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SPATIAL RESOLUTION IMPROVEMENT OF THE NUCLEAR SCANNING MICROPROBE CHANNEL OF THE ANALYTICAL ACCELERATOR COMPLEX OF THE API NAS OF UKRAINE

A.G. Ponomarev, V.I. Voznyi, I.H. Ihnatiev, S.V. Kolinko, D.V. Magilin, V.A. Rebrov
Institute of Applied Physics National Academy of Sciences of Ukraine, Sumy, Ukraine
E-mail: ponom56@gmail.com

The probe-forming system of a nuclear scanning microprobe based on a quadruplet of magnetic quadrupole lenses with three independent power supplies has been studied. In the stigmatic focusing mode, the third power supply is a free parameter affecting the ion-optical properties of the microprobe. The optimal system was selected as a result of solving an optimization problem in which the figure of merit was the reduced collimated acceptance. The numerical simulation of the beam focusing process in that one-parametric system, taking into account the experimentally measured distribution of protons in the trajectory phase space, showed that the dimensions of the beam spot on the target can be reduced several times compared to the working system. At the same time, the current density in the focused spot increases by about one order.

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INTRODUCTION

The channel of the nuclear scanning microprobe of the analytical accelerator complex of the Institute of Applied Physics of the National Academy of Sciences of Ukraine was put into operation in 2008. The performance of the microprobe was published in [1, 2]. The basic probe-forming system was selected taking into account the parameters of the Sokol electrostatic accelerator and is a separated orthomorphic quadruplet of magnetic quadrupole lenses. In this system the lenses are excited by two power supplies according to the scheme *C*1*D*2*C*2*D*1, where *C* means that the quadrupole is convergent in the *xOz* plane, *D* means that a lens is divergent in the *xOz* plane due to inverse connection to the power supply, and the number indicates the power supply to which the lens is connected to. Theoretically, such a system has been studied before and published in [3, 4]. In order to reduce positioning aberrations, a new type of integrated doublets of magnetic quadrupole lenses were used here [5]. The basic probe-forming system has low demagnifications $D_x \times D_y$=23×23, which is due to the relatively short length of the system ≈4 m and a large working distance of 24 cm (the distance from the effective field boundary of the last lens to the target), since the scanning system is located behind the last lens. For such a system, a spatial resolution of about 3 μm was obtained at a proton beam current of *I*~100 pA with an energy of 1.5 MeV. To improve the spatial resolution, theoretical and experimental studies were carried out on a probe-forming system based on a two-parametric separated quadruplet with individual lens power supplies [6, 7]. Here, the lenses of the first doublet are excited by two independent power supplies, the value of which is determined as a result of numerical simulation based on the solution of the optimization problem, and the excitation of the lenses of the last doublet is determined from the condition of stigmatic focusing. The demagnifications for the optimal two-parametric quadruplet are $D_x \times D_y$=52×96. For such a system, a spatial resolution of about 1.5 μm at a proton beam current *I*≈100 pA and 0.6 μm for *I*~1 pA has been experimentally obtained. During the operation of such a probe-forming system, its drawbacks have been identified, related to the difficulties of adjusting the system, which takes a long time, and the high excitations of the first two lenses. In this work, we consider a probe-forming system based on a one-parametric separated quadruplet of magnetic quadrupole lenses, which significantly simplifies the adjustment process and is comparable in its focusing properties to a two-parametric system.

1. ONE-PARAMETRIC QUADRUPLET OF MAGNETIC QUADRUPOLE LENSES

The layout of a probe-forming system based on a one-parametric quadruplet of magnetic quadrupole lenses is shown in Fig. 1.

