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Precise centering method for triplet of magnetic quadrupole lenses using single rigid frame

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ABSTRACT

Separated probe-forming systems can be applied to enhance the resolution of a scanning nuclear microprobe with a comparatively large working distance to accommodate the detectors at backward angles. In such systems, magnetic quadrupole lenses are placed at the considerable distance and hence require their precise alignment with the beam axes. Violation of this requirement results in a considerable increasing of a spot size on the target for a constant beam current. Positioning of magnetic quadrupole lenses in a doublet can be implemented in a single-unit design, where a yoke and poles of two lenses are made from one piece of soft iron by precise electrical discharge machining. In a case of triplet, lens manufacturing as a single-unit has technological difficulties. A lens triplet configuration presented in this work comprises placement of three single magnetic quadrupole lenses in a single rigid frame. An approach to lens alignment by the magnetic field reconstruction method was developed and successfully realized.

1. Introduction

Application of a separated probe-forming system is one of the trends for development of high resolution nuclear microprobes. Some of such systems were realized in experimental facilities [1–7]. In the separated systems, one or several magnetic quadrupole lenses are placed at the considerable distance from a group of final focusing lenses located near the target. The separation allows higher demagnification factors to be obtained compared to the conventional compact lens arrangement [8,9], and hence to decrease the size of the focused beam in spite of higher aberrations. Thus, the best resolution of $9.3 \times 32\ \mathrm{nm}^2$ was obtained in the work [10] using separated triplet with the small working distance (3 cm). Such triplet has very different demagnification factors $D_x \times D_y = 857 \times (-130)$ in xOz and yOz planes [1]. Despite this stated progress, the application of separated systems with more than three lenses, which have desirable demagnification factors usually close in the both planes, still has some difficulties. They are mainly caused by a high sensitivity of the lens positioning along the beam line axis. Since an axis of the single lens cannot be precisely adjusted to the beam axis due to the physical peculiarities, positioning aberrations related to the tilt, rotation and transverse translations misalignments occur. This causes a degradation of the beam focused on the target as mentioned in the works [1,6], and an influence of this type of aberrations on microprobe resolution is considered in the works [12,16,17].

Precise positioning of the lens system can be attained by a combination of each quadrupole into an integrated multiplets with a precise mechanical arrangement. In contrast to alignment of the single quadrupole lens by a conventional method using the image of the beam focused into a line, the alignment of the integrated multiplet by this method allows unambiguously establishing which misalignment (tilt or translation) causes a displacement of the line foci. In this case, the lens axes and quadrupole antisymmetry planes should be previously aligned. This can be achieved either through the integrated multiplets construction technology [2,14,15] or by application of the special frame for integration of the lenses and their subsequent mechanical centering [13,18]. In both cases, a method for lens spatial positioning is required. In the first case, this method imposes a manufacturing precision of the manufactured multiplet; in the second case, this method is required to centering of each lens within the integrating frame. Implementation of this method via precision measurements of the magnetic field structure in the quadrupoles was presented earlier [11].

The present work considers the frame construction, which provides a mechanical centering of three single lenses along a common axis and alignment of their antisymmetry planes. The position of the local coordinate system of a single lens relative to

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the laboratory Cartesian coordinate system was used as a criterion for the precision centering. The spatial positioning of the local coordinate system, which relates with the lens axis and its antisymmetry planes, was defined by implementation of the field reconstruction technique [11] to be described here.

2. Construction of the integrated triplet of magnetic quadrupole lenses

In the work [19], the five-lens separated focusing system was applied for the proton beam writing end-station, which is under construction in the SIMB Lab of Institute of Applied Physics, Sumy, Ukraine. This system has a doublet-triplet configuration. The final triplet is critical for its precise positioning along the beam axis as was noted in the work [20]. The single-unit construction is more favourable for this multiplet, but production of several lenses with a long common yoke is quite difficult because of the technological peculiarities of its manufacturing. Therefore, required coaxiality of the lenses can be obtained with an arrangement of all quadrupoles into the integrating rigid frame (Fig. 1).

The frame has three pairs of flanges connected with couplers. It allows each lens displacement over five degrees of freedom. The lenses are displaced and fixated with a set of ball pressure screws. Each pair of flanges has three pairs of ball pressure screws (Pos. 1, Fig. 1).

