FORMATION OF MeV ENERGY ION BEAMS WITH HIGH CURRENT DENSITY FOR MATERIALS MICRO-IRRADIATION

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A numerical analysis has been performed for the optimum configuration of a probe-forming system based on magnetic quadrupole lens multiplets in a nuclear scanning microprobe intended for irradiations of micron-size areas. The current densities expressed via the reduced collimated acceptance were calculated as function of the spot dimensions for working distances ranging from 4 to 24 cm. Consideration is being given to the advantages of the doublet of magnetic quadrupole lenses as a probe-forming system.

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INTRODUCTION

Ion microprobes for MeV-energies find wide application not only in the investigations into material properties, but also in ion-beam material modification. The use of focused proton beams in ion-beam lithography makes it possible to create 3D micro- and nanostructures [1, 2, 3]. Micro-irradiations with ions can be helpful in making masks [3], studying modified optical properties of quartz glasses [4, 5], and examining the effects of ionizing radiation on a material [6]. The problem of current concern is the application of micro-irradiations to the determination of the radiation resistance of materials. Microprobe techniques combined with a possibility of high ion dose irradiation permit experiments to be performed in-situ. As a result, the impurity migration at the grain boundaries can be determined in the course of irradiation. A deterring factor here is that it is not reasonable to build up high radiation doses by means of simple collimated microbeams since in this case the current density at the target is rather small (10^{-2} A/m^2) [7]. To increase it to desired values, in ion microprobes use is made of active focusing elements based on multiplets of magnetic quadrupole lenses (MQL) permitting an ion beam to be focused into a spot of micron size with the current density at the target of about 10^2 A/m^2. However, it is to be noted that in doing so one is faced with a problem of keeping the spot size unchanged as the beam energy is varied [8]. As was shown in Ref. [9], with the increasing probe spot size in a submicron interval the current density increases. This property is typical of probe-forming systems (PFS) with a number of lenses from 3 to 6. Yet, so far this dependence has not been thoroughly investigated, so the aim of the present paper is to consider different PFS versions used to obtain the maximum current density.

1. METHODS OF ANALYSIS OF ION-OPTIC PROPERTIES

A system of steady trajectory motion equations describing the evolution of the phase set of beam particles in the active elements under the influence of electric and magnetic fields can be written in the general vector form as follows

$$\frac{d\boldsymbol{\psi}}{ds} = \mathbf{F}(p_0, q, \mathbf{B}, \mathbf{E}, \boldsymbol{\psi}, \delta),\ \psi(s_0) = \psi_0, \tag{1}$$

where $\psi(s)=(x(s), y(s), x'(s), y'(s), \delta(s))^{\mathrm{T}}$ are the steady phase coordinates of the beam particles, $p_0=p_0(s)$ and q are the average momentum and charge of a beam particle, respectively, $\mathbf{B}=\mathbf{B}(x,y,s)$ and $\mathbf{E}=\mathbf{E}(x,y,s)$ are the vector distributions of the magnetic and electric field, respectively, in the beam transport region, and $\delta = \delta(s) = (p-p_0)/p_0$ is the relative momentum deviation of each particle, $p=p(s)$, from its average value, p_0.

In the general case, Eqs. (1) are nonlinear fundamental equations in the optics of charged particle beams. Methods of solving these equations are presented in many papers, the best known being the method of matrizants [10 - 12] based on the representation of an infinite-dimensional space of phase momenta, in which a system of nonlinear differential equations (1) in a five-dimensional steady phase space can be approximated by a system of linear differential equations. The space of phase momenta is determined by a set of linear-independent power functions $\mathrm{x}^i(s)\mathrm{y}^j(s)\mathrm{x}'^k(s)y'^l(s)\delta^m(s)$.

A solution for the nonlinear differential problem (1) is sought for as a nonlinear dependence of the ion coordinates in the target plane (z_t) on initial phase coordinates in the object collimator plane (z_0)

$$\begin{aligned} x(z_t) &= F_x(z_t) = \sum_{j=1}^{14} A_{xj}(z_t, \boldsymbol{\tau}) \cdot Q_{xj}, \\ y(z_t) &= F_x(z_t) = \sum_{j=1}^{14} A_{yj}(z_t, \boldsymbol{\tau}) \cdot Q_{yj}, \end{aligned} \tag{2}$$

where

$$\{Q_{xj}\}|_{j=1\ldots14} = \{x_0, x'_0, x_0\delta, x'_0\delta, x_0^3, x_0^2 x'_0, x_0 x_0'^2, x_0'^3, x_0 y_0^2, x_0 y_0 y'_0, x_0 y_0'^2, x'_0 y_0^2, x'_0 y_0 y'_0, x'_0 y_0'^2\},$$

$$\{Q_{yj}\}|_{j=1\ldots14} = \{y_0, y'_0, y_0\delta, y'_0\delta, y_0^3, y_0^2 y'_0, y_0 y_0'^2, y_0'^3, y_0 x_0^2, y_0 x_0 x'_0, y_0 x_0'^2, y'_0 x_0^2, y'_0 x_0 x'_0, y'_0 x_0'^2\},$$