The geometric dimensions of the quadruplet for the simulation have the following values: length of the probe-forming system *l*=385 cm; lengths of the lens effective field L_1=L_4=7.141 cm, L_2=L_3=5.067 cm; object distance a_1=a_0=250.4 cm; drift gaps a_2=a_4=3.94 cm, a_3=78.75 cm; working distance *g*=23.554 cm. Excitation layout for quadrupoles Q_2, Q_3, and Q_4 *C*1*D*1*C*2, the first quadrupole lens Q_1 is excited by a third independent power supply and can be either convergent or divergent. The value of the third power supply is a free parameter, on which the ion-optical properties of the probe-forming system depend. This value was varied to ensure a magnetic field at the poles of the quadrupoles in the range of -0.3...0.3 T. As a result, of the numerical simulation, two ranges of magnetic field values of the first lens were obtained at which stigmatic focusing is ensured. Fig. 2 shows the demagnifications as a function of the field values of the first quadrupole.

As can be seen in Fig. 2, the *C*3*C*1*D*1*C*2 quadruplet has two times higher demagnifications then the *D*3*C*1*D*1*C*2 quadruplet at significantly lower magnetic field values at the poles of the first lens (Q_1).

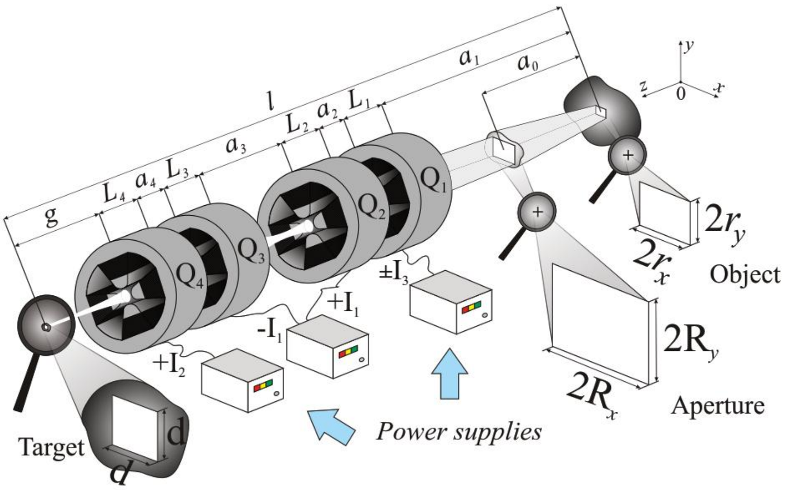

Fig. 1. Layout of a one-parametric quadruplet of magnetic quadrupole lenses

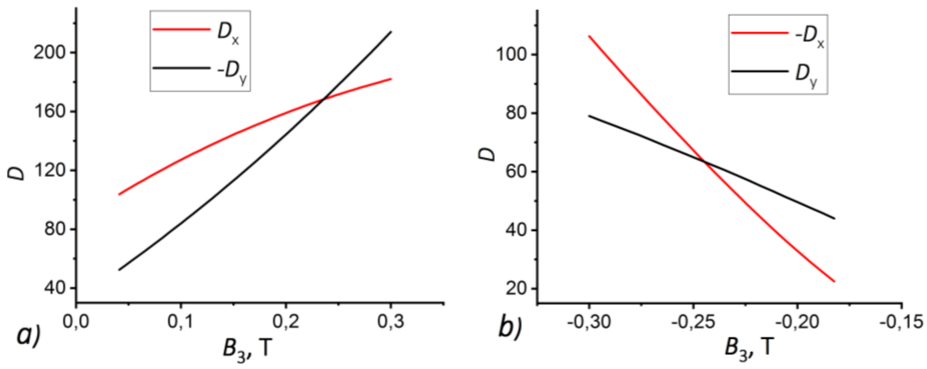

Fig. 2. Dependence of the demagnifications on the magnetic field at the poles of the first quadrupole: a – excitation layout of the quadruplet C3C1D1C2; b – excitation layout of the quadruplet D3C1D1C2

