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Precise centering and field characterization of magnetic quadrupole lenses

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ABSTRACT

A setup to investigate fields of magnetic quadrupole lenses was designed and constructed. It allows the spatial position of the axis and the multipole structure of the field of a lens (or lenses) with aperture sizes from 11 mm to be determined. The technique employed is based on the measurements of the radial component of the magnetic induction vector using a Hall probe at the points located on the three dimensional surface with subsequent data processing using the Laplace equation. The article presents design and performance characteristics of the setup as well as results from the accuracy evaluations in the measurements of the centers and parasitic multipole field components of the magnetic quadrupole lenses in the integrated doublet.

1. Introduction

To increase the demagnification of scanning nuclear microprobes separated probe-forming systems are often used with magnetic quadrupole lenses placed at a considerable distance from each other [1–4]. If these lenses have high excitation, their adjustment is vital for producing a high-quality beam spot. Therefore these systems use integrated doublets of magnetic quadrupole lenses where both quadrupoles are rigidly connected representing single unit [3,5,6]. However, imperfections caused by manufacturing defects and by hysteresis may lead to distortions in the relative position of the optical axes of each lens and to the occurrence of multipole parasitic components of the field. As a result, the beam, not being aligned with the physical axis of the magnetic quadrupole lens is refracted in the lens field, deviating from the axis at a certain angle. This deviation results in a considerable displacement of the beam from the axis along a large drift length. The beam then enters into the field of the next lens at an angle and at a large distance to the axis, considerably increasing the aberration effects. The value of this deviation depends on the supply current of the lens and changes during adjustments causing further difficulties. So, in testing the magnetic quadrupole lenses (MQL) it is necessary to determine both the multipole structure of the field and the spatial position of the optical axis.

To study the MQL field use is generally made of direct methods for induction measurements, using either a rotating coil [6–8] or 3D field mapping by a Hall probe [9,10]. Among the indirect methods the most extensively employed one is a grid-shadow method [8] in which multipole field components are calculated from the distortion of the grid image formed on a fluorescent screen by the beam passing through the MQL.

The rotating coil method permits the multipole MQL field structure to be determined via Fourier analysis of the output signal. The advantage of this method is that the multipole field components of higher orders can be obtained. To ensure the required sensitivity the rotating coil has dimensions comparable to the diameter of the lens aperture. So, the method is not suitable for the investigation of the spatial field distribution of the MQL.

3D Mapping of the MQL field with a Hall probe provides data on the magnetic field induction at fixed points inside the lens aperture. By interpolation it is possible to calculate the induction value at arbitrary points. Points where the magnetic induction is zero, determine the position of the optical axis. The multipole field components are calculated using the interpolation method based on the representation of the magnetic potential as a Fourier series. For a small-aperture ($\sim$10 mm) MQL 3D mapping presents difficulties resulting from the Hall probe dimensions which are similar to the lens aperture diameter.

In the grid shadow method a distorted grid image obtained in experiments is examined by numerical simulation of the image formation using the values of the lens field multipole components as fitting parameters. Based on this procedure of fitting the calculated image to the experimental one the MQL multipole components are obtained. The strong point of this method is that it does not impose any technical restrictions on the size of the lens aperture. However the method fails to locate the position of the MQL optical axis.

In [5] we used the setup to test the field of the integrated MQL doublet based on the measurements of the radial field component

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using a Hall probe within the MQL aperture. However, the setup was not free from imperfections, which affected the accuracy of the determination of the required field characteristics. In this paper, an improved setup is described. After recalling the employed technique and specifying the parameters with the help of a simulation, the obtained accuracy is shown as a set of dedicated measurements.

2. Setup design and technique

The setup permits a realization of a field reconstruction technique described in our earlier paper [11]. The technique consists in using a Hall probe to measure the normal vector component *Br* of the magnetic induction at points on a virtual cylindrical surface *G* covering the working area of the lens, i.e. the beam travel area. The calculation of the induction at any point of the internal volume is based on the solution of the Neumann boundary problem for the Laplace equation. The measured *Br* values are used as boundary conditions.

$$\Delta w(x,y,z)=0,\ -\mathrm{Br}(x,y,z)\big|_{(x,y,z)\in G}=\frac{\partial w(x,y,z)}{\partial n}\bigg|_{(x,y,z)\in G} \tag{1}$$

where $w(x,y,z)$ is the spatial distribution of the magnetic scalar potential in the beam travel area and n is the external normal to the surface.

To determine the technical requirements for the positioning system a numerical simulation of the setup parameters was performed including the simulation of the effect of the positioning accuracy of the Hall probe on the determination of parasitic sextupole and octupole field components [12]. The scala1 magnetic potential which describes the field in the quadrupole magnetic lens in the cylindrical coordinate system is represented as

$$\begin{aligned} w(r,\alpha,z) = {} & W_2(z)r^2\sin(2\alpha) - W_2''(z)r^4\sin(2\alpha)/12 + U_3(z)r^3\cos(3\alpha) \\ & + W_3(z)r^3\sin(3\alpha) + U_4(z)r^4\cos(4\alpha) + W_4(z)r^4\sin(4\alpha) + \dots \end{aligned} \tag{2}$$

where $W_2(z)$ is the longitudinal distribution of the main quadrupole component, $W_3(z)$, $U_3(z)$ and $W_4(z)$, $U_4(z)$ are the longitudinal distributions of the main and skew sextupole and octupole parasitic components, respectively. Eq. (2) represented in the coordinate system related to the physical lens axis Z and major planes of the quadrupole antisymmetry, X, Y, where coefficients $U_1(z)$, $W_1(z)$, $U_2(z)$ vanish.

