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A CONCEPTUAL DESIGN OF A MeV-ENERGY ION MICROPROBE WITH AN IMMERSION PROBE-FORMING SYSTEM

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The authors propose a new design for a MeV-energy ion microprobe based on the immersion probe-forming system that employs the accelerating tube at an early stage of beam focusing. The final probing beam formation on the target is provided by a separated Russian quadruplet of magnetic quadrupole lenses. As follows from the calculations, the length of this setup along the beamline (from the ion source to the target) does not exceed 4 m, but the resolution may be higher than that of most operating facilities of conventional design.

1. INTRODUCTION

Most present-day ion microprobes of MeV-energies are based on accelerators originally intended for use in nuclear physics research, and hence, are rather bulky [1]. In spite of a growing interest in microprobe applications to diverse research and technology problems, microprobe facilities that are in operation world-wide are still not numerous. The primary reasons are that they have large size, high cost and high power consumption, and are not simple to operate. In this context, to design a compact microprobe of MeV energies would mean to decrease considerably the cost and power consumption, on the one hand, and to increase the resolution, on the other, thus making a breakthrough in microprobe applications.

At the Institute of Applied Physics (IAP), National Academy of Sciences of Ukraine, works have been started to develop small-size MeV-energy microprobes with immersion probe-forming systems. A principal distinction of the novel microprobe design from the traditional one is that the components of the probe-forming system are placed along the accelerator beam line, with the object and the angular collimators positioned in front of the accelerating tube. The use of HVEE precision accelerators and a dedicated ion injector with high brightness and ion mass separation which is under development at IAP [2-4], makes it possible to dispense with a magnetic analyzer at the accelerator exit, leading to a further reduction in size and cost of microprobe facilities.

This paper proposes a new design for a MeV-energy ion microprobe based on an immersion probe-forming system where the accelerating tube is used at a early stage of beam focusing. The final probing beam formation at the target is provided by a separated Russian quadruplet of magnetic quadrupole lenses.

2. BASIC PRINCIPLES AND DESCRIPTION OF THE IMMERSION PROBE FORMING SYSTEM

A section of the ion-optic axis where the beam is exposed to electromagnetic fields is less than 15% of the overall system length (from the ion source to the target) in some conventional facilities. Therefore a principal reduction in size in a new microprobe arrangement can be achieved by drastically shortening the drift spaces.

Another aspect of the new arrangement is the role of a magnetic analyzer. In conventional accelerator-based facilities a magnetic analyzer is placed behind the accelerator to stabilize the ion beam and separate the desired ion species. At the same time, the ion beam energy of several MeV leads to a larger magnet size and fairly high magnetic induction in the beam transport area, involving greater energy consumption. As was reported in [5], the use of an analyzing magnet for the beam energy stabilization in a SINGLETRON^{TM} accelerator of new type provides the energy spread $\Delta E/E \approx 10^{-5}$, while a Generating Voltmeter (GVM) gives $\Delta E/E \approx 10^{-4}$. Our earlier investigations [6] show that in magnetic quadrupole probe-forming systems permitting submicron beam spot size to be achieved for the energy spread $\Delta E/E \approx 10^{-4}$, the main contribution to the beam broadening is made by intrinsic 3rd-order aberrations and parasitic 2nd and 3rd-order aberrations that are due to parasitic sextupole and octupole components of the lens field. Therefore positioning a magnetic analyzer behind the ion source and using a Wien filter or some other compact mass analyzer, it is possible to reduce both the dimensions of the analyzer itself and power expended in separating the desired ion species. GVM installed in the stabilizing unit would allow a sufficient energy spread with which chromatic aberrations can be neglected.

The arrangement proposed for an ion microprobe of new type is shown in Fig.1. In this design use can be made of HVEE accelerators [5, 7]. Placed behind an ion source is a mass analyzer, an object- and an angular collimators. The beam collimation is performed ahead of the accelerating structure, permitting for a current I~100 pA a significant reduction in the radiation load on the accelerating tube. Moreover, there is no need for a conventional magnetic analyzer, which paves the way for advanced ion sources with low current and high brightness. Behind the accelerating tube there is a major focusing system based on magnetic quadrupole lenses with variable power supply, a scanning system and a target chamber.