2. CHOICE OF AN OPTIMAL PROBE-FORMING SYSTEM BASED ON A ONE-PARAMETRIC QUADRUPLET

The transformation of the coordinates of the charged particles from the plane of the object collimator to the target plane is defined as

$$\begin{aligned} x_t &= x_0 / D_x + \langle x/x' \rangle x_0' + C_{px} x_0' \delta_0 + \\ &+ \langle x/x'y'^2 \rangle x_0' y_0'^2 + \langle x/x'^3 \rangle x_0'^3, \\ y_t &= y_0 / D_y + \langle y/y' \rangle y_0' + C_{py} y_0' \delta_0 + \\ &+ \langle y/y'x'^2 \rangle y_0' x_0'^2 + \langle y/y'^3 \rangle y_0'^3, \end{aligned} \quad (1)$$

where the indices $()_0$ and $()_t$ indicate that the trajectory phase coordinates (x,x',y,y') belong to the plane of the object collimator and the target, respectively; the terms $\langle x/x' \rangle$, $\langle y/y' \rangle$ are responsible for the stigmatic condition of the probe-forming system; D_x, D_y are demagnifications; C_{px}, C_{py} are chromatic aberrations, $\langle x/x'y'^2 \rangle, \langle x/x'^3 \rangle, \langle y/y'x'^2 \rangle, \langle y/y'^3 \rangle$ are spherical aberrations.

From (1) it is clear that demagnifications play a positive role in improving spatial resolution, while aberrations lead to its degradation. The peculiarity of probe-forming systems is that as the demagnifications increase, the aberrations increase significantly. To determine the influence of demagnifications and aberrations on the probe forming process, the concept of reduced collimated acceptance is introduced. Such acceptance is defined as the maximum phase volume of the beam formed by the object and aperture collimators that can be focused by a given probe-forming system into a spot on a target of given dimensions $d \times d$ (see Fig. 1) in the form

$$\alpha = 16 r_x r_y R_x R_y / a_0^2, \quad (2)$$

where $2r_x$, $2r_y$ are dimensions of a rectangular object collimator, $2R_x$, $2R_y$ are dimensions of a rectangular aperture collimator; a_0 is the object distance (see Fig. 1).

The required probe size for a given focusing system can be obtained by combining different dimensions of object and aperture collimators. Therefore, if the dimension of the object collimator is reduced due to an increase in the aperture collimator and the influence of spherical aberrations, the size of the probe remains unchanged. A smaller object collimator reduces the size of the focused beam, but at the same time, the aperture collimator provides a wider divergence angle of the beam particles, and this, which in turn, increases the effect of spherical aberrations on probe expansion. Based on this, for each focusing system there is an optimal ratio between the dimensions of the object and aperture collimators, which provides the maximum beam current for a given probe size. The dimensions of the collimators and thus the acceptance of the microprobe depend on the ion-optical properties of its focusing system, which are determined by the geometry of the system and the parameters of the lens system. The optimization problem, where the function of merit is the reduced collimation acceptance of the focusing system with rectangular object and aperture collimators, is represented as a nonlinear programming problem and can be formalized as [9]

$$\alpha^*(d) = \max_{r_x, r_y, R_x, R_y, a, \mathbf{S}} (\alpha(d)), \quad (3)$$

$$<x/x'> = h_x(B_1, B_2, \mathbf{S}) = 0,$$
$$<y/y'> = h_y(B_1, B_2, \mathbf{S}) = 0, \quad (3a)$$

$$B_1 \le B_{1\max},\ B_2 \le B_{2\max}, \quad (3b)$$

$$|F_x(x_0, y_0, x_0', y_0', \delta_0)| \le d/2,$$
$$|F_y(x_0, y_0, x_0', y_0', \delta_0)| \le d/2,$$
$$|x_0| \le r_x, \quad |y_0| \le r_y,$$
$$-(R_x + x_0)/a \le x_0' \le (R_x - x_0)/a, \quad (3c)$$
$$-(R_y + y_0)/a \le y_0' \le (R_y - y_0)/a,$$
$$|\delta_0| \le \delta_{max}/2,$$

where

$$F_x(x_0, y_0, x_0', y_0', \delta_0) = x_0 / D_x + C_{px} x_0' \delta_0 +$$
$$+ <x/x'y'^2> x_0' y_0'^2 + <x/x'^3> x_0'^3,$$
$$F_y(x_0, y_0, x_0', y_0', \delta_0) = y_0 / D_y + C_{py} y_0' \delta_0 + \quad (3d)$$
$$+ <y/y'x'^2> y_0' x_0'^2 + <y/y'^3> y_0'^3,$$

