SOURCES OF X-RADIATION BASED ON STOCHASTIC ACCELERATION OF RARE PLASMA PARTICLES

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The results of theoretical and experimental study of stochastic plasma heating are presented. The high efficiency of such heating is shown. The possibility of using such plasma as a source of X-radiation is analyzed. Such sources are compared with the closest known sources.

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The sources of X-radiation (SXR), in main, are based on the processes of two types. The first one is the radiation of an ion (atom) under electron transition to a lower power level (from which an electron was previously deleted). The second one is the radiation of accelerated charged particles. The processes of the first type underlie the schemes of x-ray lasers (collisional and recombinational pumping) under investigation. The processes of the second type underlie the beam SXR, synchrotron SXR, X-ray FEL, based on electron channeling in crystal, etc. The important class of SXR are the plasma sources. Plasma with necessary parameters is created with the help of lasers, beams, bundles of wires which are blowing up, Z-pinch, etc. One of main problems, in development of plasma SXR (both coherent, and non-coherent), is the problem of fast energy transfer from an external pump source to plasma electrons i.e. the problem of fast, effective heating (acceleration) of plasma particles. This problem becomes especially obvious, in connection with the progress in development of laser technologies. Really, a main successful direction in these technologies is the creation of lasers, which generate pulses of extremely short duration. The duration of these pulses can compose only several periods of laser radiation. As a result the power of such a laser can be extremely high despite of rather low full energy of radiation. These are so-called 3T-lasers (table-top, terawatt laser). The effective heating of solid-state plasma with such short pulses is possible only by using the stochastic mechanisms of heating. Really, as is shown in [1] stochastic heating of solid-state plasma ($n \sim 10^{22}$ cm^{-3}) using the field of laser radiation with rather small amplitude (the parameter of a wave force $\varepsilon = [e \cdot E]/[m \cdot c \cdot \omega] \approx 0.1,\ \omega = 5 \cdot 10^{15}$) up to thermonuclear temperatures ($T \sim 7$ keV) can be carried out during $t \sim 10^{-13}$ sec. If the conditions for development of stochastic instability are not created, then the heating of solid-state plasma will occur due to collisions. The minimum heating time in this case is $\sim 10^{-9}$ sec. Thus, the mechanism of stochastic heating allows to heat plasma during much more short time than traditional methods of heating. It should be noted also, that the stochastic heating is the direct mechanism of heating. It means, that the energy of a regular electromagnetic wave (laser radiation) will be directly transformed to the energy of random movement of particles. Under this condition one can enter the effective frequency of impacts $\nu_{eff} \sim 1/T_C$, where $T_C \sim 1/\omega \cdot \ln K$ is a time of correlation decoupling of, $K -$ is the relation of a nonlinear resonance width to a distance between them. T_C is commensurable with the period of microwave field. This fact also determines a possibility of fast heating of plasma electrons under development of stochastic instability of plasma particle movement.

It should be noted that to the present time many features of stochastic instability and many features of random dynamics of particles are investigated. In [2-4] the criteria of stochastic instability onset of particle movement in a field of electromagnetic waves of any nature, for all known resonances of interaction between electromagnetic waves and charged particles were obtained. However, many problems of particle dynamics are not yet completely clarified. In particular, there are important questions about conditions under which particles can be infinitely accelerated and questions about conditions under which the particle energy is limited to a specific interval. The answers to some of these questions are contained in our papers (see proceedings of this Conference).

We have studied, theoretically and experimentally, stochastic heating of plasma electrons. The high efficiency of such heating is shown. The calculations have shown, that during 100 periods of external high-frequency field the kinetic energy of particles reaches values of 1.0 MeV, average energy is of the order of 0.3 MeV in a field of two, extending towards, own waves of a cylindrical waveguide with amplitudes of 24 kV/cm in a stationary magnetic field of 1kGs. The stochastic instability develops as a result of overlapping nonlinear cyclotron resonances. The experimental results correspond to the developed theory: under excitation of these waves by an external source with a power of 0.9 MW, under exceeding the threshold value of 0.45 MW, there was obtained X-radiation with an energy of quantum, that corresponds to maximum electron energy (order of 1 MeV) during about 800 periods of an external microwave field.