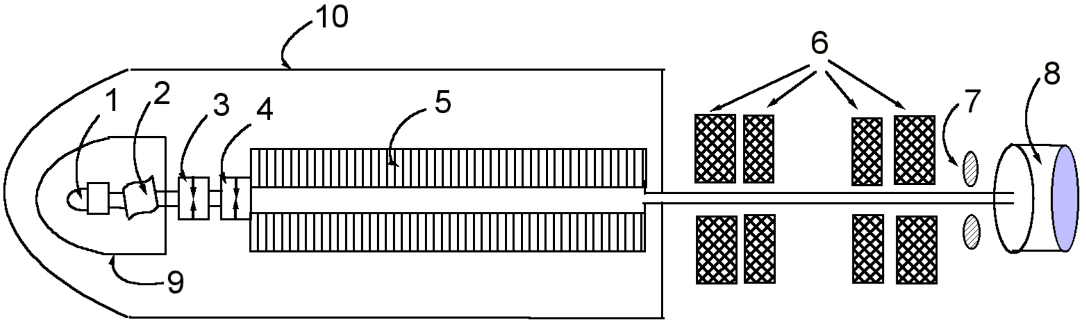

Fig.1. Schematic of a proposed novel microprobe

1 – ion source; 2 – mass analyzer; 3 – object collimator; 4 – angular collimator; 5 – accelerating tube; 6– separated "Russian quadruplet" of magnetic quadrupole lenses; 7 – scanning system; 8 – target chamber; 9 – high-voltage terminal; 10 – high-pressure vessel

3. CALCULATIONS FOR THE IMMERSION PROBE-FORMING SYSTEM

As is seen in Fig. 1, the accelerating tube is involved in the probe formation. Optimization calculations for the immersion probe-forming system were carried out including chromatic and 3 rd-order intrinsic spherical aberrations. Linear properties of the probe-forming were determined using a numerical PROBFORM code based on principles set forth in [8]. Aberrations were estimated by means of a matrix method (matrizant method) [9] underlying the MBTOOLS code [10]. The electrostatic potential distribution together with its first four derivatives on the accelerating tube axis was calculated with the help of a numerical LAPLACE-2 code [10]. Fig. 2 shows a beam envelope including aberrations and a calculated ion-optic configuration. A figure of merit for the immersion probe-forming system was found by the highest emittance technique with a numerical Max-BEmit code [11]. A comparison was made with operating facilities whose performance data were reported in [12, 13] (see Table 1).

