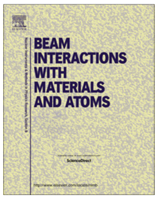
Nuclear Instruments and Methods in Physics Research B 348 (2015) 88–91

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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



Ion optics of probe-forming systems on the base of magnetic quadrupole lenses with conical aperture

A.A. Ponomarova [a],*, G.S. Vorobjov [a], A.G. Ponomarev [b]

[a] *Sumy State University, Sumy, Ukraine*
[b] *Institute of Applied Physics, NAS of Ukraine, Sumy, Ukraine*

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form 15 October 2014
Accepted 19 November 2014
Available online 5 December 2014

Keywords:
Quadrupole lens
Conical aperture
Probe-forming system
Acceptance
Nuclear microprobe

ABSTRACT

This paper describes the performance of probe-forming systems based on a new type of magnetic quadrupole lens with a conical aperture (MQL CA). The main difference in the MQL CA from the conventional quadrupole lens with a cylindrical aperture is that the poles in it are not parallel to the lens axis and positioned at a certain angle. The basic advantage of such a lens is that the conical angle of the aperture allows the profile of the longitudinal distribution of the main components of the quadrupole field to be changed. It provides for the changing of the focal length value, displacement of the principal plane relative to the centre of the lens and aberration variations depending on the conical angle. A theoretical study of the ion optics of the probe-forming systems consisting of a triplet MQLs CA was carried out. A comparison of the systems with MQLs CA and conventional systems based on the magnetic quadrupole lens (MQL) with a cylindrical aperture shows the possibility of increasing the acceptance of the first due to using the new type of lens.

1. Introduction

Proton beam writing, focusing ion beam and ion projection lithography have the flexibility and potential to become leading contenders as next generation lithography. For the proton beam writing facility to achieve circuits beyond 22 nm, one of the challenges is to reduce the focused proton beam size to 20 nm and below. Difficulties in reaching a beam size below 20 nm are the high energy of the protons, about a few MeV, and the low brightness of the ion source. Therefore, for formation of such ion-beams we have to use strong focusing optical elements, i.e. MQLs. At present, it is necessary to develop magnetic quadrupole probe-forming systems (PFSs) with demagnification $|D_x{}^*D_y| \sim 10^5 \ldots 10^6$. As the exposure rate of resistive materials depends on the current density of the proton beam, such PFSs should have a relatively high acceptance. Currently, certain progress has been made by the research group of the Centre for Ion Beam Application, Singapore [1]. They obtained a beam spot size $19.0 \times 29.9\ \text{nm}^2$ with a current of 23,200 protons per second. These parameters were achieved due to using the separated triplet MQLs with demagnification $D_x = 857$, $D_y = -130$, and a working distance of 3 cm. As is known, the triplet MQLs with two independent power supplies makes a significant difference to the demagnification and low acceptance due to the negative influence of the aberrations.

Formerly, we proposed to increase the acceptance of PFS by means of using a quadruplet MQLs with four independent power supplies [2]. The possibility of increasing the acceptance of the system with relatively high demagnifications by introducing additional power supplies to the lenses was experimentally demonstrated [3].

In this paper, we propose a different approach to improve the ion-optical properties of the PFS by modification of the MQL. Formerly, the properties of the electron-optical elements with conical symmetry were considered [4,5]. Application of such elements in the quadrupole lens allows the principal plane of the lens relative to its centre to be shifted depending on the cone angle of the aperture. The optics of such lenses were considered in [6]. The design difference between quadrupoles with a cone aperture and the conventional quadrupole lens lies in the fact that the poles are not parallel to the lens axis and positioned at a certain angle. In [6], to calculate the optics of the quadrupole lens with a conical aperture we used a matrix method known as the matriciant method developed by A.D. Dymnikov [7].

The aim of this paper is to carry out a comparative analysis of the focusing properties of a triplet consisting of MQLs with a conventional cylindrical aperture, and a triplet, where quadrupole lenses with a conical aperture are used.

---

* Corresponding author. Tel.: +380 542 68 77 68; fax: +380 542 33 40 58.
E-mail address: ponomareva_a_a@pochta.ru (A.A. Ponomarova).

http://dx.doi.org/10.1016/j.nimb.2014.11.069

2. Magnetic quadrupole lens with a conical aperture

The layout of the MQL with a conical aperture is shown in Fig. 1a. Currently, the production of such a quadrupole using wire cut electrical discharged machining is not especially difficult. The details of this machining can be found, for example, in [8]. The longitudinal geometry of such a lens is shown in Fig. 1b, where r_0, R_0 are the radiuses of the lens aperture at the input and output, respectively; L is the geometrical length of the lens and α is the conical angle of the lens aperture. The main difference with this lens is the conical angle of the aperture, which allows the profile of the longitudinal distribution of the main components of the quadrupole field to be changed. Aperture conicity also makes it possible effectively to operate the ion-optical properties of such a quadrupole lens [6]. From a physics standpoint, it can be explained that the conical angle of the lens affects the longitudinal distribution of the gradient field, which leads to a change in the charged particle dynamics of such a quadrupole lens. Therefore, if the power supply of the current-carrying coil of the lens is constant or if the poles are made from permanent magnets, it is possible to provide stigmatic focusing only by changing the conical angle of the aperture. This is due to the fact that the focal length varies with the changing profile of the gradient longitudinal distribution. Lens aberrations values also vary depending on the conical angle.