$A_{x1} = D_x, A_{y1} = D_y$ are the PFS demagnification coefficients,

$A_{x2} = f_x, A_{y2} = f_y$ are the astigmatism coefficients,

$A_{xj}, A_{yj}, j = 2, 3$ are the chromatic aberration coefficients,

$A_{xj}, A_{yj},\ j = 4,\ldots,14$ are the third-order geometric aberration coefficients,

$\boldsymbol{\tau} = \{G_1,\ldots,G_N, a_1,\ldots,a_N, g\}$ is the vector of parameters which influence the beam formation in the quadrupole PFS, G_i and a_i are the magnetic field gradient and the geometric position of the i th magnetic quadrupole lens in the PFS, respectively, g is the PFS working distance.

The PFS quality criterion follows from actual experimental requirements. The number of interactions between the beam particles and the target atoms is directly related to the number of particles reaching the target spot per unit time. Thus, a physically sensible criterion of the PFS quality is the value of current I at the target spot of given dimensions [13]. However, in calculations use is mostly made of the acceptance density rather than of the current density.

Since the current $I \approx b\varepsilon T$, where b, ε, T are the normalized brightness, emittance, and energy of the beam particles, respectively, and the maximum emittance provided by the PFS is, by definition, the PFS acceptance, $\varepsilon_{\max} = \mathcal{A}$, then, considering that the particle energy is always known a priori, and brightness is a characteristic of the ion source and the accelerating structure, which remains constant while the beam is being focused, we can express the maximum current density at the spot of square shape with a side d via a reduced collimated PFS acceptance as

$$\max(J) = \mathcal{A} \cdot b/d^2.$$

Here the reduced collimated PFS acceptance is determined by the maximum phase space produced by the object and angular collimators, which, using the PFS, is transformed in the target plane into a phase space shaped as a square with a side d.

The method of calculating the acceptance with the beam focussed into a spot of prescribed size is implemented in the MaxBEmit numerical code [13]. The method is formulated for a PFS whose ion-optic parameters are known. The probe spot size d is also prescribed.

2. PFS PARAMETERS

The present work has been performed with PFS's based on doublet-, triplet-, and distributed "Russian quadruplet" MQL's (lenses are arranged in doublets which are spaced 80 cm apart along the axis of the system) with parameters used in the real nuclear scanning microprobe of the IAP NAS Ukraine [14]. It is assumed that the angular collimator plane is positioned at the entrance to the first MQL ($a_0 = a_1$, Fig. 1).

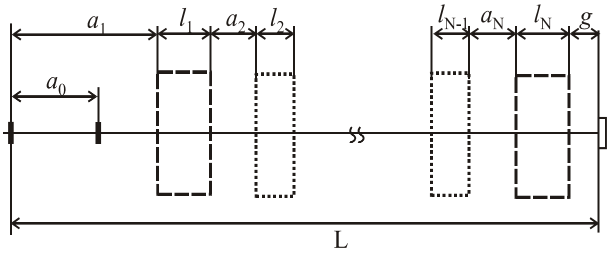

Fig. 1. A schematic representation of the PFS with MQL multiplets. a_0 – collimator separation; a_1-a_N – drift gaps; l_1-l_N – effective lens lengths; g – working distance; L *– total system length*

All PFS's have the following fixed parameters: total length $L = 4$ m, effective lens lengths $l_1 = 7.141$ cm and $l_2 = 5.067$ cm, lens separation a=3.94 cm, and lens aperture radius $R = 0.65$ cm. The working distance, g was varied from 4 to 24 cm by varying the object distance, a_0, (separation between the collimators). The calculations were performed for a 1 MeV proton beam with the maximum energy spread $\delta_{\max}=10^{-3}$. The PFS ion-optic properties such as the demagnification coefficients (Table), aberrations, and magnetic inductions at the lens poles were obtained with the help of a ProbeForm numerical code [9].

