of the flow is closed through the central hole, and part through the space, thereby a magnetic trap is formed on the magnet axis between the inversion point and infinity. The magnets were arranged in such way that the high-voltage electrode end coincided with the minimum, the inversion point, and the maximum of the magnetic field.

Studies have shown that the level of power inputted into the discharge is significantly increased when using the external permanent magnetic field. The greatest power increase is observed for case when the high-voltage electrode end coincides with the magnetic field inversion point. The level of power inputted into the discharge increases by 2-3 times. The dynamics of the discharge current, the active power inputted into the discharge, and the dependence of energy released in the discharge on the initial stored energy are presented in the work. Comparative dependencies are shown for the case with an external magnetic field and without it. It has been noted that since the intrinsic magnetic field is much higher than the external the effect of the external magnetic field occurred at the initial discharge stages, at the moment of the primary and dense near-electrode plasma formation. Changing the magnets position, the magnetic fields topology in the discharge gap changed which influenced on the discharge excitation mechanisms. The magnets position also determined the location of the DL formation and the region of local power input into the discharge.

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6-21

ION SEPARATION IN A PLASMA MASS FILTER BASED ON BAND GAP FILTER PRINCIPLE

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Separation of ions by mass/charge in a plasma rotating in an axial homogeneous magnetic field and a radial electric field with dc and ac components is considered. A radial electric field E_r is produced by coaxial electrodes. In this system, a plasma mass filter can work according to the principle of band gap filter with zones of confined and unconfined ion orbits for different frequencies. The frequency characteristics determining the trajectories of ions at the boundaries of zones are considered. The correlation of the band gap filter operating mode to the ion cyclotron frequency Ω is shown. One of the mode is combination of plasma rotating in crossed E⊥H fields and ion cyclotron resonance. For this case, the conditions [1-3] for selection of the resonant ions of uranium dioxide in the plasma mass filter, which is currently being developed for the separation of nuclear fuel and fission products have been analyzed. For given initial parameters, it is shown that when the variable component of radial electric field with $\omega = 0.57\Omega$ is superposed on the dc component, the uranium dioxide ions eject into the collision with the wall of the cylindrical chamber.

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6-22

ELECTRON ENERGY PROBABILITY FUNCTION AND DUST CHARGE IN THE TEMPORAL AFTERGLOW OF A PLASMA WITH LARGE DUST DENSITY

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The electron energy probability function (EEPF) in a dusty afterglow plasma is studied. The analytical study is carried out using the method of characteristics. Analytical expressions for the EEPF in an argon plasma afterglow with large dust density are obtained from the homogeneous Boltzmann equation for the electrons for different steady-state EEPFs (including both Maxwellian and Druyvesteyn distributions) at electron energies larger than the dust-surface potential. The two cases are considered: when the rate for electron-neutral momentum-transfer collisions is independent of the electron energy, and when it is a power function of electron energy. It is analyzed how the EEPF shape depends on the dust density, the dust size, the decay time of dust charge and the afterglow time. It is also found how the decay time of dust charge in the plasma afterglow depends on the decay time of effective electron temperature and that of electron density. The results on dusty plasma afterglow presented here are relevant to many applications involving nonstationary plasmas containing impurities, especially gas discharge plasmas used for production of novel nanomaterials.

6-23

CHARACTERISTICS OF TiN COATING DEPOSITED BY VACUUM-ARC METHOD ON ROTATING CYLINDRICAL SAMPLE

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Inhomogeneities of intrinsic stress and thickness of deposited coating arise when the vacuum-arc deposition of the coating on object of complex shape. It is possible to reduce inhomogeneities in the deposition of the coating on the surface of cylindrical sample by rotating the article around the axis of symmetry. When forming the coating, ions participate that fall at different angles and contribute differently to the rate of growth and the stresses in the coating. We theoretically investigate the dependence of the growth rate *v* and intrinsic stress σ on bias potential on substrate for the TiN coating deposited on the surface of the cylindrical sample rotating around the symmetry axis perpendicular to incident Ti^+ ions flow.

Fig. 1 displays the result of calculation of the average atom sputtering coefficient $\bar{K}(U)$ of atoms Ti at the Ti^+ ion flux falling onto the TiN coating deposited in DC mode (curve 1) and in pulsed potential mode (curve 2) on the surface of a rotating cylindrical sample. The mode of the pulsed potential with a duty cycle of 0.12 is considered. For comparison, the sputtering coefficients for ion incidence on the flat surface at the angle $\alpha = 0°$ (curves 1' and 2') and at the angle $\alpha = 70°$ (curves 1" and 2") are also given. The growth rate of the coating, per one incident ion, is calculated by the formula $v(U) = M[1-K(U)]/\pi\rho$, where M and ρ are the molecular weight and density of the coating material.

In Fig. 2 shows the calculated curves of intrinsic stresses in the coatings deposited on a rotating cylindrical sample in the DC mode (curves 1) and the pulsed potential mode (curve 2). Dashed curves show the dependence of intrinsic stresses in the coating during normal incidence of ions on the flat substrate.

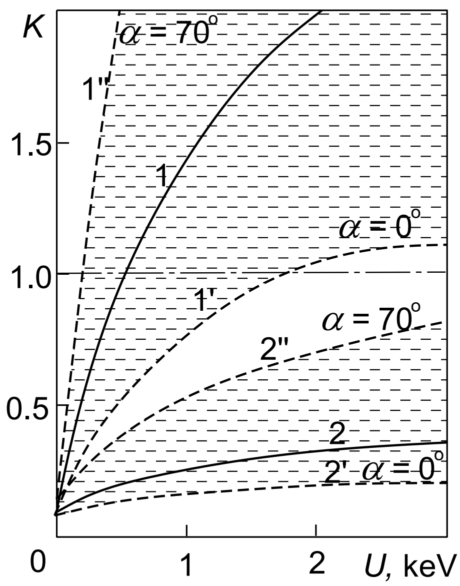

Fig. 1. Average sputtering coefficients at TiN coating deposition on rotating cylindrical sample in DC (solid curve 1) and pulsed potential (solid curve 2) modes.

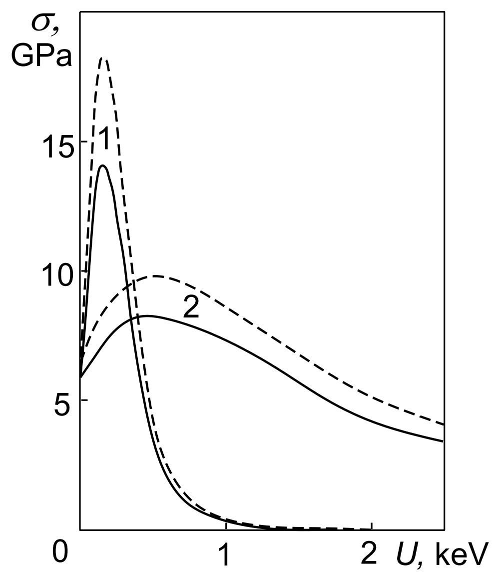

Fig. 2. Intrinsic stresses in TiN coating deposited on rotating cylindrical sample in DC solid curve 1) and pulsed potential (solid curve 2) modes.

6-24

PROPERTIES OF MICRODISCHARGE PLASMA IN THE VORTEX AIR FLOW

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The atmospheric pressure (P_{atm}) microdischarge plasma is the one of the most promising directions in the nonequilibrium plasmachemistry today. It is confirmed by a large number of researches which are devoted to the use of micro-discharge plasma in plasma-medicine. The most current interest in this direction are such things as: wound treatment starting from blood coagulation and finishing with healing acceleration; dental application of plasma; sterilization of medical equipment or living tissue, etc. A number of devices for a generation of the plasma jets have already been implemented for those purposes. The overwhelming number of designs in this area is based on using of dielectric barrier discharge, corona discharge or high-frequency types of discharges. It is known that such discharges have low gas-kinetic temperature of heavy particles and very high level of the reduced field (E/N ~ 500 Td). As a result, average electron energy in the plasma jet is ~ 10 eV. Such energies can become a reason of radiochemical processes stimulation in living tissues. In this case corresponding pathologies in the treatment tissues can cause. We have to pay special attention to the fact that there is large variety of living things that have narrow boundaries of existence in the environment. Therefore, the significantly affect the living tissues can be caused even by relatively insignificant changes in the conditions of existence. For this reason, developing of plasma generators with substantially lower values of the reduced field for medical applications is highly promising. Consequently, microdischarges can rightly be considered as one of the most promising plasma jet generators for their use in biomedicine, which can operate at substantially lower E/N values.

In this paper the microdischarge in a vortex gas flow was studied. The plasma-forming gas injection was realized in the way that minimizes exchange between the plasma and the environment. In this way we can expect the smallest energy level of the electrons in such plasma.

The temperatures of excited vibrational levels (T^*_v) and excited rotational (T^*_r) levels of molecules was determined from the emission spectra of the microdischarge plasma (in cases of small and big interelectrode distances) by using the Specair code. Also, the reduced electric field of the microdischarge was evaluative from volt-ampere characteristics at different interelectrode distances. It is noted, that the electric field of the microdischrge has a linear dependence of the voltage from the interelectrode distance in both studied cases of distance between the electrodes: small (≤ 2,5 mm) and the large one (> 3,0 mm). But in the first case, the electric field is two times smaller. It was shown that reduced electric field about E/N = 20÷35 Td are typically for the studied microdischarge. Calculations of T^*_v was carried by using the codes ZDPlasKin and Bolsig + ($N = P_{атм} / T^*_r$). The determined from emission spectra T^*_v of the plasma components coincides with the calculated ones within the limits of the error.

6-25

INVESTIGATION OF THE INFLUENCE OF Ar PRESSURE ON VACUUM-ARC PLASMA WITH Cr, Cu AND Zr CATHODES

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The method of vacuum-arc deposition is widely used in industry for the application of various functional coatings and surface modification of materials (e.g., [1]). Metal coatings of Cr, Cu and Zr can be used for metallization of ceramic materials and as an anticorrosion protection. The release of an inert gas into the deposition chamber can lead to stabilization of the vacuum arc, as well as to the appearance of an additional gas ion flux that can be used to intensify the pre-etching process of the substrate material [2].

The aim of this work was to investigate the influence of the argon pressure on the ion current of vacuum arc discharge with Cr, Cu, Zr cathodes, and coating deposition rate on the sample surfaces perpendicular and parallel to the plasma flow.

The investigations were carried out on a Bulat-6 installation [3] with magnetic stabilization of the cathode spot and a focusing solenoid equipped with a Cr (99,9 %), Cu (99,99 %), or Zr (99,9 %) cathode of 60 mm diameter. The current of the arc discharge for Cr and Cu was equal to 100 A, and for Zr - 120 A. The current of the focusing coil was 1-3 A. The argon pressure was varied in a wide range, from 1×10^{-3} Pa to 5.5 Pa. The ion collector was a flat disk Ø 200 mm placed at a distance of 200 mm from the anode, which was supplied with a negative potential of -50 V relative to the chamber walls. The deposition rate of the coatings was measured by the "shadow knife" method by the use of the microinterferometer MII-4.

The results of the measurements show that for all the metals studied, a decrease in the ion current density is observed at argon pressure above 0.3 Pa. The most significant decrease in the ion current occurs for chromium (~30 times) and copper (~7 times) in comparison with ~2 times decrease for zirconium at argon pressure >2 Pa. The ratio of the deposition rate of the coatings on the samples surfaces parallel and perpendicular to the plasma flow increases with in the gas pressure and reaches 0.25-0.3 at an argon pressure of 0.5-1.5 Pa. This is due to scattering of metal ions on the gas target. The mechanisms of scattering of plasma metal ions on a gas target are considered.

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6-26

SIMULATION OF NANOPARTICLE DEPOSITION FROM PLASMAS ON SOLID SURFACE

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Nowadays, plasmas are widely used for production and coating of nanoparticles in the including large-scale plasma-based production of single walled carbon nanotubes and integration of plasma-grown silicon single-crystalline nanoparticles in nanoelectronic and solar cell devices [1, 2]. Controlled deposition and structural incorporation of such nanoparticles will make deterministic fabrication of nanostructured films with predictable properties a reality in the near future. Moreover, to create such a technology it is important to understand the dynamics of nanoparticles in the sheath that separates the plasma from the solid wall. Movement of nanoparticles in the sheath is governed by a number of forces unique to a low-temperature plasma and is extremely sensitive to the nanoparticle charge and mass. The nanoparticle charge is usually negative in the plasma bulk, but near negative substrates can be positive, since in this region the electron density is much smaller than the ion density. In this case, the electrostatic repulsion changes to attraction and the nanoparticles can deposit on the substrate. On the other hand, at a high density of nanoparticles, their charge can significantly affect the structure of the sheath. In this case, it is necessary to take into account the mutual influence of nanoparticles and the electric field in the sheath.

In this article, using numerical simulation we compute the nanoparticle fluxes onto solid surface, which is at a floating potential. We consider the solid substrate, which interacts with plasma and assume that it is under floating potential. On the boundary of the plasma and the substrate has formed a sheath. We have a stream of nanoparticles onto this substrate from the side of unperturbed plasma. The concentration of atoms is negligible, so collisions of particles with neutrals are neglected. In addition, we neglected the collisions of ions with electrons.

To describe the potential of a self-consistent electric field, we used the Poisson equation. Ions are described by the equations of cold hydrodynamics, density of the electrons satisfies the Boltzmann distribution. Dust particles are charged by electron and ion current, described in accordance with OML theory. For the simulation of the nanoparticles we use PIC method.

Calculations were performed for different radii of nanoparticles, their densities and velocities in an unperturbed plasma. Results of simulations show that the cloud of the dust component is formed in the region of the sheath, whose position varies in time. This causes the formation of an electric potential minimum in the region of the peak of the negative charge. Modification of the sheath by nanoparticles leads to reflection and vibrations of some particles, which causes an inhomogeneous flow of nanoparticles onto the substrate.

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6-27

LOW-TEMPERATURE OZONE STERILIZER BASED ON REACTOR WITH ELECTROLYTIC CELL

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In the paper, ozone generator based on electrolytic cell for sterilization of various medical instruments (dental, surgical) in water solution has been developed. During the first switch, the ozone concentration in water in the sterilization volume comprised 5.5 mg/l after 10 minutes of operation. During the second and subsequent switches of the device, the ozone concentration in water reaches ~ 7.5 mg/l in 10 minutes. The researches carried out have shown that the ozone concentration in water in the sterilization volume tends to increase between 5°C and 20°C. With subsequent increase to 25°C, the ozone concentration decreases.

The method of neutralizing of alkaline solution from the surface of medical instruments was investigated. Alkaline solution was processed using 1% alcohol solution of phenolphthalein. It was established that 15 minutes is necessary to remove alkaline from the surface of the instrument by means of ozonization. A number of experiments have been carried out to eliminate organic residues (blood) from the surface medical instruments. The results showed that traces of blood were not presented on the surface after 10 minutes of treatment. ("Delatest" type test system was used to determine the number of blood traces).

6-28

APPLICATION OF BIPOLAR PLASMA DISCHARGE OVER THE LIQUID SURFACE FOR WATER PURIFICATION FROM CHEMICAL AND BACTERIAL POLLUTION

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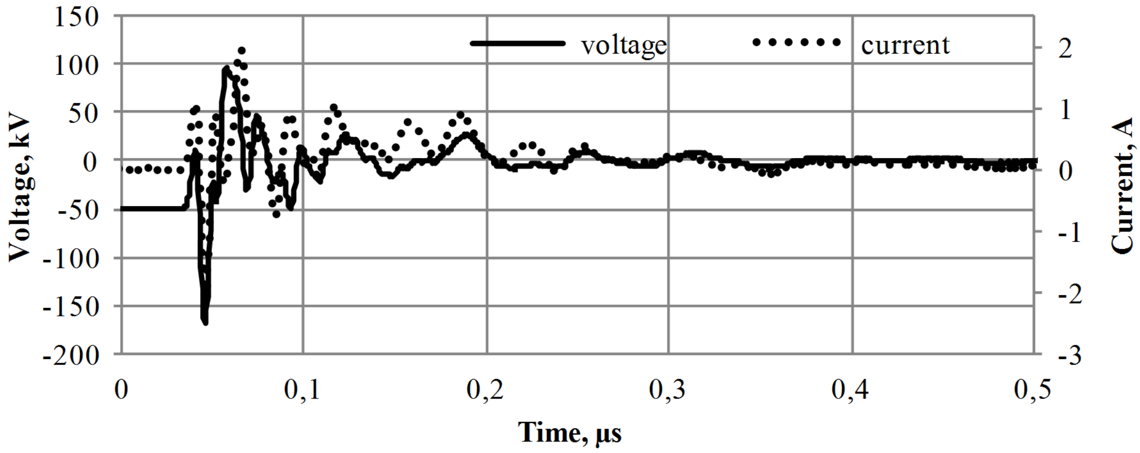
Recently, interest in the research of plasma pulse discharges above the liquid surface has increased [1]. One of the applications of such discharges is the water purification from chemical and bacterial pollution. A unipolar voltage pulse with a value of up to 30 kV at pulse duration $\tau \leq 200$ ns is used in most of generators producing high voltage pulses [2, 3]. The purpose of the work is to develop and construct a high-voltage bipolar pulse generator with U_{max} = 300 kV, $\tau \leq 50$ ns and pulse repetition frequency from 70 to 500 Hz. The use of this bipolar pulse generator will provide more significant influence of electrons, ions and active radicals from both gas phase (water vapor) and liquid on the chemical compounds and microorganisms in water [4].