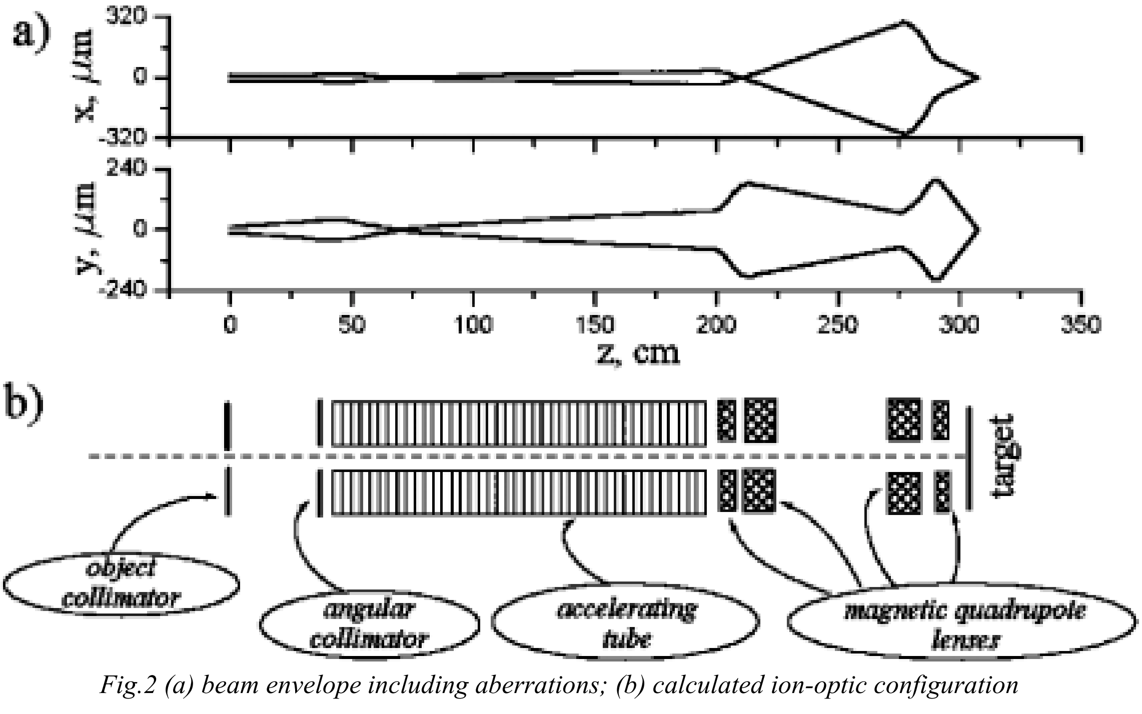

Fig.2 (a) beam envelope including aberrations; (b) calculated ion-optic configuration

Table 1. A Comparison Between Design Parameters of Selected Microprobe Facilities

	S1 system Immersion probe forming system	S2 system Russian quadruplet (short version) Cracow [12]	S3 system Triplet Oxford [13]	S4 system CSIRO-GEMOS quintuplet [13]
System length [cm]	308	230 (only PFS)	740 (only PFS)	470 (only PFS)
Pole field [T] B_1 B_2	 0.35282 0.13806	 0.30073 0.20843	 0.19715 0.22058	 0.05654 0.22058
Object distance, a [cm]	30	118	682.4	299.5
Demagnification D_x D_y	 -114.2 -114.2	 17.7 17.7	 92 -26	 -65 69
Chromatic aberrations [µm/mrad/%] C_{px}	173	-293(-295)	-343(-345)	1195 (1198)
C_{py}	43	-73 (-74)	873 (878)	-98 (-103)
Spherical aberrations [µm/mrad^3]				
$\langle x/\theta^3 \rangle$	-51	175 (166)	426 (360)	-2933 (-3320)
$\langle x/\theta\phi^2 \rangle$	-17	27 (39)	207 (496)	-226 (-478)
$\langle y/\phi^3 \rangle$	-2	6 (5)	-2197(-1855)	43 (38)
$\langle y/\theta^2\phi \rangle$	-17	27 (39)	-743 (-774)	212 (451)
Beam spot size 500 nm, E=2MeV				
Object collimator size [µm] $2{*}r_x$ $2{*}r_y$	 47.8 41.4	 5.4 6.0	 30.8 6.6	 21.8 23.6
Maximum normalized emittance $\hat{\varepsilon}$ [µm^{2}mrad^{2}MeV]	2.82	1.93	1.27	4.4

4. RESULTS AND DISCUSSION

The immersion PFS (S1 system) is compared with microprobe facilities already in operation in Cracow [12] (S2 system), Oxford [13] (S3 system), and Sydney [13] (S4 system) which are based on different version of quadrupole lens configurations: a high excitation triplet (Oxford), a separated Russian quadruplet (short version, Cracow), and a high-excitation quintuplet (CSIRO-GEMOS, Sydney). The calculations were performed for chromatic and 3 rd-order intrinsic aberrations using a MBTOOLS code. Our results presented in Table 1, in brackets, indicate that the differences in the highest aberration values are less than 15% as compared with published data for the above facilities tabulated in Table 1, columns 2, 3, and 4, not enclosed in brackets.