Let us describe in more details some theoretical and experimental results. Theoretically the stochastic heating of plasma electrons was studied both in the field of laser radiation, and under conditions of electron cyclotron resonance. Most essential is the fact that the resonance interaction of charged particles with the field of laser radiation occurs in the field of a virtual combinative wave. The amplitude of a such wave is proportional to the square of a wave force parameter. In the majority of cases this parameter is significantly less than unit.

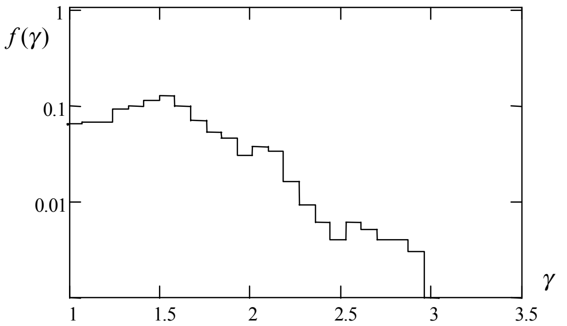

Fig. 1. Cumulative function of electron energy distribution in a field of two waves running towards one another.

Therefore the stochastic heating, which occur as a result of overlapping nonlinear resonances of combinative waves, is least effective. However, as we already mentioned above (see also paper [1]), the efficiency of stochastic heating by fields of laser radiation can be very high. The stochastic heating under conditions, when the cyclotron resonances are executed, is more preferable and more effective, because amplitudes of resonance waves, interacting with particles, are proportional to the first degree of a nonlinearity parameter. The theoretical study of the stochastic heating of plasma electrons under condition of cyclotron resonances was conducted with consideration of a field configuration which could be realized experimentally. Namely, the movement of charged particles in the H-wave field of a round waveguide of a radius A and in a constant magnetic field $\vec{H}_0$, directed along the axes of this waveguide, was considered. The analysis of particle movement in the field of one wave shows that it is difficult to reach overlapping of resonances under these conditions because the very high electromagnetic wave strengths are required. So, the analytical and numerical modeling for a wave $H_{1,1}$, $\omega/2\pi = 2.8$ GHz, in a waveguide with A=2 cm, and with an external magnetic field $H_0 = 1$ kGs shows, that the resonances are not overlapped down to $\varepsilon \approx 1$ ($E_0 \approx 300$ kV/cm). The situation qualitatively varies, when the particles are moving in a field of two waves, for example, in a field of a wave $H_{1,1}$ and wave $H_{1,2}$ which propagate towards one another. The analysis of conditions for development of the stochastic instability shows, that it develops already when the field strength is of the order of 24 kV/cm for the above-mentioned parameters. The cumulative function of electron energy distribution under these conditions is represented in Fig. 1. From this figure it is seen, that particles acquire a significant energy – the larger half of all particles have $\gamma > 1.5$. The time dependence of the average energy of particles $\langle\gamma\rangle$ and the variances $\sigma^2 = \left\langle\left(\gamma - \langle\gamma\rangle\right)^2\right\rangle$ show, that $\langle\gamma\rangle$ increases up to 1.6, and σ^2 up to 0.12 during $t = 200\pi$. The similar results are obtained when particles are moving in fields of a round resonator.

The results of experiments are represented in Fig. 2. A microwave power at the frequency of 2.7 GHz was entered into a resonator filled with plasma (density up to 10^9 cm^{-3}), in which simultaneously some types of self-excited waves were excited. When the wave power reaches the threshold value (>450 kW), the intense X-radiation was fixed. It reached the maximum value only with the H_0 value corresponding to the electron cyclotron resonance (ECR). The resonance line width of X-radiation intensity at a level of 0.5 is 10% of the resonance value of H_0. All measurements were executed for $H_0 = 0.97$ kGs. The time dependence of the incident wave power (1), reflected ave power (2) and the power absorbed in a resonator (length 60.8 cm) (3) is represented in Fig. 2. The time dependence of X-radiation intensity (4) has two maxima, which practically coincide with the maxima of the power absorbed in the resonator, 500-550 kW for 1 μs and 200 kW for 2 μs. The electron energy in the maximum of X-radiation intensity for 2 μs is about 100-150 keV, and for 1 μs it is in 8-10 times more. The maximum X-radiation intensity is reached during the time no more than 0.3 μs. This evidences on the high rate of energy transfer from excited waves to plasma electrons. The dependence of X-radiation intensity on the plasma density has a maximum. Under optimum conditions the microwave power necessary for stochastic heating decreases. It can be explained by the appearance of a plasma resonance or self-excited plasma waves, the presence of which facilitate transition to the stochasticity. The intensity of X-radiation decreases with plasma density increasing. Apparently it is connected with plasma shielding of the field.