The generator is constructed on the basis of a high-voltage inductor (Ruhmkorff coil). A Ruhmkorff coil with a supply voltage of 12 V enables to receive high voltage pulses up to 300 kV. In the generator, two MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor) are used as the current interrupter in the primary coil winding. The MOSFET is controlled by a driving oscillator on a 555 chip. Figure shows oscillograms of voltage and current in the discharge gap between the metal tip and the surface of liquid at atmospheric pressure.



Oscillograms of voltage and current in the discharge gap between the metal tip and the surface of liquid at atmospheric pressure

The constructed bipolar high-voltage pulse generator was tested by processing of water with the 280 ppm content of dissolved chloroform. After processing at U = 75 kV, I = 0.5 A during 20 min., chromatographic spectrometric studies showed that there was no chloroform in water. Processing of water with various microorganisms (for example, Esherichia coli, Candida albicans et al.) results in complete bactericidal purification of water.

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6-29

INFLUENCE OF VOLTAGE PULSE DURATION ON IGNITION OF GLOW DISCHARGE IN AIR

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Ignition of a glow dc discharge with constant (non-pulsed) voltage has been studied in detail in both short and long tubes. Unlike dc glow discharge, microsecond pulsed discharges have been studied much less, including their ignition. An advantage of the pulsed discharges is the possibility of changing the duty cycle, the fraction of the pulse period during which a voltage is applied to the electrodes. In this paper, the influence of the duty cycle on the ignition of unipolar low-pressure pulse discharge is investigated. Note that dc voltage is a special case of a pulsed voltage, for which the duty cycle is 1.

From the discharge breakdown curves measured for different values of the duty cycle D of the pulse it follows that the highest breakdown voltages are needed to ignite the discharge with short pulses, with small D. With increasing the pulse width, the strongest changes in the breakdown voltage are observed at a low gas pressure, to the left of the minima of the breakdown curves. In particular, with increasing D at a fixed gas pressure, the breakdown voltage first rapidly decreases, and then goes to saturation, which corresponds to the breakdown in a constant electric field ($D = 1$). At gas pressures near and to the right of the minimum, the behavior of the breakdown voltage remains the same, but its change with increasing D becomes less than at low pressure. The right branches of the breakdown curves for different D are close to each other and to the curve for a glow discharge.

At a low gas pressure (to the left of the minimum of the breakdown curve) two different unipolar pulse discharge modes can be observed. For short voltage pulses ($D \leq 0.4$), a low-current mode first appears (with the current that grows during the pulse). The growth of the discharge current begins some time after the application of sufficient voltage to the electrodes for the appearance of ionization processes in the gap between the electrodes. The discharge current in the low-current mode increases exponentially, this growth rate increases with increasing voltage. The discharge in this mode glows weakly and is similar to the obstructed mode of a glow discharge, in which the gap between the electrodes is too small even for the cathode layer to be located in it. Each time a voltage pulse is applied, the breakdown of the gap and the formation of a low-current mode occur anew.

Apparently, in the low-current mode during the voltage pulse, the discharge current does not have time to grow to a value large enough to form a mature anomalous pulsed discharge. The exponential current growth with time is related to a multi-avalanch ionization process, as a result of which, after passing from the cathode to the anode of a regular avalanche, a slightly larger number of positive ions appears in the gap between the electrodes than after the previous avalanche.

6-30

INVESTIGATION OF DC GLOW DISCHARGE IN CO_2 USING OPTICAL EMISSION SPECTROSCOPY

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Direct current glow discharge in CO_2 is widely used for pumping carbon dioxide gas-discharge lasers. In recent years, there has been a growing interest in plasma conversion of greenhouse gases (the main one of which is CO_2), to compounds such as methanol (CH_3OH) or synthesis gas (CO/H_2), that are important raw materials for the chemical industry or can be used as a fuel for internal combustion engines. In addition, CO_2 is a significant part of atmospheres on the planets and satellites of the solar system. Therefore, it is of interest to convert CO_2 into oxygen and carbon monoxide CO, which can be used as a rocket fuel. Studies of discharges in CO_2 are also carried out because of their use in various types of plasma reactors. In the gas-discharge plasma, different processes take place including the molecule dissociation, ionization of it and its parts, vibrational and electronic levels excitation.

This paper is devoted to optical spectral analysis of the structure of a glow discharge in carbon dioxide. Although there are many studies in the literature on the properties of glow discharge in various gases and, in particular, in CO_2, but usually its spectral studies were carried out in short tubes, or the authors measured the radiation spectra of a discharge at several specific points (cathode glow, negative glow or positive column) without plotting axial profiles of the radiation line intensities along the entire tube. Therefore, a glow discharge in carbon dioxide remains insufficiently studied.

The aim of this work was the experimental study of the longitudinal structure of a glow discharge in carbon dioxide by means of optical emission spectroscopy.

In the present work, a glow discharge in carbon dioxide gas was studied by optical emission spectroscopy. The results are given for gas pressure of 1 Torr and discharge current of 40 mA. Particular attention is paid to the processes occurring in the negative glow, the positive column and the anode glow – the most bright parts of the discharge. It is shown that in the negative glow bright emission lines of both atoms and molecules and their ions are observed: atomic oxygen 777 nm, 844 nm and 926 nm, which belong to the infrared range; lines of atomic oxygen ions O^+ (for example, 391 nm); bright lines of CO (the Angstrom system) and O_2 (Schumann-Runge system) molecules; lines of the molecular ion CO^+ (for example, 427 nm, Comet-tail system). Also, the molecular continuum (approximately 350 nm to 800 nm) is clearly pronounced. In the positive column, the lines of ions and atoms disappear, against the background of a weak continuum, only the emission of CO_2, CO and O_2 molecules is seen. However, in the anode glow the intensity of the continuum, the molecular and atomic lines increase significantly and may even exceed the corresponding intensities in the negative glow. Axial intensity profiles of a number of characteristic emission lines have been measured for the entire interval between the cathode and the anode.

6-31

STRUCTURE AND MODES OF DC GLOW DISCHARGE IN NITROGEN WITH HOLLOW CATHODE OR ANODE

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Glow discharge with a hollow cathode and/or anode is widely applied in many industrial ion devices (voltage-regulator tubes and thyratrons), in fluorescent lamps, spectral sources in atomic-absorption spectroscopy, for pumping gas-discharge lasers, for welding and melting materials with an electron gun, for modifying surfaces of solid bodies (etching, depositing thin films), in analytical and plasma chemistry.

In order to apply glow discharges optimally, one has to know their properties in various modes of burning. In the majority of papers one dealt with the glow discharge with a cylindrical hollow cathode as well as with a segmented cathode. The glow discharge with a hollow anode is less studied. And we do not know the papers comparing modes of burning and properties of the glow discharge with a "hollow cathode and a flat anode" and that of a "hollow anode and a flat cathode".

This paper reports the experiments we have performed in the discharge tube with the 56 mm inner diameter. One of the electrodes was flat and of 55 mm in diameter. Another one was hollow and of the following shape. Two plates 2 mm thick were located at the distance of 8 mm one from the other and they were fixed to a flat disc of 55 mm in diameter. Ends of plates were located at the distance of 37 mm from the flat portion of the electrode. These two electrodes served in turn as a cathode and an anode, i.e. we have considered the configurations of a "hollow cathode and a flat anode" and a "hollow anode and a flat cathode". The distance between flat parts of the electrodes was 100 mm. The study has been performed in nitrogen in the pressure range $p = 0.05 - 1$ Torr. With the optical spectrometer Qmini we have measured the axial profiles of emission lines of nitrogen molecules, atoms and ions in the 300–900 nm wavelength range.

We have revealed that the discharge with a hollow cathode and a flat anode may burn at low pressure (below 0.1 Torr) in the high voltage mode with an electron beam that can attain the anode. In this mode the negative glow does not penetrate the cathode cavity. With the gas pressure increasing the electron beam does not leave the cavity, and the discharge is burning in the glow mode. But with the voltage across the electrodes increasing a "hollow" mode sets in when the cathode cavity is filled with the negative glow. The transition between the "glow" and "hollow" modes possesses a hysteresis pattern, and the slowly growing current-voltage characteristic of the glow mode transforms jump-like into an almost vertical one for the "hollow" mode. At still higher nitrogen pressure (above 0.5 Torr) the total thickness of two cathode sheaths comprises only a small portion of the cathode cavity, the negative glow in the form of a thin film covers the cathode surface (in part in the normal mode or completely in the abnormal mode), the "hollow" mode ceases to play a remarkable role.

When we have employed a hollow anode and a flat cathode the flow of fast electrons comes only out of the flat cathode sheath, and an anode of any shape serves only as a collector of electrons. As the area of the flat cathode is much less than one of the hollow cathode, then using the flat cathode and the hollow anode one can get the discharge current less than one with the hollow cathode, and any hysteretic transitions are absent on the current-voltage characteristic.

6-32

FLAT ELECTRODE DIAMETER EFFECT ON GLOW DISCHARGE STRUCTURE AND PROPERTIES

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Glow discharge is widely applied in such devices employing glow discharge as gas discharge voltage stabilizers (voltage stabilizer diodes, surge protectors) as well as rectifiers with glow discharge etc. In order to apply the glow discharge correctly, one requires to know the conditions of its existence as well as its quantity characteristics in different gases, under various gas pressure values and electrode dimensions. In the most of the available publications the glow discharge was reported to be ignited between flat parallel electrodes of equal area. However the referred papers do not actually contain the data demonstrating how the flat electrode dimensions affect the plasma parameters of the glow discharge in discharge tubes of different length. Therefore the aim of the present paper was to study the effect of the flat electrode and anode diameter values on the current-voltage characteristics and structure of the glow discharge.

Experiments have been performed with flat electrodes of the diameter equal to 55 mm, 35 mm, 25 mm and 12 mm. The inter-electrode distance varied from 5 to 350 mm. The nitrogen pressure range studied was $p = 0.1 – 1$ Torr.

We have found that at low nitrogen pressure (e.g. 0.1 Torr) the discharge current is higher for large diameter electrodes the dependences of the discharge current density (defined as a ratio of the current to the electrode area) on voltage for electrodes of different diameter values are close to each other. However the electrode diameter affects the discharge structure substantially. So for the electrode of 12 mm in diameter the positive column is located at the distance of 150 mm from the cathode with the lowest current of discharge burning of 0.06 mA, with the current growing it moves fast from the cathode and at the current of 2.5 mA it disappears completely in the tube of 350 mm long. For the electrodes of 55 mm in diameter at low current the positive column is observed at the distance of 100 mm from the cathode, and one needs currents of several tens of milliamps for its complete disappearance. The dependences of the voltage across the electrodes on the inter-electrode distance are also differing considerably for different electrode diameter values.

At higher nitrogen pressure values (1 Torr and above) a considerable voltage drop is observed along the positive column. The electric field strength equals abouta 20 V/cm with the current order of 100 mA but with the decrease of the discharge current the field strength and the positive column length increase. Therefore with the current growing one first observes the normal mode (during which the discharge covers the cathode surface only partially), with the voltage drop across the electrodes diminishing. Then the discharge covers the cathode completely (for small diameter electrodes this occurs at low current values), however even after the transition to the abnormal mode the voltage keeps on decreasing due to the diminishing of the positive column length and voltage drop across it. And only at high current values the current-voltage characteristic assumes a growing pattern, this phenomenon being observed for high current values with large electrodes.

6-33

HYBRID MODEL OF THE PLASMA ACCELERATOR WITH OPEN WALLS AND CLOSED ELECTRON DRIFT

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The accelerator with closed electron drift is one of the kinds of the electric rocket engines and devices for ion-plasma treatment of the surface material. However, the accelerators with closed electron drift and open (gas) walls were not research sufficiently for now in contrast to the well known and widely used plasma accelerators with anode layer and with dielectric walls of accelerator channel. But this type accelerator could be interested for manipulating high-current flow of charge particle as well as can be attractive for many different high-tech applications for potential devises of low cost and compact thrusters. More than, it has some advantages, since the wall absence leads to exclusion of the wall material inclusions into the ion beam and to exclusion of the secondary electrons formation due to emission and thus to conservation of the plasma electrons dynamics. The original approach to use plasma accelerators with closed electron drift and open walls for creation cost effective low maintenance plasma device for production converging towards axis accelerating ion beam describe here. The two-dimensional hybrid model was created. The performed modeling showed that in high-current mode the ions moving to the system center and then along the axis in both directions are able to create space charge. The potential drop forms at the axis that could be used for ion beam accelerating. Note also that the presented plasma device is attractive for many different high-tech practical applications, for example, like plasma lens with positive space cloud for focusing negative intense charge particles beams (electrons and negative ions) and for potential devises small rocket engines.

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6-34

INVESTIGATION OF ELECTRON CUT-OFF IN A CILINDRICAL ELECTRODE SYSTEM IN PULSED MAGNETIC FIELD OF AN INDUCTOR

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Gas filled switches are commonly used to generate high-voltage high-current pulses in modern electrophysical equipment, in particular, in power supplying systems of accelerators. The high-speed current interrupters are of great interest, which make it possible to simplify the circuitry and effectively protect the equipment from short circuits. The simulation of the electron cut-off effect in a coaxial cylindrical electrode system of a vacuum arc interrupter is performed using pulsed magnetic field created by an external inductor. The calculation was performed using the COMSOL Multiphysics software. The model is designed for several versions of the two-electrode system: coaxial cylindrical one, coaxial cylindrical one with longitudinal slits, as well as a coaxial cylindrical system, in which the outer electrode has a radial protrusion towards the inner cylindrical electrode (the latter works as a concentrator of magnetic field lines near the inner electrode. The simulation is performed for a circuit with an anode voltage of 10 kV and copper electrodes. The introduction of the slits and the magnetic field concentrator allows to reduce the inductor operational current vastly (by tens of percents). The proposed model allows to investigate and optimize the parameters of the interrupter with magnetic extinguishing of the vacuum arc.

6-35

MULTIBEAM SYSTEM SIMULATION

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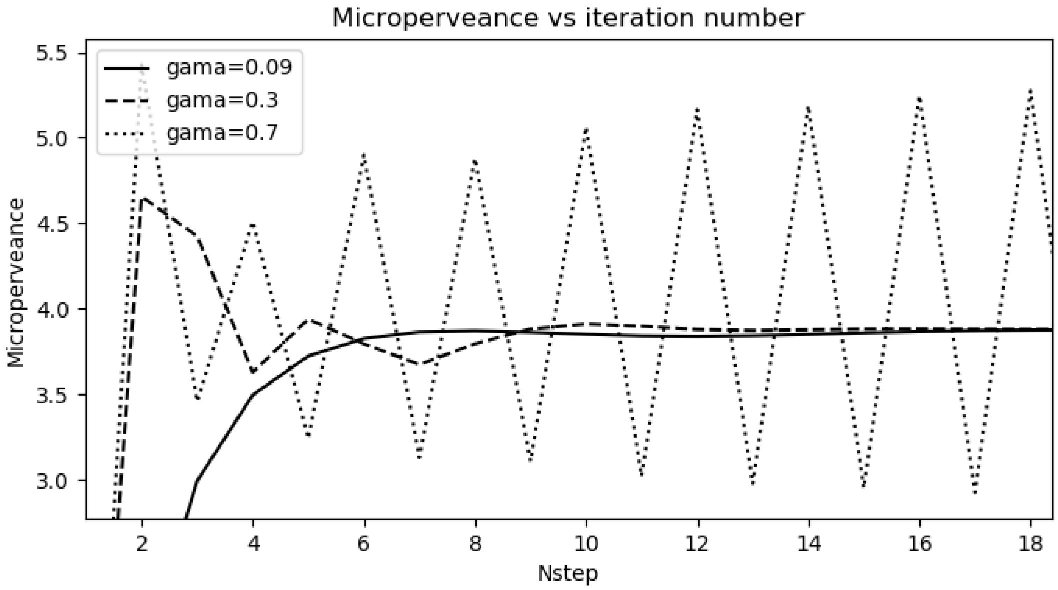
This paper is devoted to the study of the possibilities of calculating the self-consistent state of the electron and ion beam for the system used in the collective accelerator model [1, 2]. The results of numerical calculations of charged particle trajectories in a three-electrode structure are presented. A complex behavior is considered in the numerical calculations of beams with a current of limited space charge by the method of flow tubes.