S = {a_i, L_i, g, B_i} are parameters of the probe-forming system (see Fig. 1); B_i is the magnetic field at the poles of the quadrupole lenses; d is the spot size of the focused beam on the target; $\delta_{\max}$ is the maximum of the momentum spread of charged particles in the beam; $B_{1\max}$, $B_{2\max}$ are the maximum permissible magnetic field at the poles of the quadrupole lenses.

Condition (3) determines the value of the maximum reduced collimation acceptance achieved at certain optimal values of the collimator dimensions, the distance between them and the parameters **S**. Condition (3a) determines that the focusing system is stigmatic. The stigmatic state makes it possible to determine the values of the magnetic field at the poles of the lenses connected to two independent power supplies. Condition (3b) defines the limits of the magnetic field values. Condition (3c) imposes restrictions on the trajectory phase coordinates of charged particles in the phase volume formed by the object and aperture collimators. Equations (3d) take into account only chromatic and spherical aberrations, but they can be extended to include other geometric aberrations. Thus, in the optimization problem (3), the parameters of the probe-forming system and the dimensions of the collimators determine the optimal conditions for beam formation in the microprobe. To solve (3), a special algorithm has been developed, described in [10, 11] and implemented in the numerical codes ProbForm and MaxBEmit.

Solving the optimization problem (3) for a one-parametric quadruplet gave the results shown in Fig. 3, which shows the dependence of the reduced collimated acceptance on the value of the magnetic field at the poles of the first quadrupole. As can be seen from this figure, the highest acceptance is achieved for the quadruplet excitation according to the *C*3*C*1*D*1*C*2 layout, and the value of the magnetic field of the first lens is not high, which has a positive effect on the influence of positioning aberrations. The parameters of this probe-forming system are shown in Tab.

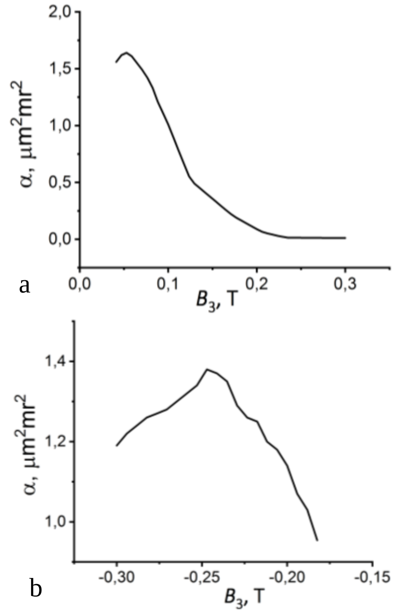

Fig. 3. Dependence of the reduced collimated acceptance α on the size of the focused beam on the target 1×1 μm on the value of the magnetic field at the poles of the first quadrupole: a – excitation layout of the quadruplet C3C1D1C2; b – excitation layout of the quadruplet D3C1D1C2

Parameters of an optimal probe-forming system based on a one-parametric quadruplet of magnetic quadrupole lenses for a quadrupole excitation layout C3C1D1C2

Magnetic field at lens pole, E=1 MeV, T B_{Q1} B_{Q2} B_{Q3} B_{Q4}	 0.052941176 0.137310082 -0.137310082 0.123760803
Demagnifications, $D_x \times D_y$	109×(-59)
Chromatic aberrations, μm/mr% Cp_x; Cp_y	 -431; 1089
Spherical aberrations, μm/mr^3 $<x/x'^3>$; $<x/x'y'^2>$; $<y/y'^3>$; $<y/y'x'^2>$	 2227; 6898; -11508; -12818
Acceptance, (d=1 μm), μm^2·mr^2	1.64

