Nuclear Instruments and Methods in Physics Research B 269 (2011) 2202–2205

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

One-stage probe-forming systems with quadrupole lenses excited by individual power supplies

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ARTICLE INFO

Article history:
Available online 26 February 2011

Keywords:
Probe-forming system
Acceptance
Quadrupole lens
Nuclear microprobe

ABSTRACT

The work deals with the ion-optical characteristics of the probe-forming systems based on a quadruplet of magnetic quadrupole lenses with four power supplies. The excitation of the lenses of a final doublet of such system is determined from the stigmatic focusing conditions, and the excitations of the first two lenses (downstream the beam) are free parameters which form a parametric set of the probe-forming systems. For this parametric set, the system acceptance reduced to the envelope dimensions in the target plane is determined as a figure of merit for the optimization task. The solution of this task gives optimal excitations of the first two lenses allowing an increase in demagnifications and acceptance of the probe-forming systems with individual power supplies in comparison with a separated Russian quadruplet.

1. Introduction

In quadrupole one-stage probe-forming systems of a nuclear microprobe it is necessary to use no less than two quadrupole lenses to create a stigmatic beam focusing on a target. The optics of these systems with two individual power supplies is studied in [1,2]. If the number N of quadrupole lenses in the probe-forming system is >2 then, as a rule, the remaining $N-2$ lenses do not require individual power supplies and are coupled to one of the final doublet lenses. However, such a combination limits their capabilities to focus the beam. The only possibility to improve such probe-forming systems is to separate these $N-2$ quadrupoles along the optical axis and to find their optimal positions. Such optimization task was the aim of our previous work [3]. In that work we considered a parametric set of probe-forming systems with two separated power supplies where the number of magnetic quadrupole lenses $N = 3–6$ and the geometrical position of the first $N-2$ lenses along the beam axis were chosen as free parameters. The same task was considered in [2,4] using other criteria of the optimal system. As a result, it was shown that the design of separated systems allows the demagnification to be increased, with insignificant aberration growth that leads to an increase of the ion current density on a target.

In some separated quadrupole probe-forming systems an optimum is realized when the first $N-2$ lenses are placed at a considerable distance from each other. However, the implementation of such systems in practice is connected with the difficulties related to the positioning aberration of single quadrupoles which have high excitations. The cause of this is, as is known, that the alignment of a single quadrupole lens axis with the optical axis does not have an exact solution when the lens influence on the beam is used as a feedback for adjustment. In order to decrease positioning aberrations, a separated Russian quadruplet with the first two lenses combined in a doublet [5–7] can be used. In the integrated doublet [8] the yoke and pole tips of the both lenses are made from one piece of soft iron which results in a rigid coupling between them. Such doublet design allows every lens axis and optical axis to be adjusted with sufficient accuracy. However, probe-forming systems with two separated power supplies still have non-optimal ion-optical characteristics due to the lenses being arranged in doublets.

The aim of the work is to improve the Sumy nuclear microprobe [7,9] with separated Russian quadruplet (Sumy SRQ) by using two additional power supplies for the lenses.

2. Formulation of the problem

An improvement of the spatial resolution of a microprobe is based on the search for a system with high demagnifications and small aberrations. However, the criteria for the optimization task, taking into account the competitive action of the demagnifications and aberrations in the probe forming process, can be determined using various approaches. A simple figure of merit presented as a ratio of the demagnifications to some spherical aberrations was chosen to be an optimization criterion in [2]. This excludes other aberrations and the probe forming process itself from the consideration. The most grounded criteria from the physical point of view

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doi:10.1016/j.nimb.2011.02.025

are two criteria permitting current density on the target to be maximized. The first criterion is determined by the minimal envelope dimensions in the target plane for a fixed current [10]. The second criterion is described by the maximal beam current with fixed envelope dimensions on the target [11,12]. In the first case, envelope dimensions are to be minimized; in the second one, acceptance is to be maximized. In both cases, the optimal sizes of the object and aperture collimators are determined as a result of the optimization process. The advantage of such task definition is the consideration of all ion-optical parameters of the probe-forming system (demagnifications and aberrations) affecting the transportation process of the phase set formed by the collimators from the object to the target plane. Unfortunately, these approaches do not take into consideration the beam phase density distribution in the object collimator plane. The optimization task allowing for a non-uniform distribution of the particles in the phase space is the next stage in simulating the probe forming in a nuclear microprobe. This approach is described in [13].

We use the second criterion based on the collimated acceptance value A_d related to the dimensions of a square-shaped envelope of width d on the target. This formulation implies that A_d is equal to the maximal phase volume formed by the rectangular object and aperture collimators that could be transported to the target plane with transverse dimensions not exceeding a square size of $d \times d$, using a multiplet of magnetic quadrupole lenses. The formalization of such an optimization task based on the acceptance value criterion is presented in [11,12].