A method for selecting the relaxation parameter of the injected current proposed (see figure), which ensures, in the calculation, the achievement of a steady state of the flow after the completion of the transient process. The current calculating results compared with the experimental data for both the high-current electron injector and for the thermoemitter of alkali metal ions. The possibility of calculating the beam of nitrogen ions formation system in the presence of an electron beam is discussed [3].

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6-36

COAGULATION AND DYNAMICS NANOPARTICLES IN LOW PRESSURE PLASMA JETS

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The use of nanoparticles is widespread in modern coating technology with special properties [1]. One of the most promising methods of applying films to the substrate are methods using low-pressure plasma jets [2]. It is important to be able to control the size of the nanoparticles, their kinetic energy, the temperature and the magnitude of the flow on the substrate. As is known, nanoparticles have the ability to coagulate, resulting in a change in their size. This process can be significant in plasma and it must be taken into account when transporting nanoparticles to a substrate in a plasma jet. The aim of this work is to simulate the dynamics and coagulation of nanoparticles in a plasma jet expanding through a round hole into a dilute gas.

We assume that the plasma consists of neutral argon atoms, single charge ions, electrons and dust particles. A hydrodynamic approach is used to describe the plasma movement in a two-dimensional axisymmetric model, which consists of the equations of continuity, momentum and energy equations for all plasma components. The model takes into account the recombination of electrons and ions on dust particles, as well as the exchange of momentum and energy between the components of the plasma. Coagulation and charging of nanoparticles in plasma are described in the framework of the sectional model [3]. According to this model, the stochastic charging of nanoparticles in a plasma is taken into account, which leads to their distribution by charge.

The simulation was carried out at different plasma pressures, ionization degrees of plasma and the concentration of dust particles at the inlet. As a result of the calculations, the spatial distributions of the plasma parameters, size and charge distributions of nanoparticles in the different points of space have been obtained. Influence of nanoparticle coagulation on the parameters of a plasma jet and the dynamics of nanoparticles is studied. It is shown that due to coagulation in the jet appear dust particles of larger radii. The maximum concentrations of these particles are at some distance from the inlet. The average charge of nanoparticles and the width of their distribution by charge increases in absolute value with an increase their radius and distance to the inlet.

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6-37

PLASMA PARAMETERS ESTIMATION IN THE NON-SELF-SUSTAINED GAS DISCHARGE WITH HOLLOW ANODE

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Low temperature plasmas have a wide variety of applications [1, 2]. Understanding of its properties is important for controlling of plasma based processes and technologies. Exact modeling of plasma behavior in the discharges with a complicated geometry by fluid equations or PIC-method has a large computational complexity. However, there is a possibility to build a simple model for estimation of plasma parameters without solving complicated equations.

Global modeling represents a numerical method of describing plasma discharges, based on fluid equations, that neglects spatial derivatives in order to enhance computational efficiency [3]. This numerical method gives a possibility for prediction of the volume averaged plasma parameters. Also it gives the relationships between main parameters and can be applied across a broad range of system properties.

A simple global model was built for estimation of the plasma properties in the non-self-sustained gas discharge with hollow anode [2, 4]. The calculated results are compared with experimental data of probe measurements. The applicability and limitations of the model are discussed.

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6-38

PLASMA-CATALYTIC SYSTEM WITH WIDE-APERTURE ROTATING GLIDING DISCHARGE

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Sustainable development demands the use of renewable raw materials and the minimization of waste generated during the production of materials required by humanity. Plasma-catalytic reforming [1] is one of the approaches to the reforming of renewable raw materials into syngas that comply with the conditions of sustainability [2]. Plasma-catalytic systems have two main chambers: the discharge chamber, which provides oxidant activation, and the reaction chamber in which activated oxidant interacts with hydrocarbon. During the plasma-catalytic reforming, discharge chamber is supplied only with an oxidant, meanwhile, the reaction chamber is supplied with the mixture of oxidant and hydrocarbon. Discharge generates active species (radicals, ions, electrons, excited atoms and molecules), which initiate reforming. Therefore, the sources of non-equilibrium (non-thermal) plasma with the high service life of electrodes play a vital part in the realization of plasma-catalytic approach. Wide-aperture rotating gliding discharge [3] can be such a source.

The plasma-catalytic system with wide-aperture rotating gliding discharge consists of the discharge chamber and quartz reaction chamber (100 mm high and with 36 mm inner diameter). The discharge was ignited between the internal T-shaped stainless-steel anode 25 mm in diameter and external grounded stainless-steel cathode, which had an aperture 20 mm in diameter in the middle. Rotating gliding discharge was powered by БП-100 power source, which provided up to 7 kV output voltage and was paired with 33 kOhm ballast resistance.

Discharge voltage and current were measured by a voltmeter and an ammeter. A digital oscilloscope was used to obtain voltage and current oscillograms with the help of 1/480 voltage divider and 10 Ohm shunt resistor. Optical emission spectra of the plasma torch in the quartz reaction chamber were registered by using a system that included an optical fiber, Solar TII (S-150-2-3648 USB) spectral device, and a PC. Spectrometer operated in 200-1000 nm wavelength range. PC was used to control the measurements and to process data collected by the spectrometer.

Plasma of rotating gliding discharge when the system was supplied only by air and the torch in the reaction chamber during the plasma-catalytic reforming of ethanol were investigated using optical emission spectroscopy. The relative intensities method was used to find the excitation temperatures of atoms based on the population of excited levels and their distribution alongside the length of the reaction chamber. Vibrational and rotational temperatures and their distribution alongside the length of reaction chamber were determined by matching measured optical emission spectra with spectra modeled in SpecAir software.

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6-39

INFLUENCE OF CORONA DISCHARGE ON PARAFFIN COMBUSTION

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Works [1-3] showed that the presence of corona discharge leads to the disturbance of the liquid surface. [1-2] showed that corona discharge causes polygonal cells to appear on the surface of the liquids with low conductivity. Our earlier experiments [4] showed that charged particles generated by corona discharge increase the vaporization rate of distilled water droplets. In addition, studies showed that charged particles have a more significant impact on the surface tension of liquids with low electrical conductivity (melted stearin, oil) than on more conductive liquids (water, bio glycerol). Liquids with low electrical conductivity are fragmented into small droplets under the influence of charged particles. This leads to the increase of the ratio between the surface area and volume of liquid. The rise of the area-to-volume ratio in hydrocarbon droplets can be used to increase the speed of mixing hydrocarbon with oxidant and the rate of hydrocarbons vaporization. All of this will allow to increase the combustion efficiency of the hydrocarbons with low electrical conductivity and to decrease the size of combustion chambers. This work focuses on the study of the combustion of melted paraffin under the influence of corona discharge.

Charged particles were generated using negative polarity corona discharge. The experimental system contained melted paraffin sample placed on a grounded metal surface, a tungsten needle, a thermocouple, a voltage divider and a resistor for current measurement. Current and voltage oscillograms of the discharge were taken using an oscilloscope. Visual observations of paraffin combustion were done by using a digital video camera. Melted paraffin temperature and flame temperature were measured using the thermocouple.

Paraffin combustion was investigated both with and without the presence of corona discharge. The time required for complete paraffin combustion was shown to decrease under the influence of corona discharge. Optical emission spectra of the paraffin flame were captured both with and without corona discharge. Emission spectra of flame contain continuous emission spectra, which could be linked to the presence of soot in the flames. Continuous spectra obtained during experiments were used to identify the temperatures at different operating modes by comparing them to the simulated spectra of the black body. Obtained temperatures can be close to gas temperature.

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6-40

DC GLOW DISCHARGE FOR SYNTHESIS DIAMOND FILMS WITH HIGH GROWTH RATE

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Studies on the use of glow discharge for the synthesis of polycrystalline diamond coatings have been conducted in the NSC KIPT for a number of years. Positive results were obtained using a glow discharge stabilized by a magnetic field; while the substrate holder was under floating potential. Later, the laboratory equipment was upgraded to avoid ion bombardment during the synthesis of diamond films. A flat cylindrical cathode was used, and the anode was a substrate holder.

As it was shown earlier, it was possible to achieve stable parameters of diamond films synthesis at a pressure of 100 mm Hg. The growth rate did not exceed 3 μm/h, which is clearly not enough for the deposition of films with a thickness of more than 100 μm. Therefore, in the process of further research, as a result of changing the geometric parameters in the discharge system, it was possible to achieve a stable burning of the discharge in hydrogen up to a pressure of 240 mm Hg. The discharge remained normal glow discharge, i.e. with increasing discharge current, the voltage between the cathode and the anode did not increase; but the temperature of the substrate holder increased proportionally in this case. The results obtained allowed to carry out a number of experiments on the synthesis of diamond films in the pressure range from 110 to 180 mm Hg. Synthesis of diamond films was carried out in a hydrogen-methane mixture with a methane concentration in the discharge chamber from 1 to 6 %. The cathode had a diameter of 66 mm, and the substrate holder serving as an anode had a diameter of 42 mm. It is known that the deposition rate of a diamond film depends on the ratio of the concentration of hydrocarbon radicals responsible for diamond growth and the concentration of atomic hydrogen. Therefore, as the pressure of the gas medium increases, it is necessary to increase the concentration of methane in the mixture in order to ensure the maximum growth rate. The studies have shown that for the maximum growth rate of a diamond film at pressures of 100-110 mm Hg 1 % of methane is enough, whereas at a pressure of 180 mm Hg the optimum concentration of methane in hydrogen was already from 3 to 4 %. The growth rate varied from 3.5 μm/h at 1…1.5 % methane and pressure of 110 mm Hg up to 7.5…8 μm/h, with a methane concentration of 2.5 % and a pressure of 160 mm Hg. The best results were obtained at a gas pressure in the discharge chamber of 180 mm Hg and methane concentrations from 3 to 4%. The growth rate of the diamond film reached 11…12 μm/h. The growth rate was determined by the weight method, averaging over 9 samples from monocrystalline silicon with a thickness of 340 μm and a size of 9x9 mm. With an increase in the concentration of methane in hydrogen above 4%, i.e. up to 5-6 %, the growth rate decreased monotonically to 9...10 μm/h. We note that the power input into the discharge did not exceed 4.5 kW at a discharge current from 5 to 7 A, which is much less than in previously published works. It should be noted that under certain deposition regimes, well-textured diamond films with an orientation of the surface of diamond crystallites (100) parallel to the surface of the sample were obtained. As shown by the research, the presented system of activation of hydrogen-methane mixture for the synthesis of diamond coatings is promising for use in technological purposes.

6-41

FEATURES OF IGNITION AND COMBUSTION OF PULVERIZED COAL IN THE FORM OF A GAS SUSPENSION.

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The use of plasma processes to activate the combustion of pulverized coal dictates the need to clarify the patterns of coal combustion in a high-temperature gaseous oxidant. The fuel used for combustion in power plants has a polydisperse composition. The particle size and their concentration in the gas suspension affect the heat and mass exchange rate with the oxidant gas and the plant walls.

Two fraction dust-air mixture is a simplest case of polydisperse suspension. So the purpose of this work is to study the characteristics of ignition and combustion of a two-fraction suspension of carbon particles in air at different temperatures. The main characteristics of fuels combustion are the ignition delay, the burning temperature and time, critical parameters (temperature, the particles diameters and mass concentrations), corresponding to fuel ignition and extinction.

The physical and mathematical modeling of the processes of high-temperature heat and mass transfer and combustion of carbon particles suspended in the gas taking into account the heat exchange by radiation and the kinetics of heterogeneous chemical reactions is carried out [1].

The high temperature heat and mass transfer and chemical kinetics are modeled for two-fraction gas suspension (diameter of fine particles 60 μm and that of coarse particles 120 μm) with equal mass fractions. The gas temperatures are in the range 1100 ÷ 1500 K. The numerical calculations for the model show that at gas temperatures higher 1400 K, small particles ignite earlier than large particles. Below 1400 K, ignition delay of fine particles exceeds this of coarse particles. And the difference increases with a temperature decrease due to higher value of heat transfer coefficient of fine particles.

Coal particles don't ignite below some critical gas temperature. It is established that the critical gas temperatures differ substantially for large and small single particles, in case of coal-gas suspension, they are practically equal. The effect of oxygen volume fraction on suspension ignition is analyzed. It is found that near the critical temperature of ignition, the oxygen concentration decreases by 30-40%. It is insufficient for self-acceleration of chemical reactions on the particle surface. Another reason is the low gas temperature, preventing the ignition of coal particles. It is established that the burning time of the fine fraction is almost 4 times less than that of the coarse fraction. Near the critical ignition temperature, the burning temperature of the fine particles is lower than that of the coarse fraction. For gas temperatures above 1250K, the situation changes: the combustion of the fine fraction occurs at higher temperature. It is found that if the gas temperature equals 1500 K, the burning temperature of fine particles exceeds that of large particles by 200K.

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6-42

ON THE MECHANISM OF THE ELECTRIC FIELD INFLUENCE ON THE ALKANI COMBUSTION SPEED

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The effect of the electric field on the burning rate of condensed fuels is actively investigated in connection with the need to improve the efficiency of burning solid and liquid fuels. This task is especially relevant for space applications, since in zero gravity the burning speed of particles and droplets of fuel is insufficient to ensure the stability of the combustion process and complete combustion of fuel. Numerous experiments have shown that in a constant electric field the burning rate of hydrocarbons increases noticeably. The hydrocarbon flame can be considered as a low-temperature plasma with a condensed disperse phase (soot particles). Primary ions and electrons in the flame front are formed mainly in the reaction [1]:

$$CH+O \rightarrow CHO^{+} + e^{-}.$$

The formation energy of the CHO^{+} ion is relatively low ~ 8.7 eV and, accordingly, the rate of this reaction is practically independent of temperature, therefore the charge concentration in the flame front is much higher than the equilibrium value. The formed ions and electrons diffuse into the preheating and afterburning zones, where they enter into various ion-molecular reactions. Present in the diffusion flame, soot particles, as a rule, carry a positive charge [2].

Therefore, the electric field affects the shape of the flame, soot formation, burning rate and ignition limits [3]. The processes of heat and mass transfer are intensified as a result of the appearance of a directed motion of charged particles («ion wind»).

We have experimentally investigated the ignition and combustion of octadecane ($C_{18}H_{38}$) and dokosan ($C_{22}H_{46}$) particles in the electric field of a flat capacitor, with a field strength of 33 kV/m to 117 kV/m, and also in the absence of a field. The processes of ignition and combustion of droplets were recorded by two chambers. The change in the size and shape of the particle / drop on the suspension was taken with a camera mounted on the microscope objective .The second camera recorded a torch flame. The resulting video files were divided into frames and processed in a MatLab package: the values of the equivalent diameter of the drop, the height of the torch, and the aspect ratio of the drop and flame were found.

From the graphs of the time dependence of the diameter and the square of the droplet diameter, the ignition delay time and the burning time, as well as the combustion rate constants, were determined. An analysis of the shape of the flame in an electric field was carried out, it was established that the flame was deflected to the negative electrode, the height of the flame decreased noticeably (> 20 %), the transverse dimension increased by 60% as compared with the torch without the field. According to our estimates, the heat flux to the droplet surface increases several times, which leads to an intensification of the evaporation of the fuel and an increase in the burning rate. Thus, the rate constant of alkane combustion increases in the electric field by 10-15%, and, accordingly, the burning time of the drops decreases. It should be noted that at E> 80 kV/m the melting of alkanes is noticeably slowed down. This effect must be taken into account when estimating the total melting and burning time of alkane particles.

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NUMERICAL SIMULATIONS OF SECONDARY STREAMER PROPAGATION IN CATHODE DIRECTED STREAMER CHANNEL

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The secondary streamers, which arise after the bridging of the discharge gap by the primary cathode directed streamer, are the parts of the primary streamer channel with comparatively large electric field strength and, as consequence, with comparatively large light intensity. In the paper [1], it is presented a sufficiently simple model of the instability development, which leads to monotonous increase or decrease of electric field strength at the different parts of the primary streamer channel, dependently on the sign of the difference between the local value of effective attachment frequency and the effective attachment frequency value averaged in the space, where the role of coordinate is played by potential. For the instability development, the dependence of the effective attachment frequency on the electric field strength is necessary, in which the derivative of the frequency with respect to the electric field strength is positive. A movement of the ends of the mentioned parts of the channel may take place, in principle, in connection with the change of the electric field strength in the different points of the channel, but there are the causes for the movement of the both ends, front and back, to cathode.