3. FOCUSING PROPERTIES OF AN OPTIMAL ONE-PARAMETRIC QUADRUPLET

An optimization approach based on the criterion of maximum reduced collimated acceptance represents a step towards the optimization of real systems. This approach allows us to take into account all possible aberrations of the system and does not require any assumptions or restrictions. Nevertheless, the main disadvantage of this approach is that it ignores the real initial distribution of ions in the trajectory phase space occupied by the beam, which is usually inhomogeneous. As a result, the final distribution of the beam current density inside the spot on the target is not taken into account. An inhomogeneous distribution of beam brightness has been noted in a number of studies of ion sources [12–14]. In the most widely used RF sources and duoplasmatron type sources, the maximum beam divergence angle is about 1 mr at an energy level of ~10 keV. When ions are accelerated to energies of several MeV, the divergence angle decreases by more than an order of magnitude. This may result in the optimal dimensions of the aperture collimator exceeding the beam dimensions. In this case, the beam will not match the acceptance of the probe-forming system.

To determine the distribution of ion current density on the target surface (final distribution), it is necessary to know the distribution of charged particles in the trajectory phase space at the entrance of the probe-forming system in the plane of the object collimator (initial distribution). Article [15] presents a method for measuring the beam brightness distribution in the object plane using two slit collimators. Here the brightness distribution is expressed as

$$b(x, y, x',y') = b_0 \cdot b_x(x, x') \cdot b_y(y, y'), \quad (4)$$

where

$$b_\tau(\tau,\tau') = \exp\left[-\frac{1}{2(1-\kappa^2)}\left(\frac{(\tau-\tau_0)^2}{\sigma_\tau^2} - 2\kappa\frac{(\tau-\tau_0)(\tau'-\tau'_0)}{\sigma_\tau\sigma_{\tau'}} + \frac{(\tau'-\tau'_0)^2}{\sigma_{\tau'}^2}\right)\right],$$

$\tau = x, y$, b_0 is axial beam brightness.

The brightness distribution parameters at the Sokol electrostatic accelerator with an RF ion source for an energy of 1 MeV are given in [16] and have the following values b_0=(6.7 ± 1.1) pA/(μm^2·mr^2·MeV), σ_x=621 μm, $\sigma_{x'}$=0.088 mr, x_0=-49 μm, x'_0=-0.016 mr, κ_x=-0.41, σ_y=667 μm, $\sigma_{y'}$=0.098 mr, y_0=-11 μm, y'_0=0.001 mr, κ_y=-0.89.

Thus, the beam brightness distribution in the trajectory phase space makes it possible to determine this distribution in the analytical form (4) using experimental data. The beam has a distribution of the form (4) in the selected phase volume using collimators. In this case, it is necessary to solve the problem of determining the current density of the beam focused on the target. The current density distribution in the probe is based on the transformation of the phase set of particles from the plane of the object collimator to the target plane in the form (1). The initial phase volume of the beam, specified by the dimensions of the object and aperture collimators, is determined by particles that are randomly distributed under the hypersurface $b(x,y,x',y')/b_0$, taking into account the distribution (4) using the reject method [17].

Determination of the focusing properties of a probe-forming system based on a one-parametric quadruplet and, for comparison, for a basic system based on an orthomorphic quadruplet, was carried out for collimator sizes that provide a beam current on the target of I≈100 pA. For a one-parametric quadruplet: r_x=50 μm, r_y=30 μm, R_x=100 μm, R_y=50 μm, with I=122 pA. For an orthomorphic quadruplet: r_x=35 μm, r_y=35 μm, R_x=75 μm, R_y=75 μm, with I=110 pA. The results of calculating the current density distribution on the target for both quadruplet configurations are shown in Fig. 4. From this figure, it is clear that the resolution for the nuclear microprobe channel can be improved several times using a one-parametric quadruplet of magnetic quadrupole lenses, while the current density increases by an order of magnitude, which is important for applications such as proton-beam writing.