The general scheme of the quadruplet with individual power supplies is shown in Fig. 1, where all probe-forming system parameters are indicated. The optimization task in [2–4] is based on the selection of the geometrical parameters of the probe-forming systems. Two parameters describing the fields B_1 and B_2 on the tips of the first two magnetic quadrupole lenses are added to the task definition in the current work. B_1 and B_2 as well as geometrical parameters influence the ion-optical characteristics of the probe-forming systems that determine A_d. Therefore, optimal values of B_1 and B_2 can be obtained from the solution of the optimization task with fixed geometrical parameters as follows

$$A_d^* = \max_{B_1, B_2} A_d(B_1, B_2),$$
$$|B_1| \leqslant B_{1,max}, |B_2| \leqslant B_{2,max} \quad (1)$$

3. Simulation and evaluation of one-stage quadruplet with individual power supplies

The geometrical parameters of the Sumy SRQ [7] that closely resemble the real optical system and are considered for the simulation of the beam optics are the following (using the indications in Fig. 1): $a_1 = 2.504$ m, $a_2 = a_4 = 0.0394$ m, $a_3 = 0.7875$ m, $g = 0.23554$ m, $L_{1,eff} = L_{4,eff} = 0.07141$ m, $L_{2,eff} = L_{3,eff} = 0.05067$ m, lens bore radius $r_{a,i} = 0.0065$ m, $i = 1$–4. The maximal field value on the tip for all lenses is $B_{max} = B_{i,max} = 0.42$ T, $i = 1$–4. The one-stage quadruplet of magnetic quadrupole lenses with individual power supplies has the same parameters. However, the excitation configuration differs from the Russian quadruplet. The configuration of the third and fourth lens is fixed as $C3D4$, where $C3$ denotes that the lens is connected to the third power supply and provides beam convergence in the xOz plane and $D4$ denotes that the lens is connected to the fourth power supply and provides beam convergence in the yOz plane. With such connection, the field on the lens tips is varied in the ranges $0 < B_3 \leqslant B_{max}$ and $-B_{max} \leqslant B_4 < 0$.

The field values B_1 and B_2 for the first two lenses are being changed in the range $[-B_{max}, B_{max}]$. This means that if the field on the tip has a positive value, the magnetic quadrupole lens provides beam convergence in the xOz plane and vice versa, for negative values of the field, the lens shows beam convergence in the yOz plane. Thus, possible variants of the connection between the first two lenses are fully described.

A 2 MeV proton beam with a momentum spread of $\delta = 5 \cdot 10^{-4}$ and an acceptance value $A_{1.0}$ reduced to the envelope size $d = 1.0$ μm in the target plane was considered in the optimization task (1). The Sumy nuclear microprobe is based on a Van de Graaff electrostatic accelerator. The momentum spread of charged particles for this accelerator is a half of the measured energy spread in the beam [7,9]. For calculating the ion-optical characteristics, which include demagnifications, chromatic aberrations and intrinsic aberrations of the 3rd order, the matricant method was used [13]. The matricant method is based on a strict mathematical formalism permitting a full set of the probe-forming system aberrations to be obtained analytically for a rectangular field model of the magnetic quadrupole lenses. This fact is important for the optimization tasks. A comparison of the ion-optical characteristics obtained with numerical code based on the matricant method and other codes is presented in [12].

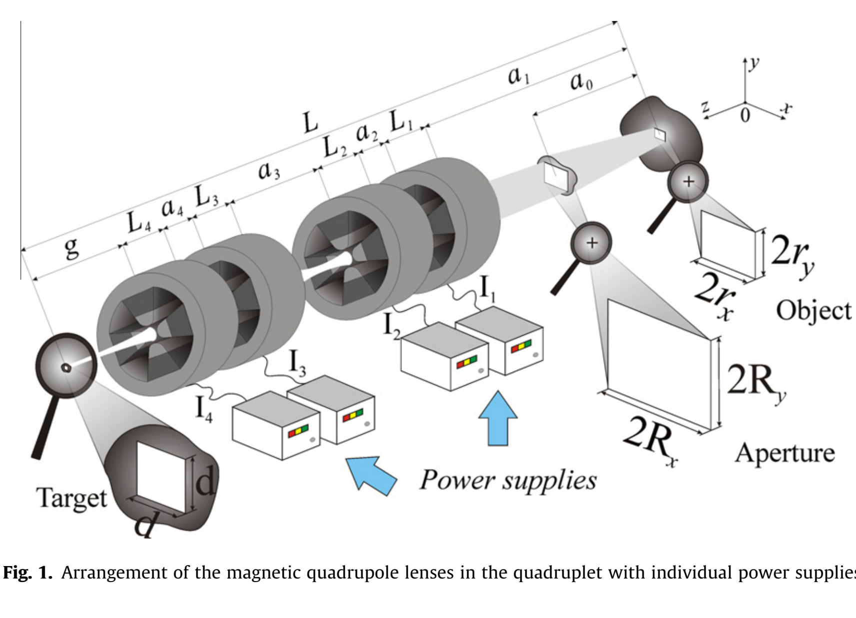

Fig. 1. Arrangement of the magnetic quadrupole lenses in the quadruplet with individual power supplies.