The leading edge of the secondary streamer moves to cathode in connection with the considerable decrease of the difference of the densities of positive and negative ions in the remainder of the primary streamer channel in front of the edge. The difference decreases through the negative ion density increase due to electron attachment, but this difference remains positive, and the local value of electron density is approximately equal to it, in connection with plasma quasi-neutrality. And the small electron density in the given part of the channel requires the large electron velocity, and so, the large electric field strength, for the approximately constant conductivity current along the channel.

The similar process near the back end of the secondary streamer with its movement to anode does not develop, as nearer to the needle anode the electric field strength is so large that the ionization rate is near or greater than the attachment rate. Here some excess of the attachment on the ionization takes place at the side part of streamer channel. And then, near the back end of the secondary streamer, the transverse dimension of the end of the channel remainder decreases, the electric field strength near the end of the channel remainder (that is, in the back end of the secondary streamer) increases, the ionization rate increases, and the process similar to the process of the primary streamer propagation begins to develop, but now it proceeds with larger initial electron density in front of ionization zone.

The similar development of the anode directed streamer from the tapering end of the channel reminder near the front end of the secondary streamer does not take place, as the anode directed ionization waves under the constant or the slow varying applied voltage do not have the tendency to the transverse localization.

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6-44

THE MECHANISM OF THE PLASMA ARC TRANSITION FROM THE DIFFUSE TO THE CONTRACTED ATTACHMENT TO THE SURFACE OF THE HOLLOW THERMIONIC CATHODE AT ATMOSPHERIC PRESSURE

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A review of the current state of the electric arc plasma torches development shows that for existing industrial designs with "cold" electrodes, practically all methods for the electrode lifetime increasing are realized. Therefore, the obtained resource values for such plasmatrons are close to the maximum achievable values.

Currently, electrode sheath processes in plasma arc devices with thermionic cathode at atmospheric pressure have been fairly well studied, and the results of investigations have been generalized in a number of works. The results of these studies show that the lifetime of such cathodes is largely determined by the mode of the electric arc attachment- diffuse or contracted. The contraction of the arc to the surface of the electrode leads to a significant increase in the specific heat fluxes to the cathode and a sharp increase in its erosion.

A promising area for the development of plasma equipment for industry is the use of hollow high-emission cathodes, which have proven themselves in the technique of electro-vacuum devices, as well as in electrically reactive propulsion systems, providing a resource of thousands hours.

Traditionally, the existence of two stable forms for arc attachment is associated with the existence of bifurcation points in the problem of the thermal balance of the cathode. Experimental studies of the reasons for the spontaneous transition of an arc from one regime to another were carried out mainly for low-current arcs, while research in arcs with currents of the order of 100 A and more remains few, and yields contradictory results.

From the authors point of view, the transition from diffuse to contracted attachment to the electrode surface for thermionic cathodes can be explained by an increase in the electron work function for the cathode material as a result of its contact with oxygen-containing gases. After deterioration of emission properties, maintenance of arc root attachment is possible only with increasing temperature of the emitting surface due to compression of the attachment region.

A significant dependence of the emission properties from the atmospheric composition near the emitting surface is a well-known fact. However, up to the present time this phenomenon has been ignored in studies devoted to the modeling of cathode sheath processes. Most authors, while describing the operation of thermionic cathodes, give table data for the magnitude of the work function for different materials, use them in simulations, ignoring the fact that these data were obtained during testing under conditions of deep vacuum. At the same time, the simplest estimates in the current work show that even with the use of high-purity argon, at pressures close to atmospheric, the partial pressure of the active gases contained in it exceeds the critical values for all known thermionic materials.

To confirm the hypothesis of possible reasons for changing the attachment mode, the following numerical experiment is carried out in this paper. Commercial code ANSYS Fluent was used for developing the mathematical model of the process. The electric arc between a cylindrical hollow cathode and a copper anode was simulated. The Ba3Sc4O9 + W composition obtained by the high-temperature impregnation of a tungsten sponge with a barium and scandium was selected for the cathode material. Experimentally obtained dependences of the emission properties for a given material from the partial air pressure and temperature were used. Argon was used as the shielding gas.

The current work aimed to investigate the mechanism of electric arc transition modes and to give a background for further research of the cathode sheath processes.

6-45

ON THE PECULIARITIES OF ELECTRICAL CONDUCTIVITY IN ARC PLASMA CONTAINING STAINLESS STEEL AND TUNGSTEN

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Arc plasma is often used in metallurgical applications such as plasma etching, spraying, cutting and welding. The presence of metallic vapors is widely observed in arc plasma [1, 2]. The influence of stainless steel and tungsten impurities on the electrical conductivity of arc plasma is considered in the ambient atmosphere of argon and water vapor. The calculations are carried out, and it is shown that a small amount of metal causes the essential changes in the value of electrical conductivity in comparison with the case of pure gaseous mixtures of argon and the water vapors.

The Grad method of moments [3, 4] is used to calculate the electrical conductivity. The approach based on Lorentzian plasma model [5, 6] is used for control of calculation procedure. The obtained results are compared with the data calculated with the Chapman-Enskog method [7-9]. It is deduced that for the case of the Grad method the suitable precision of calculations of transport coefficients can reached for more simple and faster calculation procedure than in the case of the Chapman-Enskog method.

The applicability of the calculation procedure based on the Grad method is presented for the case of thermal plasma. It is shown that the approximation of 13-moments is suitable to calculate the coefficients due to heavy particle transfer. For electronic transport coefficients it is needed to use the higher approximations of the Grad method.

Also, it is shown that in the case of plasma mixture containing stainless steel and tungsten the electrical conductivity may be drop down in dense metal vapors. The obtained results are discussed in connection with the experimental and literary data.

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6-46

STRESS AND TEXTURE FORMATION IN METAL NITRIDE COATINGS DEPOSITED FROM FILTERED VACUUM-ARC PLASMA UNDER CONDITIONS OF ION IMPLANTATION

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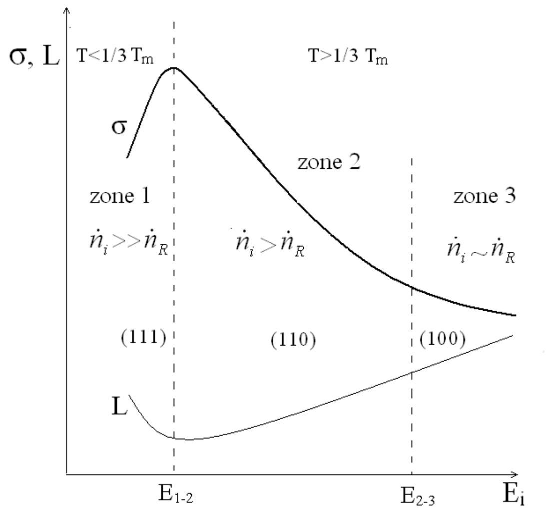
A theoretical analysis of the synthesis of nitride coatings deposited from a highly ionized flow of a filtered vacuum arc plasma under ion implantation conditions is provided. During the coating deposition is provided a high pulsed bias potential to a substrate with an amplitude of up to 3 kV. A thermodynamic approach based on the concept of nonlocal thermoelastic peaks (NTP), which are generated by implanted ions is used to explain the known experimental regularities of structure formation and stress state in coatings. The radius, the depth of the accumulation and the temperature in the peaks are determined, depending on the energy that the ions acquire under the action of the accelerating potential. The structure and stress level in the coatings are considered together, as a result of the competition between two differently directed processes in the NTP: radiation-induced of defects formation and their annealing. It is believed that the result of competition provides a minimum of free energy of the synthesized coating.

A diagram is proposed for the formation of a structurally-stressed state of coatings based on nitrides of transition metals with a cubic structure which deposited under ion implantation conditions. As the energy of the ions increases, three zones are identified. The first zone ($E < E_{1\text{-}2}$) corresponds to a low value of the temperature in the peaks $T < 1/3\ T_m$, which leads to low migration activity of the atoms (T_m - melting temperature). With increasing ion energy, the rate of formation of interstitial atoms $\dot{n}_i$ grows much faster than the relaxation rate $\dot{n}_R$, the level of compression stresses increases. The main contribution to the free energy is provided by the deformation energy, the minimum of which is provided by the orientation (111). As the energy of the ions increases, the size of the crystals in this zone decreases, since the probability of crystallite nucleation is increasing. In the second zone ($E_{1\text{-}2} < E < E_{2\text{-}3}$) the temperature in the peak slightly exceeds $1/3\ T_m$, which accelerates the relaxation processes and leads to a decrease in the stress level. The possibility of recrystallization processes and the increase in the volume of NTPs to 20-30 nm^3 causes the growth of the crystallite size and change the preferential orientation to [110]. In the third zone ($E > E_{2\text{-}3}$), the temperature in the peaks decreases slightly, remaining above $1/3\ T_m$, and the volume of the NTP reaches 100 nm^3. The rate of defects formation and their relaxation equalize, deformations decrease, and the preferential orientation changes to [100], which minimizes the surface energy, which becomes the main component of free energy. In the third zone the stress value stabilizes at a relatively low level and almost does not change with increasing ion energy.



The diagram of formation of the structurally-stressed state of coatings transition metal nitrides with cubic structure deposited under ion implantation conditions

The increase in the deposition temperature leads to a shift in the boundary between the zones toward lower energies, the more rapid decrease in the stress level and an increase in the crystallite size.

6-47

THE ANTIMICROBIAL ACTIVITY OF MAGNETRON SPUTTERED OXIDE COATINGS DOPED BY DIFFERENT Ag CONCENTRATIONS

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The standard methods for sterilization of medical instruments and products require time, intensive treatment, and aggressive chemicals using. The antimicrobial coatings formation on the surface of metal and plastic medical products is a possible alternative and effective way to improve the quality of modern implants, stents, and optical lenses. The antimicrobial properties of aluminum oxide coatings deposited by magnetron sputtering method on the glass substrates and doped by different concentrations of Ag against representative strains of microorganisms associated with hospital-acquired infections such as Gram-positive Staphylococcus aureus, and Gram-negative Escherichia coli bacterium were analyzed in vitro. Alumina coatings were deposited in a high vacuum pumping system with a base pressure of 6.6 Pa by high-frequency magnetron sputtering. A combined aluminum/silver target with a different areas ratio was used. The distance to substrate was about 3 cm. The magnetron system was equipped by RF generator with frequency 13.56 MHz. Argon as the sputtering gas and oxygen for the reactive deposition were applied. Flows for both argon and oxygen were regulated using mass flow controllers operated by two-channel process control unit. The forward power RF magnetron discharge was 80 W, reflective power 42 W, DC bias -163V. The coating deposition rate was 0.2 μm/hour, layer thickness of the order of 50 nm.

The microstructure and morphology of the coatings were studied by JEM-700F scanning electron microscope. The Energy-dispersive X-ray spectroscopy (EDS) method with a high-energy electron beam was used for determination of the elements and the Ag distribution in the Al_2O_3-Ag samples. X-ray photoelectron spectroscopy was carried out using ESCALAB MkII (VG Scientific) electron spectrometer using AlKalpha X-ray source (excitation energy hν=1486.6 eV). The instrumental resolution measured as the full width at a half maximum (FWHM) of the Ag3d5/2, photoelectron peak is 1 eV.

The following microbial strains and were selected: S. aureus 1337, methicillin resistant strain (MRSA) and E. coli from the Collection of Institute of Microbiology, BAS. The microbial suspensions (400 μl) were put on the coated and uncoated surfaces of glass substrates. The number of viable cells was determined and analyzed by optical microscopy.

The results demonstrate the principal possibility to increase the antimicrobial activity of the aluminum oxide coatings doped by different concentrations of Ag against representative strains of microorganisms. The effect of the antimicrobial action of coated surfaces results in the lethality of the studied bacterial strains during 24 hours of testing period. The activation of surface antimicrobial properties of various medical products is very challenging for many biomedical applications.

6-48

METHOD OF INCREASING THE LONGITUDINAL CURRENT OF H^- IONS FROM PIG WITH METAL HYDRIDE CATHODE

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H^- negative hydrogen ions have a high neutralization efficiency over a wide energy range, they are used both in solving the problem of controlled fusion, and in the production of a number of medical radionuclides for diagnostics and contact radiation therapy. The main requirements imposed on the H^- ions sources are its brightness and ecological purity. However, nowadays it is not possible to meet these two requirements in one device, since an increase in the efficiency of the source is achieved only by injection cesium vapor into it. For environmentally friendly use, it is necessary to have cesium-free sources with H^- volume production. The formation of negative ions in these sources occurs due to the dissociative thermal electrons attachment to vibrationally excited hydrogen molecules H_2^*, which are formed due to collisions with electrons energy of ≥ 50 eV. Therefore these sources are double-chambered, which invariably entails H_2^* molecules loss and a decrease of the H^- ions production efficiency. Moreover, due to a change in the discharge properties when a metal hydride cathode (MH-cathode) is using, it opens the possibility for longitudinal extraction of negative ions.

The original separation of regions with fast and slow electrons exists in the Penning discharge: in the anodic layer, the electrons are heated to the necessary energy due to the diocotron instability, and in the cathode region there is a large number of slow electrons obtained both from secondary emission processes and from reflection and scattering. If one or both cathodes are made of metal-hydride, the H_2^* molecules are formed due to the activation of desorbed hydrogen directly at its surface. This significantly increases the efficiency of ion production in the discharge volume. Moreover, due to a change in the discharge properties when a metal-hydride cathode (MH-cathode) is using, it opens the possibility for longitudinal extraction of negative ions.

The possibility of increasing the current of negative hydrogen ions extracted in the longitudinal direction from the Penning discharge with a metal hydride cathode by changing the potentials at the discharge cathodes is investigated. An electromagnetic filter is used to separate negative ions from the extracted flux of charged particles. A significant correlation between the extracted total current and the current of negative ions from the cathode potential was found. The optimal parameters for the effective extraction of H^- ions are determined. The current of the H^- ion beam at a level of 10 μA was obtained.

6-49

HYDROGEN INJECTOR BASED ON PENNING DISCHARGE WITH METAL HYDRIDE CATHODE

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An important part of the sources of ionized and neutral particles, as well as devices for gas supply of toroidal traps are pulsed gas injectors. For devices operating on hydrogen or its isotopes, it is convenient to use getter injectors as a source of hydrogen, which are comparable in speed or superior to piezoelectric injectors, and can compete with electromagnetic ones in terms of gas flow. To their disadvantages one can be attribute the need for periodic rather laborious regeneration and the ability to work with only one type of gas – hydrogen. However, the undeniable advantages of getter injectors stimulate work on their development and improvement. The main element of the getter injectors is a storage material based on reversible getter alloys, for example, zirconium and vanadium. These alloys have a sufficiently large hydrogen capacity and allow multiple recharging. Slow injection of hydrogen is due to the smooth heating of the entire accumulator, and fast – by the release of pulsed energy on its surface. The amount of hydrogen flow is determined by the size of the surface.

The paper presents the results of the investigation of a neutral-hydrogen impulse injector based on a Penning discharge with a metal hydride hollow cathode. The source of chemically pure hydrogen is a getter alloy $Zr_{50}V_{50}$ made in the form of a hollow cathode. The main release of hydrogen into the gas phase occurs under the influence of a discharge current (of the order of 20 A) in a short time, on the order of several hundred microseconds, during the operation of the high-current discharge regime. It is shown that the propagation velocity of the gas front depends on the discharge current and is determined by the temperature of the surface of the metal hydride cathode. The maximum value of the velocity of propagation of the gas front is obtained at a level of 3×10^7 cm/s with the amount of hydrogen desorbed per 600-microsecond pulse of the order of 1.5×10^{-3} cm^3 under normal conditions and the energy expended is 1.5 J.

Taking into account the possibility of the injector operating at high vacuum, the Penning discharge with its wide operating pressure range fits best. Additional features of this injector are the ease of implementation and operation. In addition to the neutral hydrogen flow, it is also possible to form a hydrogen plasma stream. The latter is important for cathode or anode transformers of quasi-stationary plasma accelerators.

6-50

ELECTROLYTE-PLASMA PROCESSING OF A SURFACE MODIFIED BY A HIGH-CURRENT RELATIVISTIC ELECTRON BEAM

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The implementation of manufacturing techniques for metal parts of complex shape is associated with the need to attract effective finishing methods. These methods must meet a number of requirements: prompt processing, the ability to automate the process, eliminating the anisotropy of residual stresses on the surface. Particular attention should be paid to products with a modified surface layer, the thickness of which is from 1 μm to 200 μm. Such layers should not be treated with an abrasive method, because the abrading method can locally or completely remove the modified layer. The most obvious example is the high current electron beams (HCEB) for surface modification. HCEB method has the possibility of modifying the surface layer to a depth of up to 200 μm, the disadvantage of the method is the pronounced surface relief, which is unacceptable in a number of technological applications. In this connection, the possibility of applying electrolyte-plasma processing to reduce the surface roughness of materials that had been pretreated by the HCEB method was investigated.