It is worth noting that the S1 system has demagnification coefficients well above those of the S2, S3, and S4 systems for smaller aberrations.

Of great importance is the choice of a criterion for comparison between different systems. In [11] the authors propose to use as a figure of merit the highest emittance, ε, of a beam that can be transformed by the given PFS into a spot of required size. The normalized emittance $\hat{\varepsilon} = \varepsilon \cdot E$ where E is the beam energy, for known normalized beam brightnesses, $\hat{b}$, determines the post-collimation beam current value

$$I = \hat{\varepsilon} \cdot \hat{b}\ .$$

Assuming that the normalized beam brightness and energy at the target (E=2 MeV) are similar for all systems in question and bearing in mind that for the S1 system the beam energy at the object collimator entrance was taken to be 0.02 MeV, we may declare the following. The beam current in the case of the beam transport to the target without any losses, for the S1 system would be a factor of 1.5 and 2 greater than that for the S2 - and the S3 system, respectively, but a factor of 1.5 less compared to the S4 system. The latter can be attributed to the fact that in the S4 system the working distance g=8.5 cm. This, however, does not permit a scanning system to be placed behind the lenses, which because of the lens aberrations limits the scanned area.

The S1, S2, and S3 systems have g=15 cm resulting in decreased emittance [10], but at the same time they have enough space to accommodate the scanning system.

5. CONCLUSIONS

A proposed new design of a small-size ion microprobe of MeV energies has the overall length of ~ 4 m, permitting a horizontal microprobe version of "desk" type or a vertical one of "tower" type to be created. The advantages of this design over conventional microprobes are small dimensions, low energy consumption, reduced vibrations, lower cost, and possibilities of using advanced ion sources. By reducing the number of ion-optics elements along the beam path from the ion source to the object collimator, it is possible to decrease the degradation of beam brightness.

The implementation of the above concept would require modifications in the accelerator design, e.g. a high-pressure vessel of shell type for easier accelerator maintenance, as well as a greater manufacture accuracy.

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REFERENCES

1. G.J.F. Legge // *Nucl. Instr. and Meth*. 1997, v.B130, №9.
2. С.А. Кузема, С.Н. Мордик // *ЖТФ*. 2001, т.71, вып.11, с.124.
3. S.N. Mordik, A.G. Ponomarev // *Nucl. Instr. and Meth*. 2002, v. A480, №359.
4. V.I. Miroshnichenko, S.N. Mordik, V.V. Olshansky et al. // *Nucl. Instr. and Meth*. 2003, v. B201.
5. D.J.W. Mous, R.G. Haitsma, T. Butz et al. // *Nucl. Instr. and Meth*. 1997, v. B130, №31.
6. V.A. Brazhnik, V.I. Miroshnichenko, A.G. Ponomarev, V.E. Storizhko // *Nucl. Instr. and Meth.* 2001, v. B174, №385.
7. K. Jimbo, Y. Katoh, A. Kohyama // *Nucl. Instr. and Meth.* 2002, v. A448, №466.
8. V.A. Brazhnik, S.A. Lebed, V.I.Miroshnichenko et al. // *Nucl. Instr. and Meth*. 2000, v. B171, №558.
9. A. Dymnikov, R. Hellborg // *Nucl. Instr. and Meth*. 1993, v. A330, №323.
10. A.G. Ponomarev, K.I. Melnik, V.I. Miroshnichenko et al. // *Nucl. Instr. and Meth*. 2003, v. B201, №637.
11. A.G. Ponomarev, V.I. Miroshnichenko, V.E. Storizhko. Optimum Collimator Shape and Maximum Emittance for Submicron Focusing of Ion Beams. Determination of the Probe-Forming System Resolution Limit // *Press in Nucl. Instr. and Meth.* A.
12. V. Brazhnik, S. Lebed, W. Kwiatek et al. // *Nucl. Instr. and Meth*. 1997, v. B130, №104.
13. C.G. Ryan, D.N. Jamieson // *Nucl. Instr. and Meth.* 1999, v. B158, №97.