The integrated triplet comprises two upgraded OM50m lenses (Fig. 2, a) and SL1 elongated lens manufactured in the SIMB Lab (Fig. 2, b). The SL1 lens (length 110 mm, aperture radius 6.5 mm, yoke diameter 235 mm) has a pole shape similar to that of the lenses [21] and differs only in the extended length. The OM50m lenses (length 60 mm, aperture radius 7.5 mm, yoke diameter 200 mm) were modified through replacement of the current-carrying coil of the lenses [22] in order to provide excitation by the standard permanent current sources with the maximum current of 10 A.

3. Method for centering of single lenses within integrated triplet

The method based on determination of the spatial position of the ion-optical axis of each lens, their antisymmetry planes positioning and further repositioning of these three lenses with respect to each other. For this purpose, the radial component of a vector of magnetic field induction was measured over a virtual cylindrical surface at some points along the triplet axis. This surface enveloped an area of the beam propagation in the lens aperture and was connected to the laboratory Cartesian coordinate system (Fig. 3).

Field structure inside of the surface was calculated by solving the boundary Neumann problem for the Laplace equation. The

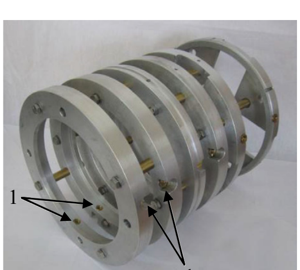

Fig. 1. The frame for integrated triplet. (1) are visible counterparts of the ball pressure screws for the first pair of flanges.

measured radial components of a field were the boundary conditions:

$$\Delta w(x,y,z) = 0, \quad B_r(x,y,z)|_{(x,y,z)\in G} = \frac{\delta w(x,y,x)}{\delta n}|_{(x,y,z)\in G},$$

where $w(x,y,z)$ is a spatial distribution of a scalar magnetic potential in the area of the beam propagation.

The original measurement facility was constructed for testing the integrated doublet of the magnet quadrupole lenses [14]. A precision magnetic field sensor AD22151 (Analog Devices) with a linear output, outline dimensions of $6.2 \times 5 \times 1.75$ mm^3 and a sensitivity area of 0.5×0.5 mm^2 was used as a probe for field measurements. The positioning mechanism uses precision modules of linear (M-403.82S) and angular (M-060.2S) movements manufactured by Physik Instrumente. In order to test the triplet, the movement range of the Hall probe was not sufficient for measuring the field structure of all lenses. An additional the same Hall probe AD22151 was installed to capture the working area of three lenses at a distance of 113 mm from the center of the first one. Its position was calibrated with respect to the first probe; hence, their positioning accuracy was 3 μm in radial axis and 0.02° by an azimuth angle. The facility allowed detection of a spatial position of the axis with 2 μm accuracy. Relative measurement error of the field magnetic induction was 10^{-3}. The lenses were warmed up before determination of axis position in order to eliminate the influence of their thermal expansion [11].

We have evaluated the influence of hysteresis on the axis displacement in the case of the inverse excitation of the lens pole by maximal currents in the coils. In this case, translational displacement of the axes did not exceed 10 μm. During the alignment process all lenses were excited in the same polarity. In future during the alignment of the integrated triplet on the beam the polarity will be changed, but in this case the excitation will be one order of magnitude smaller than in normal mode.

Relying on the obtained data, the spatial position of the axis and the antisymmetry planes of each lens with respect to the laboratory coordinate system were preliminary detected. All spatial position data obtained from field reconstruction are verified by using four micrometers. Precise centering of the lenses in the frame, involved further lens displacement and alternate determination of the axes position and the antisymmetry planes.

4. Results and discussions

The centering procedure was performed in two stages because construction peculiarities of the test facility restricted measurements for all three lenses in the same time. On the first stage, OM50m_1 (the first lens OM50m (Fig. 2) which is nearest to SL1 lens) and SL1 lenses were mounted in the frame and adjusted on the test facility (Fig. 3, a). Lenses were warmed up for several hours before the measurements in order to sustain an operating current in the coils and to minimize the thermal effect of the lenses on the results of the measurements. Spatial position of the axes and of the antisymmetry planes of each lens was defined with respect to the laboratory coordinate system. All further displacements were performed with the OM50m_1 lenses, the SL1 lens axis was used as a reference. The measurements were carried out by the first Hall probe (D1). At first, the rotation angle of the lenses were set and their axes were aligned then. The required displacement of the lens defined from the measurement of the field structure was verified with the comparator micrometers with a scale division of 1 μm (Fig. 3, a).

On the second stage, the frame with the third OM50m_2 lens was mounted onto the facility additionally to two aligned lenses (Fig. 3, b). Here all procedures were performed with a new lateral