The radius r of an aperture in the longitudinal direction z for a lens with a conical aperture varies in accordance with:

$$r(z) = r_0 + (R_0 - r_0) \cdot (z - z_i)/L. \tag{1}$$

Distribution of field gradient $W_2(z)$ on the axis of the lens is shown in Fig. 2. In the middle of the lens, away from the edges, the gradient can be represented as an analytical model:

$$g_1(z, z_i) = G \cdot \varphi(z, z_i), \tag{2}$$

where G is the value of the transverse field gradient, which depends on the current value in the coils and the magnetic properties of the pole material;

$$\varphi(z, z_i) = \frac{1}{[1 + b(z - z_i)]^2};$$

$$b = (R_0 - r_0)/(L \cdot r_0) = tg(\alpha)/r_0.$$

It should be noted that the profile of the longitudinal distribution $\varphi(z)$ in the MQL with a cylindrical aperture has a symmetrical form relative to the geometric centre of the lens. In contrast, in the MQL CA this distribution does not have such symmetry. Therefore, the determination of the effective length L_{eff} of the field for such a lens is related to the magnitude of the field gradient and location of this gradient distribution relative to the centre of the lens. Connection of the effective length to the lens geometry is determined by a coordinate z_0 in Fig. 1b. One approach to define L_{eff} is the condition of coincidence of the ion-optical properties of the first-order for the quadrupole lenses with real and model field gradient distributions. The effective length of the field is defined as:

$$L_{eff} = L + s_1 r_0 + s_2 R_0, \tag{3}$$

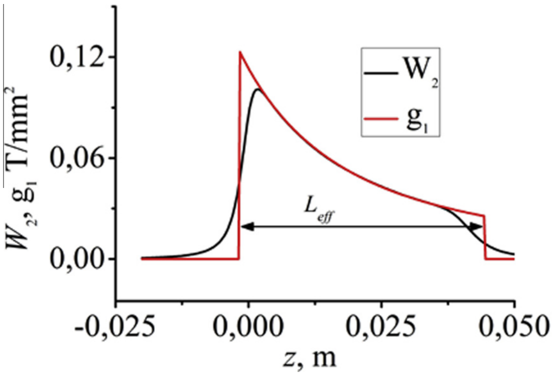
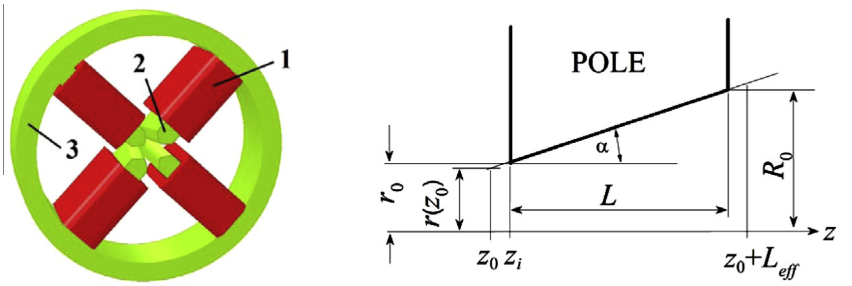


Fig. 2. Longitudinal distribution of the field gradient in the MQL CA ($W_2(z)$ is the real distribution; $g_1(z, z_i)$ is a model distribution).

where the parameters s_1 and s_2 are determined from the condition of coincidence of the focus position in the x and y transverse directions for real and model field distributions in the lens. For the different values of the length of the lens L, for the input and output radius aperture r_0 and R_0, parameters s_1 and s_2 have different meanings within the limit $0.50 \leqslant s_1 \leqslant 0.66$ and $0.58 \leqslant s_2 \leqslant 0.72$.

Fig. 3 demonstrates the dependence of the focal length and coordinates of the principal planes from angle α at a constant value of the current in the coils for a single lens. To calculate the parameters of the lens with a conical aperture the following should be accepted: the value of the current in the coils $NI = 500$ A coil, $L_{eff} = 0.041$ m, $\min(r_0, R_0) = 0.003\ m$, $\max(r_0, R_0)0.015\ m$. The beam parameters are protons with energy 1 MeV. The magnetic quadrupole lens with a cylindrical aperture equivalent to the magnetic quadrupole with a conical aperture was determined by the choice of pole excitation β_c, which corresponded to the condition min $[(F_x - F_{xC})^2 + (F_y - F_{yC})^2]$, where $F_{x(y)C}$ are focal lengths of equivalent MQL with a cylindrical aperture. In this case, the first-order properties of both lenses are sufficiently close. Fig. 4 demonstrates the relationship between the chromatic and spherical aberrations of the lens with a conical aperture and the corresponding aberrations equivalent lens with a cylindrical aperture depending on the cone angle α. It should be noted that for the calculation of MQL aberrations with a conical aperture an analytical model of the magnetic field gradient distribution was used. Comparative analysis of the aberration calculations of the MQL with a conical aperture for an analytical model and real distribution of the gradient field for the



(a) (b)

Fig. 1. MQL CA: (a) layout of a lens, where 1 is current-carrying coil, 2 is pole tip, 3 is yoke; (b) longitudinal geometry of the MQL CA pole.