PFS Demagnification Coefficients

g, cm	Doublet		Oxford-type triplet		Distributed "Russian quadruplet"	
	D_x	D_y	D_x	D_y	D_x	D_y
4	-10	-98	139	-25	178	178
8	-9	-62	81	-21	100	100
12	-8	-44	54	-17	63	63
16	-7	-33	-40	-14	44	44
20	-6	-27	31	-13	32	32
24	-6	-22	25	-11	24	24

3. RESULTS

Calculations done for a PFS based on MQL multiplets are shown in Fig. 2 as the reduced collimated acceptance plotted vs the spot size for varied working distances. As can be seen in Figs. 2,b and c, the density of the reduced acceptance for the triplet-based and the distributed "Russian quadruplet"-based PFS, has pronounced peaks whose magnitude depends on the working distance. For the doublet-based PFS (see Fig. 2,a) the maxima of the reduced acceptance density were not found since starting from the spot size of 130 µm, 1 MeV proton beam envelopes extend beyond the beam line dimensions which are closely related to the MQL aperture size at their location (Fig. 3,a). Beam envelopes for the other two PFS's presented in Figs. 3,b and c, demonstrate that the beam line dimensions are not a critical factor, limiting their maximum reduced acceptance density.

It is also evident in Fig. 2 that the use of the PFS based on the distributed "Russian quadruplet" for irradiation purposes does not seem reasonable from the viewpoint of the desired rate of dose accumulation since the highest current density in this PFS is only half as large as that of the triplet-based PFS and about one-third that of the doublet-based PFS. A general tendency to be observed for all PFS versions examined is that with a small spot size the most advantageous is a system with a small working distance. If a PFS is examined only in terms of the maximum current density, ignoring the spot size, one would see that the best parameters for the doublet-based and the triplet-based PFS are achievable with the working distances in the range from 8 to 12 cm. It is, however, not possible to obtain such parameters for the distributed "Russian quadruplet" because its reduced acceptance density increases steadily with the working distance. The doublet-based PFS characterized by greater acceptances as compared with other compact multiplets [15] have turned out to be more suitable for micro-irradiation purposes.

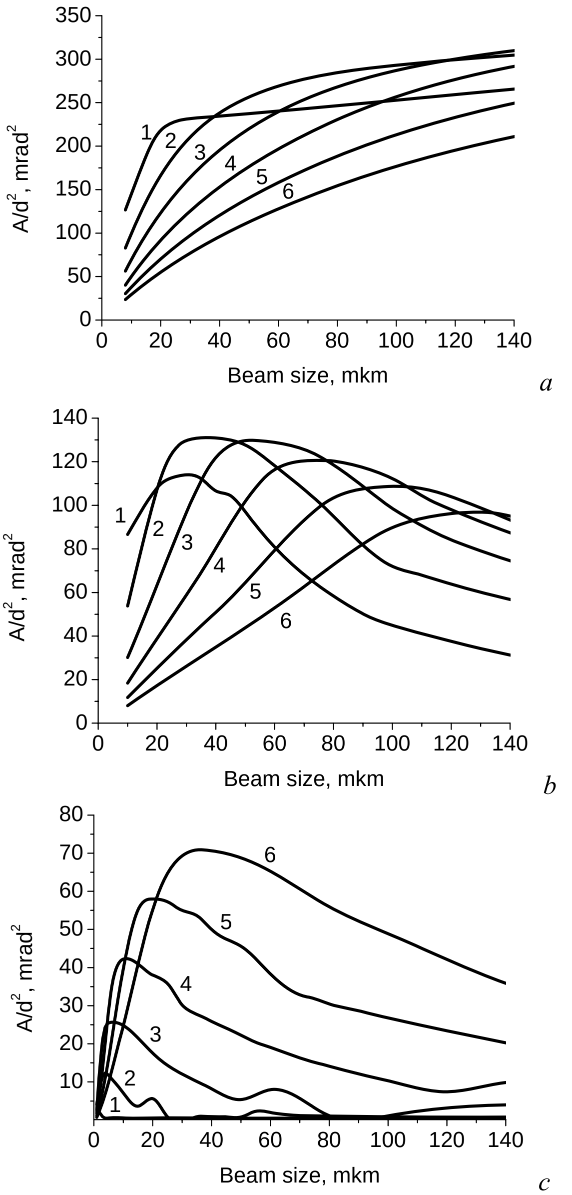

Fig. 2. The reduced acceptance density versus the spot size for various working distances in the PFS based on the a) MQL doublet; b) MQL triplet; c) distributed “Russian quadruplet”. The working distances are denoted by numbers: 1 – 4 cm; 2 – 8 cm; 3 – 12 cm; 4 – 16 cm: 5 – 20 cm; 6 – 24 cm

CONCLUSIONS

PFS versions based on MQL multiplets have been analyzed in terms of the highest attainable current density at the target expressed via the reduced collimated acceptance. A PFS type has been identified which is most advantageous for micro-irradiation applications. The current densities were calculated as function of the working distance and spot size. The highest current density for MQL doublet-based PFS is shown to be limited by the beam line dimensions. The results obtained will be used in further investigations with the nuclear scanning microprobe at the Institute of Applied Physics, National Academy of Sciences of Ukraine.