The samples of stainless steel 12X18H10T were irradiated at the accelerator of the NSC KIPT TEMP-A by electron beams. The parameters of the electron beam are as follows: the energy of the particles is 350 keV, the beam current is 2 kA, the pulse front duration is 5 μs. The irradiation mode is a single pulse. After irradiation, the samples were subjected to electrolyte-plasma processing (EPP). Further, the state of the surface of various target regions was studied. Surface profile studies were performed using a multifunctional Micron-gamma device. Optical and scanning electron microscopy was carried out using the METAM P-1 and JEOL-840 microscope, respectively. After exposure to the objects of investigation of the high-current electron beam, the surfaces were subjected to electrolyte-plasma processing. The processing was carried out on an installation that consists of a reservoir, an object immersion system, a power source, a control system, a measurement system, and system of data collection. The electrolyte was a solution of $(NH_4)_2SO_4$ with a concentration of 30 g/l [1-3].

As a result of EPP on the non-irradiated surface, technological impurities and traces of rolling are eliminated. On the irradiated surface, traces of the removal of frozen droplets and irregularities resulting from swelling and also the reverse condensation of the evaporated material are visible. The effect of decreasing the roughness by the results of surface profilometry measurements is established.

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6-51

ON THE INFLUENCE OF ZIRCONIUM AND TANTALUM IMPURITIES ON THE TRANSPORT PROPERTIES OF MULTICOMPONENT THERMAL PLASMA

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The influence of zirconium and tantalum impurities on the transport properties of thermal plasma is considered in the ambient atmosphere of argon and carbon dioxide. The calculations are carried out, and it is shown that a small amount of metal causes the essential changes in the values of transport coefficients in comparison with the case of pure gaseous mixture of argon and carbon dioxide. It is revealed that the influence of the Ramsauer effect on transport properties can be neutralized by additions of metal into ambient argon.

The Grad method of moments [1, 2] is used to calculate the transport coefficients (electrical and thermal conductivities, viscosity, diffusion coefficients). The approach based on Lorentzian plasma model [3, 4] is used for control of calculation procedure. The obtained results are compared with the data calculated with the Chapman-Enskog method [5-7]. It is deduced that for the case of the Grad method the suitable precision of calculations of transport coefficients can reached for the more simple and faster calculation procedure than in the case of the Chapman-Enskog method.

The applicability of the calculation procedure based on the Grad method is presented for the case of thermal plasma. It is shown that the approximation of 13-moments is suitable to calculate the coefficients due to heavy particle transfer. For electronic transport coefficients it is needed to use the higher approximations of the Grad method.

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6-52

INFLUENCE OF COLD ATMOSPHERIC PLASMA OF MICRODISCHARGE ON FUNGAL MYCELIUM AND SPORES GROWING

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Current methods of inactivation and elimination of microorganisms and their spores possess a number of disadvantages: high cost, difficulties with usage of the method among the potential users, formation of remainders on the processed surface, formation of disinfection products, change in properties of the surface and, finally, development of resistant strains of microorganisms. For this reason, development of more advantageous methods of microorganism inactivation and elimination remains a prospective area of research.

Cold plasma discharge application to the microorganisms is among the developing methods of microorganism inactivation and elimination. While traditional methods, based on chemical, physical (ultraviolet and γ-radiation), mechanical (pressure) and heat processes, have the mentioned disadvantages, cold plasma discharge methods possess a number of significant advantages, such as safe and controlled plasma application to the organisms. Due to the recent availability of cold plasma discharge sources that are spatially uniform and highly controlled, their application in atmosphere pressure conditions has become a reality in the realm of medicine, namely in microorganism inactivation and elimination.

The scope of this work was to analyze cold plasma discharge chemoactive particles influence on two fungal microorganisms: *Cyathus olla* and *Penicilium sp.*

In *Cyathus olla,* speed of mycelium growth increased on 0,6 mm/day after cold plasm discharge processing which meant that short cold plasma discharge may stimulate growth of the mycelium of this microorganism. *Cyathus olla* is a relatively common fungus with a worldwide distribution and a subject of agricultural research due to its potential to accelerate the breakdown of crop residue and reduce the population of plant pathogens, such as canola stubble. Therefore, our results may be a basis for further research of this fungus growth stimulation by plasma in fundamental and applied science.

On the contrary, cold plasma discharge processing of Petri dishes with *Penicillum sp.* resulted in growth lag of the colonies. At the same time, the size of the spores in processed colonies appeared to be damaged with the size 2 μm bigger than in a control dish. We also found that *Penicillum sp.* spores were more sensitive to plasma processing on the second day after sowing. This means that *Penicillum sp.* may be more sensitive to plasma processing on the stage of germination.

As a conclusion, cold plasma chemoactive particles demonstrated contrary effects on spores and colonies of two fungal species. As soon as fungal microorganisms play important role in agriculture, medicine and farmacy, our research may establish a basis for further investigation of cold plasma discharge influence on fungal microorganisms and its application in various realms of industry, agriculture and medicine.

6-53

USE OF A PULSED POWER SOURCE FOR THE DEPOSITION OF POLYCRYSTALLINE DIAMOND COATINGS

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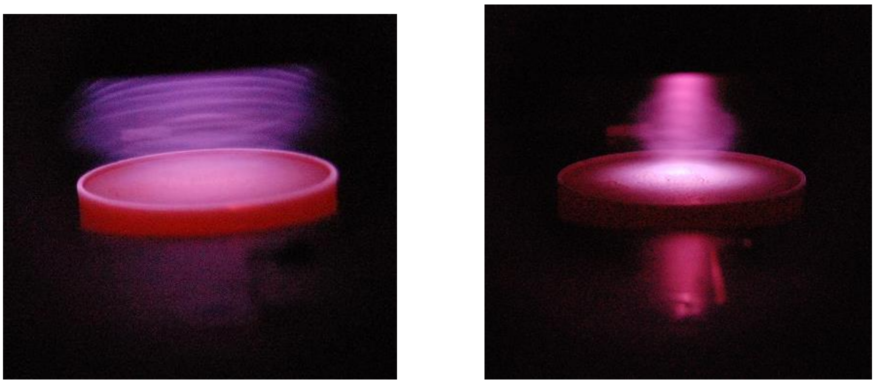
According to the literature data, the use of pulsed power supplies to excite microwave plasma leads both to an improvement in the quality of diamond coatings and to an increase in the growth rate without increasing the average power of the power supply [1-2]. To date, the processes of depositing of diamond coatings from the gas phase in a continuous DC glow discharge plasma in crossed E / H fields have been thoroughly studied and worked out at the equipment available at the NSC KIPT.

The use of a pulsed power supply on such equipment to excite and maintain a glow discharge plasma has shown that the stability of burning of a glow discharge in comparison with a constant power supply is much higher. This allowed us to increase the supplied to the discharge gap power without the risk of turnover a glow discharge into the arc (Figure). In studies with using a pulsed power supply, the pressure in the chamber was 8×10^3 Pa, the amount of methane in hydrogen varied from 0 to 1.5 %. It was found that an increase in the pulse frequency from 10 kHz to 50 kHz, at a constant duty cycle and power, leads to an increase in the temperature of the silicon substrates by 40 °-50 °C. With a further increase in the pulse frequency to 100 kHz, the temperature of the substrate was practically unchanged. A change in the duty cycle from 1.05 to 1.43 results in an increase of the substrate temperature by 45 °C at a methane concentration of 0.4 % and by 160 °C at a methane concentration of 1 %. The growth rate of the diamond coating increases with an increase in the duty cycle of pulses with all other parameters of the discharge unchanged (substrate temperature, pressure, composition of the gaseous medium, etc.). Studies performed with using a pulsed power supply allow us to find the optimal regime for the diamond film synthesis process with high stability and relatively low power consumption of the process itself.



a) *b)*

A picture of discharge with a) pulse and b) DC of the glow discharge excitation. Hydrogen environment, pressure 8×10^3 Pa, I = 5 A

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6-54

DEVICE FOR THE DEPOSITION OF NANOSTRUCTURAL DIAMOND COATINGS TO THE SURFACE OF DRY GAS DYNAMICS SEALS

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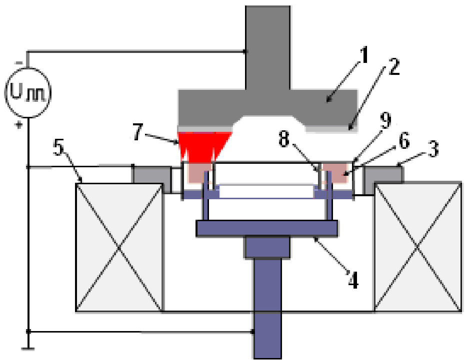
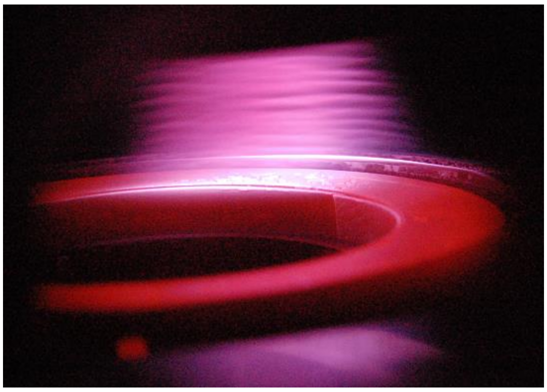
Specialists of the NSC KIPT in cooperation with the LLC NPF «Grace-Engineering" (Sumy) developed a process for depositing hydrogenated carbon diamond-like (a-C:H) coatings with a gas-phase plasma method on the surface of dry gas-dynamic seals (DGS) of medium pressure compressors. It is known that diamond polycrystalline or nanostructural coatings have significantly higher thermal stability, hardness and wear resistance in comparison with a-C:H films. In this connection, their use is extremely promising for use in hardening the DGS, operating at pressures above 100 atm, at which a-C: H coatings, as it turned out, are not workable.

The purpose of this work was the development of processes for depositing diamond nanostructural coatings on the surface of the DGS. At the moment, the NSC KIPT has facilities with well-developed processes for depositing diamond nanostructural coatings from the gaseous phase in a glow discharge plasma in crossed E/H fields onto substrates with the diameter of 20-40 mm. But the minimum diameter of the commercially available DGS is about 120 mm. Therefore, in order to provide the opportunity to study and refine the processes of depositing nanostructured diamond coatings to commercial DGS, the upgrade existing equipment was needed. After a series of experiments, we stopped at the design of plasma device with the annular cathode and the annular substrate holder shown in Figure. Using of such device has made it possible to obtain a stable glow discharge and to reach the temperature of the DGS above 950 °C. The growth rate of the diamond coating was in the range 0.5-0.7 μm/h with an unevenness not more then 30 %.



a)



b)

Diagram of a device for the diamond coatings deposition with the help of a glow discharge plasma in crossed E/H fields: a) after the equipment has been upgraded; and b) a photo of the discharge

1 - water-cooled copper annular cathode, 2 - molybdenum overlay, 3 - anode, 4 - substrate holder, 5 - electromagnet, 6 - sample (DGS), 7 - glow discharge channel, 8 - inner protective ring, 9 - outer protective ring

6-55

THE CONCEPTUAL DESIGN OF A DEMO-IMITATION SEPARATOR - THE MODEL OF A PLASMA MASS FILTER FOR IRRADIATED OXIDE URANIUM FUEL

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The demonstration - imitation plasma separator for simulating separation of nuclear fuel and fission product ions in spent nuclear fuel (SNF) plasma rotating in E⊥H fields is currently being developed. Expected setup productivity is ~15 -20 tons/year of the material - imitator, that corresponds to the production of SNF per year in WWER-1000 reactor. Actinide, lanthanide, zirconium and molybdenum oxides are the main SNF components at conversion into plasma during magnetoplasma SNF reprocessing [1]. Thus, a non-radioactive multicomponent mixture of these components can be used as a working material for research. The installation includes: plasma source ($n_e \sim 10^{14}$ cm^{-3}); magnetic system (working fields: B ~ 2.5 T in the plasma source area, B ~ 0.1 T in the separation area); coaxial electrode system for creating an electric field E_r; a tuner; a pumping system; a cooling system; longitudinal and end collectors. The longitudinal collector is located along the length of the vacuum chamber, and it has sections for collecting the ions of different masses. It is assumed that the collision plasma is injected from the plasma source in axial direction to separation area of the mass filter. When plasma moves in a decreasing magnetic field, the plasma flux expands, and in the separation area with a homogeneous magnetic field, where the plasma is collisionless ($n_e \sim 2 \cdot 10^{11}$ cm^{-3}), a spatial separation of heavy and light ions occurs. A feature of this system is the combination of plasma rotation with resonance at the cyclotron frequencies (ω_{ci}) of the target ions [3]. In this case, the resonant ions are UO_2^+ that eject to the side surface of the chamber at a radius of R = 1.3 m, E_0 = 400 V/m, B = 0.1 T and addition of a.c. component to radial electric field E_r equal to $0.6E_0 \sin(\omega t)$ for $\omega = 1/2\omega_{ci}$ (UO_2). The tuner allows selectively tuning the a.c. voltage component with a radio frequency, ω. Depending on the state of the working material, the separator may have a horizontal or vertical position.

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6-56

DESIGN AND RESEARCH OF COMBINED MAGNETRON-ION-BEAM SYSTEM SPUTTERING SYSTEM

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In the present paper the design and characteristics of the compact combiner magnetron-ion-beam sputtering system with specific parameters corresponding to industrial application are presented. The system allows to deposit coatings both by means of a magnetron discharge, and by sputtering complex compositional targets by high-energy ion beam.

Computer simulation and optimization of the topology of magnetic field lines for a magnetic system which is common for the magnetron discharge and the Hall-type ion source have been carried out. The ignition curves, discharge characteristics of the system, in dependence on the type of working gas, magnitude and topology of the magnetic field have been researched both for autonomous operation of the planar magnetron discharge and ion source and for their combination. The spatial characteristics of sputtered atoms flow and ion beam are also presented.

6-57

INVESTIGATION OF INTERACTION BETWEEN ION-BEAM PLASMA AND PROCESSED SURFACE DURING THE SYNTHESIS OF TANTALUM DIBORIDE AND PENTAOXIDE

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Last years low-pressure magnetron sputtering with ion-beam or plasma assistance is actively investigated for application in technologies of thin-film coatings deposition. It is known that in the transport space of an ion beam the ion-beam plasma usually appears neutralizing the positive space charge of the beam. In the case of simultaneous operation of ion beam and magnetron discharge an interaction between the ion-beam plasma, the magnetron plasma and the processed surface can play an important role, but it is not studied.
The paper presents the studies results of a nonequilibrium beam plasma parameters in the multipurpose cluster setup comprising a DC magnetron, an ICP plasma source, and a medium-energy ion source. The equipment allows independent control of the flows of metal atoms, of reactive particles, and of ions of rare and reactive gas.

The dependence of the particle fluxes towards the processed surface on the parameters of the deposition process was measured. The process parameters which were varied are the following: magnetron discharge power, pressure, target-sample distance, inductive discharge power, and bias potential applied to the samples. The effect of nonequilibrium heating of the sample surface due to relaxation of kinetic energy of ions, atoms and electrons, as well as energy of exothermic chemical reactions at synthesis of Ta_2O_5 and TaB_2 films was studied. The influence of ion bombardment on the parameters of the growing film is also investigated.

6-58

PECULIARITIES OF THE OXIDE PLASMA CREATION USING CARBONATE COMPOUNDS

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In previous work [1, 2] plasma methods for the recycling of spent nuclear fuel (SNF) was proposed. SNF mostly consists of oxide compounds from nuclear fuel and decay products. This is why studying the features of creation and parameters of the oxide plasma are of great interest. There are two ways to create the oxide plasma: either by direct ionization of the oxide or by way of heating the compounds, whose decay produces the oxide. In the present work, the process creating the oxide plasma was studied on carbonate compounds of calcium $CaCO_3$ and neodymium $Nd_2(CO_3)_3$. This allows a significant reduction in the energy input of the discharge. The experiment was conducted on a two-stage source with reflective discharge [3]. The ratio of ionization potential φ_i and dissociation energy ε of the oxide compounds in the plasma was taken into consideration by choice of materials. As a result, a number of emission spectra of the plasma for the different conditions of the burning plasma arc were obtained. The physical quantity ε/φ_i affects the redistribution of concentrations between ionic components and the mapping of the corresponding lines in the plasma emission spectrum. When $\varepsilon/\varphi_i<1$, the dissociation of oxide molecules occurs, the subsequent ionization of atoms and the production of corresponding lines in the spectrum. These spectral lines correspond to atomic ions. When $\varepsilon/\varphi_i>1$, the ionization of oxide molecules takes place without dissociation. In this case, the spectrum lines correspond to molecular ions. It is noted that the discharge ignition and burning conditions depend on the decomposition temperature of the investigated compounds.