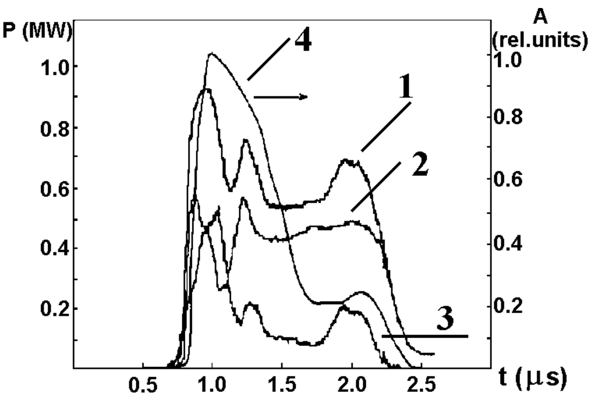

Fig. 2. Time dependence of the incident wave power (1), reflected wave power (2), power absorbed in a resonator (3) and the X-radiation intensity (4).

The above-described scheme of stochastic heating is much more effective than the scheme realized in traps with magnetic plugs. Really, to analyze quantitatively a comparison of these two schemes, we can introduce the effective frequency of impacts in a trap with magnetic plugs $\nu_{eff} \sim 1/T$, where T is the time of particle passing between plugs. This frequency is significantly less than that characterizing the stochastic heating (see above). The sources of X-radiation can be created on the base of stochastic heating of plasma. The source of such radiation, which is closest to our experimental setup is the system developed at the Russian Center of Science «Kurchatov Institute» and at the University of Peoples' Friendship. In the system, offered in [5], the authors consider the plasma which is formed as a result of the beam-plasma interaction in the system «Oratoriya»-10. In this case the electron temperature reaches ~ 100 keV. The further increase of the electron energy up to values of the order of 1 MeV is supposed to be attained using the adiabatic compression of plasma by the external magnetic field being increased from 1 kGs up to 10 kGs.

It is easy to see that the same temperatures can be reached much easily with the use of stochastic heating**.** Mention also, SXR GYRAC [6] in which for acceleration of plasma particles the regular mechanism of gyromagnetic autoresonance is used. This mechanism requires to change in time an external magnetic field for maintaining the resonance.

It should be born in mind that if the plasma is rather dense (solid-state), then for evaluation of the soft X-radiation intensity a model of an absolutely black body can be used. In this case the analysis of stochastically heated plasma radiation shows, that such a plasma can be SXR, which competes with the systems of synchrotron + ondulator type. The similar evaluations of the laser plasma are given in [7].

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REFERENCES

1. V.A.Buts, K.N.Stepanov // *JETPh Letters.* 1993, v. 58, p. 520.
2. V.A.Balakirev, V.A.Buts, A.P.Tolstoluzhskii, Yu.A.Turkin // *JETPh.* 1983, v. 84, p. 1279-1289.
3. V.A.Balakirev, V.A.Buts, A.P.Tolstoluzhskii, Yu.A.Turkin // *JETPh.* 1989, v. 95, p. 1231.
4. V.A.Buts, O.V.Manuilenko, K.N.Stepanov, A.P.Tolstoluzhskii // *Plasma Physics Reports.* 1994, v. 20, p. 794.
5. V.M.Atamanov, T.A.Biman, L.I.Elizarov et al. // *Problems of Atomic Science and Technology. Issue: Plasma Electronics and New Acceleration Methods* (2), 2000, v. 1, p. 46-49.
6. V.V.Andreev, A.M.Umnov // *Plasma Sources Sci. Technol.* 1999,v. 8, p. 479.
7. T.Letardi, F.Flora, C.E.Zheng, P.Di.Lazzaro, S.Bollanti // *J. of Technical Physics, J. Tech. Phys.* 2000, v. 41, # 1, Special Issue, p. 51-71.