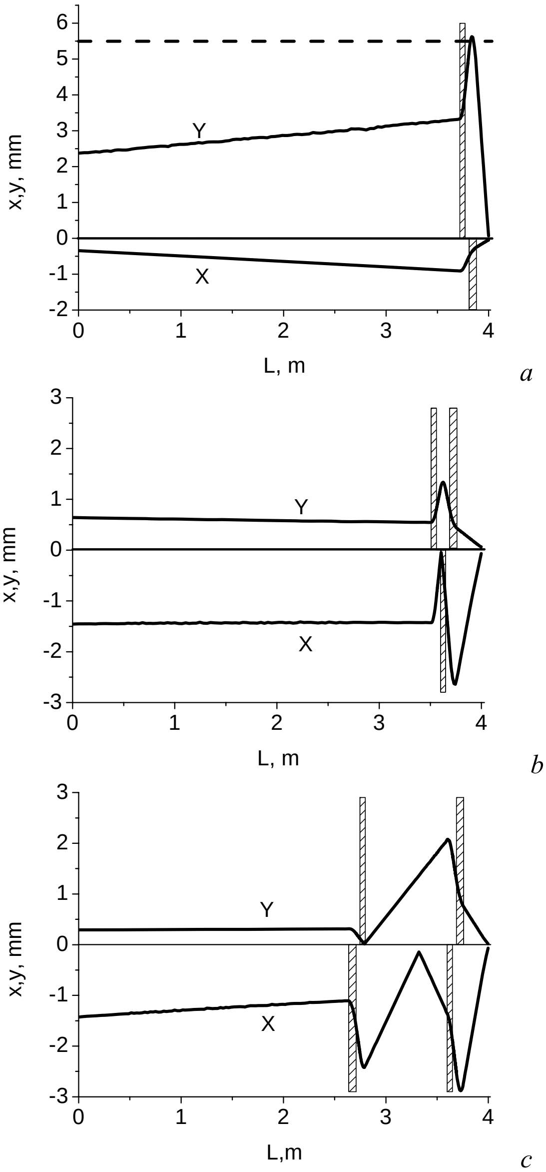

Fig. 3. Proton beam envelopes for the PFS based on the a) MQL doublet with a working distance g=12 cm and a spot side d=130 µm; b) MQL triplet with g=24 cm and d=140 µm; c) distributed “Russian quadruplet” with g=24 cm and d=140 µm. Shown diagrammatically are MQL’s with dimensions given to scale and with a sign of the effective lens field polarity. A dashed line represents the beam line boundary

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ФОРМИРОВАНИЕ ИОННЫХ ПУЧКОВ МэВ-НЫХ ЭНЕРГИЙ С ВЫСОКОЙ ПЛОТНОСТЬЮ ТОКА ДЛЯ МИКРООБЛУЧЕНИЯ МАТЕРИАЛОВ

А.В. Романенко, А.Г. Пономарев, В.И. Мирошниченко

Проведен теоретический численный анализ оптимальной конфигурации зондоформирующей системы на базе мультиплетов магнитных квадрупольных линз в ядерном сканирующем микрозонде для задач облучения микроскопических областей материалов. Найдены зависимости плотности тока, выраженные через приведенный коллимированный аксептанс, от размеров пятна на мишени для рабочих расстояний в диапазоне 4…24 см. Показано преимущество использования в качестве зондоформирующей системы дублета магнитных квадрупольных линз.

ФОРМУВАННЯ ЙОННИХ ПУЧКІВ МеВ-НИХ ЕНЕРГІЙ З ВИСОКОЮ ГУСТИНОЮ СТРУМУ ДЛЯ МІКРООПРОМІНЕННЯ МАТЕРІАЛІВ

О.В. Романенко, О.Г. Пономарьов, В.І. Мирошніченко

Проведено теоретичний чисельний аналіз оптимальної конфігурації зондоформуючої системи на базі мультиплетів магнітних квадрупольних лінз у ядерному скануючому мікрозонді для задач опромінення мікроскопічних областей матеріалів. Знайдено залежності густини струму, виражені через приведений колімований аксептанс, від розмірів плями на мішені для робочих відстаней у діапазоні 4…24 см. Показано перевагу використання в якості зондоформуючої системи дублету магнітних квадрупольних лінз.