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6-59

GENERATION OF SILVER NANOPARTICLES IN A PLASMA-LIQUID SYSTEM WITH A SECONDARY DISCHARGE SUPPORTED BY A ROTATING GLIDING DISCHARGE

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Production of nano-materials with different nature, like carbon, non-metallic or metallic nanoparticles in plasma systems is one of the perspective directions of plasma technology. In the world there is a problem with bacteria that are resistant to antimicrobial drugs (they are called superbacteria). Every year they kill up to 700000 people and every year this number increases. Development of new classes of antibiotics is slow and increasingly paying attention to research alternative methods of combating microbial infections. One of the important directions in developing alternative antibiotics is the use of nanoparticles. The noble metal nanoparticles (silver especially) has wide application in medicine: sterilization, healing acceleration and stabilization of bactericidal ointments. One of the effective methods to produce such particles is the processing of these metals salt colloidal solutions using electric discharge. The plasma-liquid system with secondary discharge that supported by rotating gliding discharge can be used for this task. The interest to systems with rotating gliding discharge is caused because such discharge allows to obtain non-equilibrium atmospheric pressure plasma with large cross section. This provides a large contact area between the plasma and the treated liquid. The plasma-liquid system with secondary discharge that supported by rotating gliding discharge was used in this work for production of nanoparticles of noble metals. A potential jump created by a secondary discharge above the liquid surface provides more efficient penetration of active particles from plasma into the liquid.

The scheme of plasma generator with secondary (non-self-sustained) discharge is maintained between the liquid surface and the channel of primary (self-sustained) discharge. The plasma-forming gas was supplied in the discharge chamber through two supply channels tangential to the inner cylindrical wall of the reaction chamber. The working liquid was placed below primary discharge in a glass vessel. The electrical potential is transferred to the liquid through the electrode at the bottom of the vessel. For the generation of discharges, DC and AC power supplies were used. Solution of $AgNO_3$ with addition of different concentrations of surface-active substances was used as a working liquid.
Parameters of liquids after plasma treatment were investigated by absorption spectroscopy method.

The Atomic Force Microscope (AFM) and Dynamic Light Scattering (DLS) measurements were used to determine the particle sizes obtained during the processing.
The sizes of received nanoparticles were from tens to hundreds of nanometers.
The possibility of obtaining time-stable colloidal solutions of silver nanoparticles in a plasma-liquid system with a secondary discharge supported by a rotating gliding discharge was shown.

6-60

INTERACTION OF LOW-ENERGY PROTONS WITH ALUMINUM SURFACE

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Aluminum and its alloys are often used in energetic as constructional materials. It has the melting temperature of 658.7 °C. It is a chemical element of third group of the periodic system, its atomic number is 13, and the relative atomic mass is 26.9815 Aluminum has only one stable isotope, ^{27}Al in nature. The advantages of aluminum and its alloys are low density (2.7 g / cm^3), relatively high strength characteristics, good thermal and electroconductivity, processability, high corrosion resistance. Aluminum is one of the most important technical materials. Therefore, it was chosen as one of the materials for studying the interaction of low-energy protons with its surface.

The proton irradiation was carried out in RF discharges in hydrogen at current of 5.5 A, and negative bias voltage (without breakdown) 250 - 260 V. Exposure was 11 hours, the heating temperatures were 150 - 400 °C. The working pressure in RF discharges was 0, 13 Torr at an intensity of magnetic field 300 Oe. Average proton energy was 250 – 260 eV [1].

The aluminum sample surface investigations after proton irradiation were carried out on an electron microscope. We found that after the irradiation process the sample surface changes significantly. The surface is becoming more uneven with the appearance of fine structure after treatment. Blistering is observed on the irradiated surface of the aluminum sample, i.e. swelling of the surface layer of the material in the form of spherical bubbles, which in some places burst (break away from the surface).

The essential cleaning of the aluminum surface from oxides due to the sputtering are occurs. It is also possible to reduce the aluminum oxides in the hydrogen plasma. For example, in work [2] arguments are discussed regarding the activity of hydrogen plasma during the reduction of metal oxides and semiconductors.

The hydrogen content near the aluminum surface increases by an order of magnitude after irradiation with protons. However, the hydrogen content decreases with depth after irradiation. The molecular hydrogen is not observed.

In mass spectra of the secondary ion emission a number of atoms masses (isotopes of Cr, Fe, Ni, Ti, Mn, etc.), belonging to the sample holder material (stainless steel 12X18N10T) are observed. There are also isotopes of other impurities that can be re-sputtering from the sample holder and silicon plate, which covers the untreated part of a sample.

In addition, the distributions of individual masses of the chemical elements (H, O, Al, Cr, Si, Ta, Nb, Al, Cu, C} from the penetration depth into the samples during argon ion beam sputtering with up to 1200 sec were determined.

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6-61

PECULIARITIES OF INTERACTION OF LOW-ENERGY PROTONS WITH MOLYBDENUM SURFACE

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One of the most important problems that arise before the developers of thermonuclear devices is the study of nonmagnetic materials and their alloys having high melting temperatures. It is also important to create new constructional materials that will be in contact with the thermonuclear plasma and should be as inert as possible in relation to this plasma.

Molybdenum is one such material. It has a melting temperature 2896 K, the boiling temperature 4912 K, the high deformation resistance, and small thermal neutron capture cross section. Therefore, it was chosen by us as one of the materials for studying interactions with low-energy protons.

Irradiation with protons was carried out at a modernized ion source [1] at HF discharge currents in hydrogen of 5, 5 A and negative bias voltage on samples of 250-260 V. The exposure was 11 hours, the sample heating temperatures were 150-400 C. The operating pressure in the plasma chemical reactor 0, 13 Torr. The magnetic field strength was 300 Oe. The average energy of the protons was 250 - 260 eV.

After irradiation of molybdenum foils by protons, the surface was examined with an optical microscope. We found that after the irradiation process the surface of the molybdenum foil changes significantly, it becomes more uneven with the appearance of a fine structure. In addition, there is a significant clearing of the surface from the oxides due to the sputtering of the molybdenum surface. Thinning of the foil is at a rate of ~ 0.1 μm / h at a temperature of 300 °C and an ion current density of ~ 1.5 mA / cm2. It is also possible that simultaneously the reduction of molybdenum oxides in the hydrogen plasma occurs.

Comparative studies of the mass spectra of the secondary ion emission measured in the treated and untreated samples in the mass range m / z = 1 - 250 atomic mass units were carried out. Sputtering of samples in the measurement of the mass spectra of secondary ion emission was carried out by argon ions with an energy of 500 eV and a current of 4 mA. The spectra are registered on the basis of the INA-3 device with a common ion-optical system, in which a quadrupole mass analyzer is used.

After irradiation of molybdenum with protons, the hydrogen content near the surface of the sample practically does not increase. The hydrogen content in molybdenum does not vary in depth, but it is constant both before and after irradiation. Molecular hydrogen in both samples is not observed. Seven isotopes of Mo and the same number of its oxides are separated. A number of masses of atoms belonging to the material of the substrate holder made of stainless steel 12X18N10T (isotopes of Cr, Fe, Ni, Ti, Mn, etc.) are observed. Isotopes of other impurities that can be resputtered from the substrate holder and silicon, which were covered the unprocessed portion of the sample, are also observed.

We also investigated the distributions of individual impurity masses (H, O, Al, Cr, Mo, Ta, Nb, Al, Cu) from the penetration depth into the samples by sputtering samples with an argon ion beam for 1200 seconds (to a depth of 2 μm).

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6-62

INVESTIGATION OF NONEQUILIBRIUM IN PLASMA OF ARC DISCHARGE BETWEEN MELTING ELECTRODES

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In this paper the physical manifestation of the nonequilibrium of arc discharge plasma in air with copper, nickel and silver impurities, which are evaporated from the electrodes, is considered. Such problem can take place in case of necessity to find out the composition of such multicomponent plasma. Usually abovementioned composition can be calculated on the base of preliminary experimentally obtained, as a rule, temperature, electron density and the ratio between the concentrations of metal impurities in the plasma in the assumption of local thermodynamic equilibrium (LTE) [1]. The last one ratio between impurity concentrations can be found from the corresponding ratio of intensities of the spectral lines of these elements, assuming that the levels, between those the radiative transitions are occurred, are populated in accordance with the Boltzmann law. In addition, it is assumed according to the LTE model, that ionization equilibrium in plasma take place as well.

At the next step of research one can calculate the radial distribution of the radiation intensity of each components of the plasma (in this case, the impurities evaporated from the electrodes). The radial distance of plasma column, within which the calculated and experimental profiles of radiation intensity are coincide with a certain accuracy, can be treated as LTE zone of arc discharge. The realization of both laws, namely, Boltzmann and Saha, are confirmed in such manner within this zone of considered plasma. An opposite situation (i.e. when both aforementioned profiles are not coincided in some spatial points) will be indicate on the deviation from LTE in plasma.

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6-63

SPECTROSCOPY OF HETEROPHASE PLASMA OF ELECTRIC ARC DISCHARGE BETWEEN W AND MO ELECTRODES

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Electric arc was initiated in air at 3.5 A current in discharge gap 8 mm between two cylindrical vertically oriented electrodes made from tungsten or molybdenum. Optical emission spectroscopy was carried out by diffraction spectrometer accomplished with CCD-matrix. Registered spectrum was investigated in special graphical user interface.

In order to apply diagnostic techniques of optical emission spectroscopy, first, it is required to select 'convenient' spectral lines for plasma analysis, which must correspond following criteria: these lines are supposed to be isolated in the emission spectrum and to be intensive enough for their guaranteed registration. Moreover, the difference between excitation energies of their upper levels must be as large as possible, since it allows determining the temperature with minimal error.

Spectrum of electric arc discharge between metal electrodes as usual contains atomic lines of metals, which can be used for plasma diagnostics. In case of high-melting metals as tungsten and molybdenum, not only linear spectrum, but continuous emission in background was also observed.

We assume that continuous spectrum can be explained by emission of metal particles injected in arc from electrodes. The phenomenon of MoO_3 crystals grow at electric arc plasma source was described in previous works [1, 2]. Molybdenum trioxide evaporates from lateral surface of electrode at 1150 ^{o}C. The upward convectional flows transport evaporations and particles into crystals growth zone and further into plasma volume. Due to high temperature in plasma the substances will heat, and cause continuous emission spectrum. Such continuous spectrum can be calculated according to Planck's formula and can be compared with registered one. Further heating obviously tends to destruction of substances to atomic scale, but convectional flows permanently support new portion of relatively cold substance in arc volume.

Taking into account of continuous radiation intensity allows correctly calculate plasma temperature, for example, by Boltzmann plots method. And also, such calculation allows to estimate the temperature of macroscopic particles distributed in plasma volume.

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6-64

STRUCTURE AND MECHANICAL PROPERTIES OF NANOCRYSTALLINE COMPOSITE TiC-aC:H COATINGS DEPOSITED FROM TITANIUM PLASMA IN BENZENE VAPOR WHEN THE RF POTENTIAL IS APPLIED TO A SUBSTRATE

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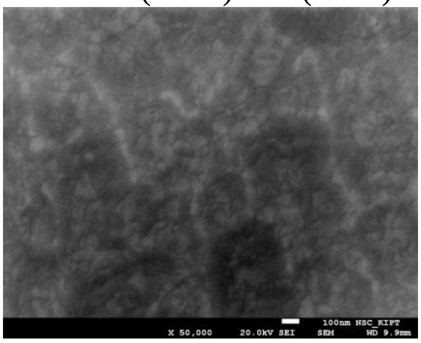
Nanocrystalline composite TiC-aC:H coatings are characterized by high hardness, strength and abrasion resistance, as well as increased thermal stability in comparison with known aC:H coatings [1, 2]. By the method of co-deposition of Ti-plasma from a vacuum arc and plasma of a high-frequency discharge in benzene vapor, we have previously obtained coatings containing, according to Raman spectroscopy, carbide TiC and aC:H phase [2].

In this work, when the coatings were deposited, the arc current with Ti cathode was 100 A, the benzene vapor pressure was ($1\ 10^{-3}$-$1\ 10^{-2}$) Torr. The RF potential of the substrate was set in the range (50-1500) V, the frequency of the RF oscillations was 7 MHz. The phase composition of coatings was determined from the Raman spectra, and the structure - based on the analysis of surface morphology of SEM images. The mechanical properties were measured by nanoindentation.

Since the surface relief is determined by the size and spatial orientation of the growing elements of the crystalline structure (crystallites, grains), its analysis allows us to draw conclusions about the structure of the coating material. The morphology of the surface of composite TiC-aC:H coatings deposited at RF potential of 1000 V is practically independent of the pressure in the range $(2\text{-}6)\bullet10^{-3}$ Torr. The surface microrelief of these coatings resembles cauliflower, with the dimensions of structural elements (100-400) nm, hardness 8 GPa, which is significantly lower than in aC:H coatings deposited in the RF discharge in benzene vapor. A much denser structure has coatings deposited at RF potential (200-500) V. In SEM images (Figure), it is seen that the surface relief is formed by mosaic-sized structural elements (30-50) nm in size, grouped into cells in the form of depressions separated by narrow (width (30-50) nm) ridges. Such a fine-meshed structure is characteristic of solid polycrystalline materials deposited under columnar growth conditions [3]. Nanoindentation showed that TiC-aC:H coatings with such a structure deposited at an RF potential on a substrate (200-500) V, are characterized by the greatest nanohardness (30-35) GPa (Table).



SEM image of the TiC-aC:H coating surface. RF potential 500 V, 6 10^{-3} Torr

Mechanical characteristics of TiC-aC:H coatings, deposited at pressure of 6 10^{-3} Torr

RF-potential,V	100	200	500	1000
Hardness, GPa	22	33.5	30.7	8
Young modulus, GPa	250	400	350	220

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6-65

COMPARISON OF BLISTERING UNDER H_2, D_2 AND He PLASMA IRRADIATION OF BULK W AND W COATINGS

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Tungsten (W) is one of the main candidates for materials of the first wall of fusion reactors [1], due to combination of such properties as a high melting temperature, high density and wear resistance, as well as low sputtering ratio and low hydrogen permeability. Earlier we have shown some advantages of the coatings, deposited by ion-plasma methods, over the tungsten foils with respect to the formation of blisters [2]. However, the structural differences in the materials have not been studied in details.

The goal of this work is the comparative study of the blistering of tungsten in different structural states under the influence of particles of low-energy hydrogen (deuterium) and helium plasma.

Three types of tungsten samples were investigated: bulk tungsten foil with 20 μm thicknesses, prepared by powder sintering, tungsten coatings deposited by cathodic arc evaporation and by argon ion sputtering. Structure, phase composition and residual stress of bulk tungsten foil and coatings were studied by the X-ray diffraction analysis using the DRON-4-07 diffractometer in Cu-Kα radiation and the scanning electron microscope JSM-7001F. The mechanical properties were measured by Nanoindenter G200. The disk-shaped samples have been irradiated with hydrogen, deuterium, and helium ions using a glow gas-discharge plasma at 1000 V, producing an ion flux of 10^{19} D^+ (H^+, He^+)/($m^2 \cdot s$).

The result of the investigations by SEM shows the difference of blistering for W samples. For instance, the density and the average size of the blisters on the bulk tungsten foil are larger than on the W films deposited by ion sputtering. No blistering is observed in the W coatings deposited by cathodic arc evaporation in the investigated range of doses.

Observed difference in the formation of blisters in the samples can be explained by their structural differences. Bulk tungsten and coatings are differing greatly in the level of internal stresses and crystallite sizes, which is observed by XRD method. This is a clear difference in the structure of coatings obtained by cathodic arc evaporation and argon ion sputtering, for cathodic arc evaporation coatings columnar structure is absent.

The conclusion to be drawn in this study is that the difference in the substructure characteristics of the material and determines the formation mechanism and the presence of blisters after irradiation by the plasma of a glow discharge in the investigated range of doses.