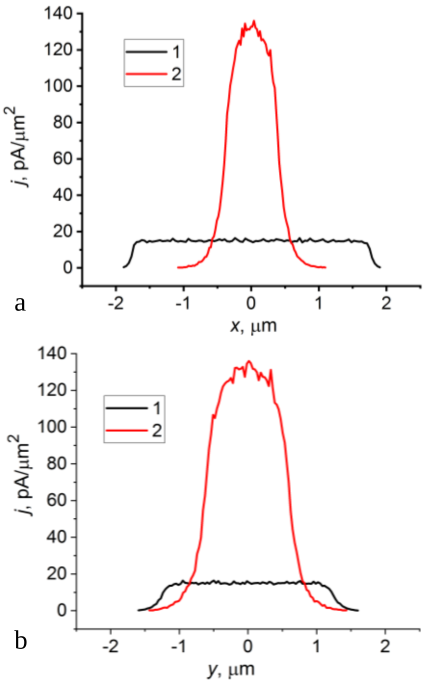

Fig. 4. Current density distribution of a focused proton beam on the target for one-parametric (2) and orthomorphic (1) quadruplets: a – xOz plane; b – yOz plane

CONCLUSIONS

A probe-forming system based on a one-parametric separated quadruplet of magnetic quadrupole lenses is considered, where the first lens has an independent power supply, and the remaining three lenses are connected to two current sources according to the *C*1*D*1*C*2 layout. In this case, the independent power supply of the first lens is a free parameter on which the ion-optical properties of the system depend. It is shown that a change of the magnetic field at the poles of the first lens in the range of -0.3...0.3 T affects the demagnifications. As they increase, the aberrations increase significantly. To determine the optimal probe-forming system, an optimization problem was solved in which the function of merit is the reduced collimated acceptance. This approach allows us to take into account the influence of demagnifications and all aberrations on the process of probe formation. To determine the focusing properties of an optimal probe-forming system based on a one-parametric separated quadruplet of magnetic quadrupole lenses, an approach is used that takes into account the inhomogeneous distribution of charged particles in the trajectory phase space formed by the object and aperture collimators. As a result, it is shown that the use of a one-parametric quadruplet can improve the spatial resolution several times, while the current density in a focused beam on a target increases by an order of magnitude compared to the basic system based on a separated orthomorphic quadruplet.

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УДОСКОНАЛЕННЯ ПРОСТОРОВОЇ РОЗДІЛЬНОЇ ЗДАТНОСТІ КАНАЛА ЯДЕРНОГО СКАНУЮЧОГО МІКРОЗОНДА АНАЛІТИЧНОГО ПРИСКОРЮВАЛЬНОГО КОМПЛЕКСУ ІПФ НАН УКРАЇНИ

О.Г. Пономарьов, В.І. Возний, І.Г. Ігнатьєв, С.В. Колінько, Д.В. Магілін, В.А Ребров

Проведено дослідження зондоформуючої системи ядерного скануючого мікрозонда на базі квадруплету магнітних квадрупольних лінз із трьома незалежними джерелами живлення квадруполів. У режимі стигматичного фокусування третє джерело є вільним параметром, який впливає на іонно-оптичні характеристики мікрозонда. Оптимальна система вибиралася у результаті розв'язання оптимізаційної задачі, в якій функцією цілі був приведений колімований аксептанс. Проведене чисельне моделювання процесу фокусування пучка у такій однопараметричній системі з урахуванням експериментально виміряного розподілу протонів у траєкторному фазовому просторі показало, що розміри пучка на мішені можуть бути зменшені у кілька разів у порівнянні з діючою системою. При цьому щільність струму в сфокусованій плямі збільшується на порядок.