Since inside the lens the field depends weakly on the longitudinal coordinate z the most significant coordinates for accurate positioning are r and α. The simulation was therefore performed for a two-dimensional geometry, with the filed described by the scalar magnetic potential as

$$\begin{aligned} w(r,\alpha) = {} & W_2r^2\sin(2\alpha) + U_3r^3\cos(3\alpha) + W_3r^3\sin(3\alpha) \\ & + U_4r^4\cos(4\alpha) + W_4r^4\sin(4\alpha) + \dots \end{aligned} \tag{3}$$

The multipole field components were chosen similar to the typical values: $W_3(0)/W_2(0)=0.002$ [1/cm], $U_3(0)/W_2(0)=0.004$ [1/cm], $W_4(0)/W_2(0)=0.006$ [1/cm^2], $U_4(0)/W_2(0)=0.008$ [1/cm^2]. Next, we assign points (r_i, α_i) on the circle; the radial component $\mathrm{Br}_i=-\partial w(r,\alpha)/\partial \mathrm{n}\big|_{r=r_i,\alpha=\alpha_i}$ was calculated at each i-point.

The simulation of the positioning error on the radial coordinate r was done as follows. In the calculation of Br_i as described above, in Eq. (3) r_i was replaced by $(r_i+\Delta r_i)$, where $\Delta r_i=\delta_i\times\Delta r_{max}$, Δr_{max} is the prescribed maximum value of the positioning error and δ_i is a random quantity in the range $-1\dots1$ obtained by a random-number generator for each i. The thus obtained values of induction Br_i including positioning error, were thus used to calculate the multipole components by the field reconstruction technique described above. The simulation of the positioning error for the α angle was carried out in a similar way. The error of the numerical simulation technique was determined in the same way, but setting $\Delta r_{max}=0$, $\Delta\alpha_{max}=0$.

Comparing the analytically specified and calculated multipole components allows the relative error of the technique to be found. Results obtained show that for the positioning accuracies of the Hall probe $\Delta r_{max}<5\ \mu$m and $\Delta\alpha_{max}<2'$ the error in determining the parasitic multipole components is $<10\%$ for sextupole and $<20\%$ for octupole components, while the error of the numerical technique is $<2\%$.

A simulation to determine the affect of inaccuracy of the Br measurements in the fringe field region of the MQL was carried out in a similar way. Results obtained show that the MQL field structure can be reconstructed adequately for the induction measurement inaccuracy $<2\%$. The fringe fields affect the MQL field in the inner region on the depth of order of the aperture radius and make a moderate contribution to the integrated higher order field content of the MQL.

The setup to test the integrated doublet field previously described in [5] had a construction imperfection: the Hall probe was placed at the end of the rotative tube at a considerable distance from the carriage of the linear movement mechanism forming a big arm. As a result, even small angular backlashes in the rotation bearings and carriage lead to a considerable shift of the rotational axis of the probe. The resulting positioning accuracy without the use of additional accessories was not satisfactory. To provide a minimum acceptable accuracy we have to use additional guide sleeves fixed to the MQL. A tube with the Hall probe was polished and lapped to sleeves. However, this design caused difficulties in linear positioning and was not easy to use. Moreover, the accuracy of the employed positioning modules did not satisfy requirements resulting from the numerical simulation.

Based on the calculated requirements to the positioning system a new setup to investigate the field of the magnetic quadrupole lens was developed. A layout of the setup is shown in Fig. 1.

The Hall probe **1** is mounted on the lateral surface of the tube **2** made of nonmagnetic material that passes through the working gaps of the magnetic quadrupole lenses **3** under study. The tube can be rotated about its axis by means of an angular positioning module **4** and moved along its axis by means of a linear positioning module **5** driven by stepper motors. In this case the Hall probe traverses the cylindrical surface sensing the magnetic induction vector component normal to this surface. A general view of the setup is presented in Fig. 2.

A precision magnetic field sensor AD22151 [13] with a linear output, outline dimensions of $6.2\times5\times1.75$ mm^3 and a sensitivity

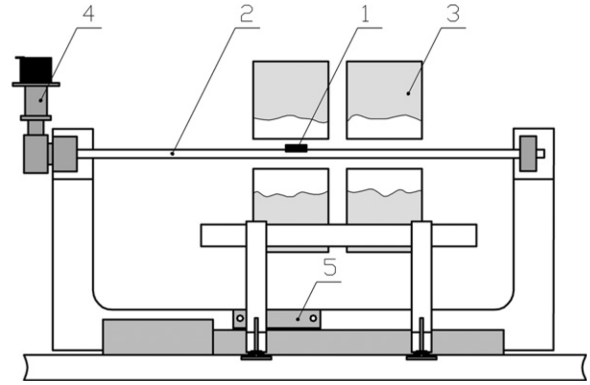

Fig. 1. Layout of the setup to investigate the MQL field.