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6-66

INVESTIGATION OF ABRASIVE WEAR OF DIAMOND-LIKE COATINGS FOR SILICON CARBID SEALING RINGS

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Earlier, the NSC KIPT developed a process for depositing diamond-like coatings (DLC) without the use of an intermediate metal sublayer on the end faces of silicon carbide ring elements for dry gas seals (DGS) of high-pressure compressors [1]. The counterbody for the coating in the DGS is the reciprocal end ring made of silicon nitride. The contact of their surfaces during start-up braking leads to abrasive wear. In connection with this circumstance, an investigation of the abrasive resistance of diamond-like coatings for silicon carbide rings of dry gas seals is an actual problem.

One of the main requirements for coating is adhesion to the substrate. The experiment shows that providing the required level of adhesion of DLC that have a sufficiently high hardness and are operable in the DGS conditions is quite a challenge. The reason is the large internal residual stresses in such coatings, the greater, the higher their hardness. Several variants of the solution of this problem have been suggested in the literature. Some improvement in the adhesion of single-layer DLC can be achieved using a sublayer of metal (usually carbide-forming: titanium or chromium). The use of a multilayer architecture allows the application of single-layer DLC with a thickness of several microns to different materials.

In our experiments, the abrasion resistance of multilayer DLC of two types was investigated: quasigradient (the hardness of each next deposited layer increased) and multilayered, consisting of periodically repeating soft and hard solid layers 0.5-0.6 microns thick each. The coatings were deposited by a vacuum arc method from a plasma source with a rectilinear particulate filter to two types of substrates: 12Cr18N10T stainless steel plates of size 20x17 mm of 1.5 mm thickness and coupons of silicon carbide with a diameter of 15 mm with a thickness of 6 mm. Abrasive tests were carried out according to the scheme of a rotating abrasive disk - a plane. DLC deposited on stainless steel were tested.

At the end of the test process, the abrasive wear of the samples was assessed visually by optical microscopy as well as by weighing. Adhesion of multilayered DLC deposited on coupons of silicon carbide was evaluated based on the results of a scratch test (the load on a diamond indenter with a spherical tip of 500 microns radius was from 0.5 to 4 kg).

The best adhesion to silicon carbide (over 3 kg) was shown by three-layer quasigradient DLC. Also quite good adhesion showed DLC with periodically repeating soft and hard layers (5 layers, while the top layer is soft) with a total thickness of 3.2 microns, which survived without breaking the test at a load of 3 kg. Multilayer coatings consisting of 4, 8 and 12 layers (with the hard upper layer) with a total thickness of 2.3, 4.1 and 6 microns respectively were scratched to the substrate at loads of 1-1.5 kg.

Thus, an increase in the thickness of DLC on silicon carbide to 6-7 microns due to the use of a multilayer architecture of coatings with alternating soft and hard layers (the upper layer is soft) has led to improved abrasion resistance, but the adhesion of such coatings is worse compared with the quasigradient ones.

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6-67

METHOD FOR MEASURING EXTERNAL AND INTERNAL PARAMETERS OF PLASMA WITH UNGROUNDED GAS DISCHARGE ELECTRODES

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In experimental studies of gas discharges, the main task is to study the external (discharge current, discharge voltage) and internal parameters of the gas discharge plasma, such as: plasma concentration, ion and electron temperatures, plasma potential and their space-time distribution. The existing traditional methods of measuring such parameters involve the use of a number of diagnostic tools and recording equipment that require good grounding. At the same time, recently gas-discharge devices working both in stationary and pulse modes, with electrodes of the system, detached from the ground, are of interest. In such cases, monitoring the discharge parameters by traditional methods is difficult, and in some cases impossible.

This work is devoted to the method of measuring the external and internal parameters of gas-discharge plasma in conditions of non-potential "ground" using a multigrid probe with ungrounded electrodes and a casing. The technique was developed in the plasma of a pulsed high-current high-voltage magnetron discharge with the electrodes detached from the ground [1, 2]. This technique makes it possible to measure ion and electron densities and plasma temperatures and potentials, as well as the ion and electron energy distribution functions, with the usual accuracy for probe measurements. The measurements were carried out by a three-electrode probe installed in the cathode sputtering zone. Selection of the investigated particles was carried out through a screen located under a floating potential. The electron and ion energy distribution functions were calculated from the measured delay curves. The standard measurement technique assumes the grounding of one of the terminals of the power supply and the first grid of the energy analyzer. In our case, because of the structural features, both the MRS and the three-electrode probe are not grounded

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6-68

STRUCTURE AND PROPERTIES OF TiO_x AND TiN_xO_y COATINGS FORMED IN VACUUM ARC PLASMA FLUXES

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Now, attention is paid to three-component compounds of transition metals of the MeN_xO_y type [1]. This is explained by the fact that such coatings have high operational and decorative properties [1-3].

In the present work, the structure, microhardness and protective properties of oxide and oxynitride titanium coatings were studied depending on the negative potential on the substrate and the oxygen pressure, and also on the oxygen content in the gas mixture (N_2+O_2).

Experiments to obtain coatings were carried out on a "Bulat-6" system equipped with a Ti cathode of 60 mm diameter. Variable parameters of the process were the negative potential of the substrate, the pressure of the gas mixture, which was prepared in advance with different oxygen concentrations from 0 to 100 %.

It is shown that titanium coatings deposited in a pure oxygen atmosphere at a pressure of 3×10^{-2} Pa represent a dispersed system of oxides which composition depends of the bias potential on the substrate. Unlike titanium oxide coatings, TiN_xO_y coatings are single-phase, which lattice parameter varies with the partial pressure of oxygen. At optimal technological parameters of the coating deposition, TiN_xO_y system has high microhardness (34 GPa), corrosion resistance and decorative properties.

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6-69

PROBE MEASUREMENTS OF PARAMETERS OF DENSE GAS-METALLIC PLASMA IN THE INHOMOGENEOUS MAGNETIC FIELD OF A PLANAR MAGNETRON DISCHARGE

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Currently, the so-called high-power pulse spraying (HiPIMS – High Power Impulse Magnetron Sputtering) has become the most widespread among the systems of ion sputtering in thin film technology. The bottom line is to take advantage of the evaporation and spraying method in one process. It is known that the sputtering takes no more than 15% of the energy flux of the ion bombarding ions, and the remainder causes the target to be heated up to the melting point. In addition to physical sputtering, the flow of matter is formed due to a vaporized substance. This significantly increases the rate of deposition of coatings, and also improves the adhesive properties of films. In high-power sputtering, the principle is the same, the only difference is that, because of the large pulse power densities, the fraction of ionized atoms in the flow sharply increases (from 5% in systems with a classical magnetron to 60...80%), which also significantly affects surface morphology and the crystallization form of the synthesized coatings. The energy spectrum of ions coming from the discharge plasma to the target cathode determines the sputtering coefficient of the target material and, consequently, the performance of such devices.

This paper is devoted to measurements of the temperature and density of electrons and ions both in the stationary and pulsed modes of operation of a longitudinal planar MPC with a magnetically insulated anode in stationary and pulsed operation modes with an additional pulse high-current high-voltage power source [1, 2, 3]. The measurements were carried out according to the standard procedure for Langmuir double probes. The obtained current-voltage characteristics show that the temperature of both ions and electrons increases twofold in the pulsed mode of operation of the magnetron in comparison with the stationary regime, and the density increases by two orders of magnitude.

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6-70

HYDROGEN-REDUCTION OF SILICON TETRACHLORIDE IN A LOW-TEMPERATURE NONEQUILIBRIUM PLASMA OF A HIGH-FREQUENCY INDUCTION DISCHARGE

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Recently, technological processes and installations based on the application of low-temperature plasma are becoming increasingly important. High-frequency induction (HFI) discharges are widely applied, both for the purpose of studying low-temperature plasma, and for industrial applications of results in various plasma technologies. There are a lot of literature devoted to the experimental and theoretical studies of discharges in induction FHI - plasma devices, including works on direct numerical simulation. However, the presence of a large number of works on the subject under discussion is not yet a sign that all questions of theory and practical use have been successfully solved, rather just evidence of the steady interest to the topic.

Therefore, in order to study the process of polycrystalline silicon production via plasma-chemical method, issues considered the creation of experimental equipment that provides the necessary matching of a high-frequency generator with perturbation of a low-temperature nonequilibrium plasma in the vapor gas mixture of H_2 - Ar - $SiCl_4$. The thermodynamic calculation of processes of chemical transformations was conducted. The process of the reduction of silicon tetrachloride in the modes of optimal matching of the generator with the load was carried out. Also, valuation of energy costs per kilogram of received silicon was conducted.

6-71

STUDY OF DEGRADATION MECHANISM OF METAL-CUTTING TOOLS AND THEIR HARDENING BY ZrN PVD COATINGS

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The wear behavior of packaging knives made from high-alloy steel of X205Cr12KU type used in wrapping machines of MC1DT-T type (MC Automations, Italy) has been investigated. ZrN nanostructured coatings deposited by physical vapor deposition (PVD) with RF discharge mode have been employed to act as protective coatings on such knives due to their high hardness and chemical stability [1-3]. The chemical composition, microstructure, and physical-mechanical characteristics of the ZrN coating have been studied by means of optical microscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD), energy dispersive spectrometry (EDS) and nanoidentation method.

The maximum nanohardness of the ZrN coating reached 32.05 GPa, which was 3.4 times higher than the tool matrix and was 57.65 % higher than that of the base metal spec-carbide phase. The application of coatings allowed stabilizing the working surface layer under deformation and to prevent the carbide phase from being crushed. Due to ZrN coating an increase in wear resistance by 3 times under production conditions was achieved.

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6-72

COMPLEX EVALUATION OF STRUCTURAL STATE DEGREE OF CUTTING KNIVES STRENGTHENED BY PVD NANOCOMPOSITE COATINGS

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Technological cycle of thin-walled cutting knives made of 65G steel used in confectionary is insufficient and comprises 1-2 shifts only [1]. To increase the service life of cutting tools various PVD coating are applied. Structure and properties of the strengthened layer strongly depend on the substrate material and application method [2, 3]. The service life of tools reinforced by various methods differs due to structural heterogeneity of coatings, formation of various nonequilibrium phases that implies on microhardness and durability of reinforced tools.

In the paper, a new mathematical approach to determine the degree of heterogeneity of TiN nanocomposite coatings applied on thin-walled cutting knifes using Bulat-6 type device operated at various regimes (standard PVD, RF mode) was proposed. The surface topography and elemental composition of the obtained coating was studied by SEM. Evaluation of the structural heterogeneity of strengthening coatings was carried out using the developed optical and mathematical method.

It was established that TiN coating obtained using RF mode on cutting tools prevented diffusion of components from the base metal and degradation of the working layer, ensuring its stability during operation. The durability of the cutting knifes is increased by 47 times. It was shown that further durability of the strengthened tool can be improved by using high-quality cold-rolled metal.

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7-01

A HIGH SPEED 140 GHZ MICROWAVE INTERFEROMETER FOR DENSITY FLUCTUATION MEASUREMENTS IN URAGAN-2M STELLARATOR

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A single-channel 2 mm (14 GHz) interferometer has been deployed for plasma density diagnostics in the Uragan-2M stellarator (U-2M). The extremely compact microwave interferometer utilizes two independent horn antennae for emitting and receiving the microwave respectively. The beam path lies on the equatorial plane (with vertically orientated plasma ellipse) so the system would minimally suffer from beam path deflection problems due to the symmetry of the cross section. The whole system discards the reference leg for maximum compactness, which is particularly suitable for the small-sized stellarator. An auto-correcting algorithm (phase wrapping) is developed to calculate the phase evolution, and the result displays good phase stability of the whole system. The intermediate frequency is fixed, nevertheless it can reach its full potential of 1 MHz for best temporal resolution. The good phase resolution coupled with the fast time response of the detection system will permit use of the interferometer as a diagnostic to measure plasma density. Multiple measurements during various plasma discharges (plasma production/heating and vacuum chamber wall cleaning) proved the interferometer's capability to track typical (low frequency ~ 10-30 kHz) density fluctuations in U-2M, which enables this system to be utilized in the study of longwave MHD activities.

A new focusing lens group/new horn antenna system (for quasi vertical orientated line of sights (LOS)) and an oblique orientated vacuum window are in preparation for test and installation. The position of LOS could be split operation into two categories: profile or edge density measurements. With this carefully designed setup the interferometer will be able to boost the signal to noise ratio, which allows this system to show good performance even with the small-diameter central column itself when the vacuum chamber act as a reflector (with or without a dedicated retro-reflectors placed on a vacuum chamber surface). This upgraded system will be utilized to investigate detailed edge density fluctuations in the various improved confinement regimes available on U-2M.

7-02

DEVELOPMENT OF LIGHT ATOMIC INJECTOR FOR BEAM EMISSION SPECTROSCOPY (BES) DIAGNOSTIC OF URAGAN-2M TORSATRON

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The main idea of this report is improvement of the light atomic injector for BES diagnostic. BES complex consist of the neutral beam injector (including the ion beam accelerator and neutralizer) and the secondary light signal registration system. Diagnostic is used to study space plasma density profiles, impurity ions and magnetic field distribution in the edge zone of fusion plasmas. This method is based on the detection of the probe beam glow of atoms excited by the plasma electrons.

This report describes the investigation of two types of neutralizers –with open and closed evaporators. Based on the tests of 2 types of neutralizers, a new closed type design was developed. Such a neutralizer can work with a flowing stream of sodium vapor or supersonic. The investigation was carried out with the following parameters of the injector: the energy of the sodium ion beam to 30 keV, the ion current to 1.5 mA, and the beam diameter of 15 mm. Neutralization of the beam was carried out on sodium vapor at an evaporator temperature of up to 300 degrees.

7-03

THE STUDY OF THE RADIAL LOCATION OF QUASI-COHERENT MODES BY HEAVY ION BEAM PROBE IN THE TJ-II STELLARATOR

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Heavy Ion Beam Probe (HIBP) becomes recently an effective tool to study plasma potential and turbulence in toroidal fusion devices. This diagnostic was recently applied for the studies of Geodesic Acoustic Mode, MHD-tearing modes and quasicoherent modes on T-10 tokamak. In the TJ-II stellarator (B_0=0.95 T, $<R>$=1.5 m, $<a>$=0.22 m) an advanced Dual HIBP, consisting of two toroidally separated HIBPs becomes an effective tool to study Alfven Eigenmodes in NBI heated plasmas ($P_{NBI}\leq$1.1 MW, E_{NBI}=32 keV). The L-mode hydrogen plasma was investigated at various magnetic configurations with rotational transform $\iota(a)/2\pi=1/q$ ~ 1.5 - 1.6. Co-, counter and balanced beam injection were explored. HIBP is capable to measure simultaneously the oscillations of the plasma electric potential, density and poloidal magnetic field.

The recent experiments have shown that both steady frequency and chirping Alfven Eigenmodes takes place with 150 kHz< f_{AE} <380 kHz at the both pure NBI and combined ECR and NBI heated plasmas with low density $\bar{n}_e$ = (0.3 – 1.5)×10^{19} m^{-3} in both Low Field Side (LFS) and High Field Side (HFS) of the plasma column, as measured by HIBP. On top of that, the low-frequency modes with f < 30 kHz were also observed. There are several types of the low-frequency modes like Suprathermal electrostatic modes, tearing-like modes, quasicoherent modes with long-range potential correlations. Some of them are visible on the plasma potential power spectrogram, while others have also density and magnetic components.

The aim of the present study was to detect the spatial location for each type of the discussed modes. The spatial HIBP scan passing from LFS via plasma centre to HFS and back was used to detect the spatial locations. These data was supported by the data from the second HIBP that was either at the fixed spatial point or also scanned radially and also the data by Mirnov Probe Array and bolometer array (AXUV-detectors). The paper presents the spatial location for each of the discussed modes.

7-04

PLASMA POTENTIAL CORRELATIONS BETWEEN HEAVY ION BEAM PROBE AND LANGMUIR PROBE ON THE T-10 TOKAMAK

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Geodesic Acoustic Modes (GAM), the high-frequency counterpart of zonal flows, can be a possible mechanism of the turbulence self-regulations. Theoretically, GAM presents a symmetric oscillation of plasma electric potential ($m = n = 0$), having also some minor density component ($m = 1, n = 0$).

GAMs have been studied with two main diagnostics: Langmuir probes and Heavy ion beam probing (HIBP), a unique method for direct measurement of the electric potential in the hot plasma core. Diagnostics were separated by a half of a torus of the T-10 tokamak (R= 1.5 m, a= 0.3 m, B < 2.5 T).

It was found that coherency between core plasma potential by HIBP (with probing ions Tl^+, accelerated up to 300 keV) and floating potential by Langmuir probes was up to 0.8 at the GAM frequency, that was unexpectedly high for such a large distance between observation zones: half of torus in toroidal and about π in poloidal direction. Such coherency only appears when Langmuir probe was located inside Last Closed Magnetic Surface, at about $\rho = 0.95$.

The value of the coherence coefficient decreases with increasing in radial distance between HIBP sample volume and Langmuir probes position. The cross-phase between plasma potential oscillation measured with HIBP in the core and floating potential measured with Langmuir probes at the edge at the GAM frequency was ~ - 1.5 – -2.2 rad. Its value increases with increasing in radial distance between points of observation of two diagnostics. We assume that phase shift caused by the radial distance, since m=n=0 for GAM, so the plasma potential perturbations propagate outward with decreasing radial velocity from ~ 7 km/s at $\rho = 0.6$ to ~ 2 km/s $\rho = 0.9$.

On top of GAM, there are also found the strong coherence and finite cross-phase for MHD tearing modes and the analysis will be presented in the paper.

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7-05

DETERMINING LOCAL INHOMOGENEITIES OF THE ROTATING PLASMA DENSITY VIA MICROWAVE REFRACTION

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In this paper we describe the method to determine the local inhomogeneities in the rotating plasma. The procedure is based on the spectrum/correlation analysis of plasma reflected signals with normal and oblique orientated microwave probing beam [1].

The method was tested and optimized using the mechanical model. The model is the alumina cylinder which mimics the microwave radiation reflecting surface of the rotating plasma. The cylinder was made in several versions. In the initial version of the mockup, the reflecting surface was grooved with characterized inhomogeneities of several millimeters. In the second version, three major grooves were cut out on the cylinder surface. In the latter design, the cylinder rotation axis was displaced from the center of the cylinder by 2 cm. For receiving or transmitting the microwave radiation, two identical pyramidal horn antennas were used, which were displaced in azimuth relative to each other by 60°±3°. The microwave radiation frequency was 36 GHz. The spectrum/correlation analysis of reflected signals allow to determine the rotational rate of the cylinder. Additionally, it is possible identify the presence of grooves on the cylinder surface, its radial displacement, their azimuthal arrangement, and the radial sizes of the grooves.

The experimental evaluation of the method was performed at the MAKET plasma device, which is capable to produce a high-power impulse reflex discharge in crossed E×B fields [2]. For the probe frequency of 37.1 GHz the electron plasma density attained $n_e \geq 6.5 \cdot 10^{13}$ cm^{-3}.

In the experiments, the reflected microwave signals were registered at both normal and oblique probing. The analysis of the reflected signals gives the possibility to determine the plasma density fluctuations, with the azimuthal mode m=3, and the angular rotational velocity of azimuthal density waves, which reaches to be $(2\text{-}4) \cdot 10^4$ rad/s.

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7-06

A DUAL HEAVY ION BEAM PROBE DIAGNOSTIC ON THE TJ-II STELLARATOR

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First High Ion Beam Probe (HIBP) diagnostic is being used on TJ-II stellarator from 2000-th. It has shown significant results on plasma profiles and oscillations. The second HIBP system have been recently installed on TJ-II. Dual HIBP system, consisting of two identical HIBPs located ¼ torus apart, provides measurement the long-range correlations of parameters in full plasma colum. Low noise high gain (10^7 V/A) preamplifiers with 1 MHz bandwidth sampling is used. It allows to study broadband turbulence and quasi-coherent modes like geodesic acoustic modes, alfven eigenmodes, suprathermal electron induced modes, etc. New capabilities a dual HIBP diagnostic in plasma potential and density investigations were demonstrated on TJ-II stellarator in measurements of the correlation between fluctuations in different poloidal and toroidal locations: on the same field line, on the same magnetic surface or on different magnetic surfaces at different points, disposed toroidally and/or poloidally.

7-07

DIAGNOSTICS OF OPTICAL CHARACTERISTICS OF GAS-DISCHARGE PLASMA IN A MIXTURE OF ZINC DIIODIDE VAPOR WITH HELIUM

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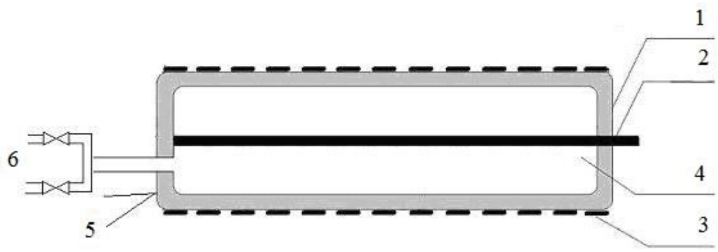
Gas- discharge atmospheric plasma in mixtures of zinc diiodide vapor with helium is a working medium of exciplex sources of coherent and spontaneous radiation in the visible spectral range of the spectral bands with a maximum intensity at wavelength (λ) 602 nm. Interest in the study and creation of exciplex sources of spontaneous radiation of visible spectral light source is that they are more effective than the existing ones.

The aim of studies was to make a diagnosics of spectral, energy and temporal characteristics of parameters of gas-discharge plasma in mixtures of zinc diiodide and helium, to identify regularities in these characteristics and to determine the partial pressures of the mixture components at which the maximum power of the radiation in the orange spectral range is reached

Plasma was created of a high-frequency (f = 130 kHz) atmospheric pressure barrier discharge on mixtures of of zinc diiodide vapor and helium in the device (Figure) with the construction similar to that used in studies [1]. In this device the inter-electrode distance (was 0.0029 m), the length of the electrodes (0.03 m) and working volume (was equal to 1 cm^3). Diagnostics of spectral, temporal and energy characteristics of the radiation of gas-discharge plasma was carried out on the experimental setup description of which is presented in our articles [1].



The construction of the gas -discharge radiation source: 1- quartz tube, 2- inner electrode, 3- external (mesh) electrode, 4- discharge zone, 5- thermocouple, 6-valves of the pumping system and gas inlet

It was established that the spectrum of the radiation source consists mainly of overlapping spectral emission bands with a maximum intensity at wavelengths (λ) 602 nm (with close intensities) of zinc monoiodide in the range 590-608 nm and zinc lines at 468.0, 472.2 481.0, 636.2 nm, the helium lines at 501.6, 587.6 and molecular iodide bands, the most intensive of which was the band $I_2(D' \rightarrow A')$ with maximum at $\lambda = 342$ nm. The pulses of the discharge current had amplitude 40 mA and a duration 0.6-0.8 ms at voltage amplitude 3 kV. Specific average power of the radiation from the working volume reached 30 mW/cm^3, efficiency relative to input power in the discharge ~8%. No more than 75 % of radiation power of the radiation source falls on the spectral band B→X of zinc monoiodide molecule (λ_{max} = 602 nm) with band width 15-16 nm.

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7-08

FEATURES OF MAGNETIC DIAGNOSTICS APPLICATION IN THE U-2M TORSATRON

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Magnetic measurements in stellarator-type magnetic traps allow one to determine a number of important plasma parameters, such as the longitudinal plasma current, the Pfirsch-Schlüter currents, the plasma energy content, the shift and deformation of magnetic surfaces, the magnetic island structure; the plasma MHD activity, etc [1, 2, 3].

At present, modernized magnetic sensor arrays have been developed and tested to carry out the research program on the U-2M torsatron. Diamagnetic loops and a Rogowski coil will be used to register variations of the toroidal and poloidal magnetic fluxes, respectively. To register variations of the zero, first and second harmonics of the poloidal magnetic flux, a set of 14 Mirnov coils will be used. The registration of toroidal magnetic flux variations and variations in zero harmonic of the poloidal magnetic field generated by the longitudinal plasma current makes it possible to determine the plasma energy content. The value of Pfirsch-Schlüter currents, the presence of magnetic islands, the shift of magnetic surfaces, the structure of MHD-fluctuations, corresponding to the first harmonic will be determined by registration of variations of the first and zero harmonics of the poloidal magnetic field. The registration of variations in the second poloidal magnetic field harmonic also enables one to determine the presence of magnetic islands, the deformation of magnetic surfaces, and the structure of MHD-fluctuations with second azimuthal harmonics. The magnetic sensors discussed above allow the registration of magnetic field variations in the frequency range from 10 Hz to 200 kHz.

The main difficulty in performing magnetic measurements in the U-2M torsatron is to take into account the contribution of the image currents arising in the metal environment under the action of plasma currents. Furthermore, the electronic equipment that registers useful signals from the magnetic sensors should have the necessary time resolution to provide discrimination, amplification and integration of the useful signals in conditions where the external magnetic field instability and the intense RF interference are observed during plasma experiments. Besides, as shown in previous experiments on the U-2M torsatron, it is necessary to provide improved thermal protection of the magnetic sensors, because the plasma creates inadmissible heat loads on the constructional elements of the facility, which are in contact with the last magnetic surface of the plasma confinement volume.

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3. V.K. Pashnev, E.L. Sorokovoy, A.A. Petrushenya, F.I. Ozherel'ev, D.I. Baron, Behavior dynamics of low-frequency MHD-fluctuations and main plasma parameters in U-3M torsatron in RF-heating mode // *Problems of Atomic Science and Technology. Ser. "Plasma Physics".* 2016, № 6, p. 33.

7-09

COMPARATIVE ANALYSIS OF THE REFRACTION OF MICROWAVES AT DIFFERENT FREQUENCIES IN AN INHOMOGENEOUS PLASMA OF A HIGH POWER IMPULSE REFLEX DISCHARGE

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The methods based on refraction of microwaves in an inhomogeneous plasma can be successfully used in plasma diagnostics. These methods are feasible only with inclined microwave probing. To have a full set of data, the angle of transmitting horn antenna has to be varied with respect to the plasma, what in practice is not always technically possible. For the case when there is no possibility to vary this angle, it was proposed to use the rays diverging from the transmitting horn antenna that are directed at oblique angle to the plasma [1]. The experimental results obtained in the previous paper [2] demonstrated that by the use of interferometry methods based on refraction, the evaluation of an average plasma density in the peripheral layers of plasma volume is possible.

The numerical and experimental studies on the refraction of microwaves at two frequencies 36 and 71 GHz in an inhomogeneous plasma of an impulse reflex discharge in longitudinal magnetic field were carried out. The critical densities N_{cr} for these frequencies are $1.6 \cdot 10^{13}$ cm^{-3} and $6.3 \cdot 10^{13}$ cm^{-3}, respectively. Inclined probing was realized on account of microwaves rays which fall to the plasma at oblique angle relatively to the plasma column. The calculations of trajectories of microwave rays at 37 and 71 GHz frequencies for different maximum values of plasma density were carried out. It was determined the cases when the microwave rays at these frequencies fall and do not fall to the receiving horn antenna shifted at the angle of 60 degrees with respect to the radiating antenna axis.

Plasma was probed by microwave (O-wave) simultaneously at both frequencies. The amplitude of microwave scattered signal were measured depending on the time after start of the discharge. At frequency 36 GHz the minimal amplitude of receiving signal was registered when plasma density in the layer achieved the value N_{cr}. In contrast, for the same conditions, the maximum signal amplitude was observed when probing frequency was 71 GHz. The experimental results are in satisfactory agreement with results of the numerical model.

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7-10

DEVELOPMENT AND CALIBRATION OF HIGH-FREQUENCY MAGNETIC PROBES

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The magnetic probes were designed to create 3D array of high-frequency magnetic field sensors (1 - 20 MHz). They are intended for high-frequency electromagnetic field measurements in torsatrons "Uragan-3M". "Uragan-2M" (IPP, KIPT, Kharkov), as well as in the linear experimental setup "IShTAR" (Max Planck Institute for Plasma Physics, Garching) [1-3].

The main purpose of such probe arrays is to measure high-frequency magnetic fields and basic wave parameters (wavelength, polarization, propagation speed).
Thus, it will be possible to conclude on the type of waves excited in the plasma edge. Also, it will possible to obtain information about the amplitude ratios of different wave harmonics in the special distribution of the phase velocity.

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7-11

FEATURES OF THE DYNAMICS OF SUPRATHERMAL ELECTRONS AFTER RF HEATING OFF AT THE URAGAN-3M TORSATRON

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In the case of the low plasma density operation we observe the high level of electron cyclotron emission at the frequencies that match the second and third harmonics of the extraordinary mode after RF heating pulse off [1].

The present work describes the recent experimental results of the suprathermal electrons dynamics after turning off the RF heat pulse at the Uragan-3M torsatron (n_e=2×10^{12} cm^{-3}, T_e=300 eV, P_{RF}=115 kW, B_0=0.69 T). In the absence of main suppressive techniques (resonant magnetic perturbations and massive gas injection) an attempt was made to describe the factors, which contribute to the generation of the suprathermal electrons for the Uragan plasma experimental conditions. The temporal evolution of the ECE emission intensity and it dependence on the working gas pressure in the torsatron vacuum chamber is presented. The ECE emission shows strong correlation with other diagnostics (plasma density, plasma current, HXR emission, plasma spectroscopy). The gradual increase of the pressure (after RF off) could be is one of the reasons that temporarily sustain the process of electron acceleration. The results of the ECE emission on the rate in magnetic field change (δB/δt) are also given.

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7-12

INFLUENCE OF INCREASED SLIDING SPEED ON THE STRUCTURE AND PROPERTIES OF PISTON RINGS WITH ION-PLASMA COATING

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The results of previous studies by the authors about determining the degree and nature of the wear of serial oil scraper piston rings of the D100 diesel engine have confirmed their low wear resistance. It should be noted that these rings by the adopted technology are made of gray cast iron without the use of reinforcing technologies to increase the wear resistance of their working surfaces.

To enhance their stability, they were hardened by a PVD multilayered TiN/CrN composition with a total thickness of 1.7 μm with components different proportion.

To assess the nature and rate of wear of such rings, comparative bench tests were carried out on a specialized machine in conditions of sliding friction during reciprocating motion. One sample of the cylinder liner and two samples of the piston ring of the each variant were fitted into the machine. The constant speed of friction for each variant was 1.3 m/s. The value of the specific pressure on the ring working surface is chosen 0.8 MPa. The total test time is 100 hours. The total length of the friction path was 468 km. Herewith, the level of weight wear, the change in microhardness, and the height of the working surfaces of the rings were measured.

According to the test results, it was revealed that the total wear rate of the cylinder liner, estimated by weight loss, and worked in tandem with the reinforced piston rings was 6 % lower relative to the cylinder liners that worked with the serial rings. The results of testing of the rings with PVD coating at a given speed show that the total wear rate is reduced by 12 times. The rate of wear of the surfaces in height shows that this figure for reinforced rings is 4 times lower. The initial average microhardness of the TiN/CrN coated rings is 120 times higher than the serial ones.

Micro-X-ray spectral analysis revealed that the proportion of the coating components (by the ratio of Ti and Cr) was 3 % after the tests, and the proportion of the ring base (C, O, Si, Mn, Fe) increased up to 95.67 %, which indicates about significant wear of the deposited coating at this friction speed. In this case, the proportion of Cr decreased after the test in 38 times, and the proportion of Ti in 18 times from the original coating composition

It revealed the structuring and degradation of the inclined surface adjacent to the working surface of the piston ring, on the value that close to the working surface height (0.45 – 0.5 mm). This is due to the localization of the stress-strain state due to the applied external load, which corresponds to the Saint-Venant principle.

7-13

SPATIAL ENERGY CHANNELLING IN PLASMAS WITH FAST IONS

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Destabilized shear Alfven modes and Fast Magnetoacoustic Modes (FMM) can transfer the energy and momentum from the region where particles (e.g., fast ions) drive the plasma instability to another region, where the destabilized waves are damped. This phenomenon named “spatial channeling” (SC) was predicted in [1,2]. A key element of the SC is that the energy and momentum of fast ions are transferred by the waves (eigenmodes), not by diffusion or heat conduction. It is clear that the channeling can be more efficient than diffusion or heat conduction provided that the wave group velocity across the magnetic field v_g is sufficiently large,

$$v_{\mathrm{g}} \gg \chi/L \ ,$$

where χ is the diffusivity, L is a characteristic length.

In a recent work [3] it was found that the energy flux due to FMM driven by fusion alpha particles is sufficiently large to be a possible explanation of the unexpected improvements of the plasma energy confinement and anomalous ion heating observed in deuterium-tritium experiments in JET [4]. On the other hand, fast-ion-driven instabilities are typically associated with Alfven eigenmodes. The Alfven waves (in contrast to the fast magnetoacoustic waves) are known to propagate along the magnetic field, so that their transverse group velocity in a homogeneous plasmas in a homogeneous magnetic field vanishes. The transverse group velocity of Alfven eigenmodes in realistic plasmas was not calculated yet. This is done in this work. The maximum energy flux transmitted by an eigenmode is shown to be proportional to the mode energy density and the group velocity of the waves constituting the eigenmode in the direction transversal to the magnetic flux surfaces. This group velocity is calculated for two types of Alfven eigenmodes - the Toroidicity-induced Alfven Eigenmodes (TAE) and the Global Alfven Eigenmodes (GAE) - and found to be considerable.

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