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A high excitation magnetic quadrupole lens quadruplet incorporating a single octupole lens for a low spherical aberration probe forming lens system

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ABSTRACT

This paper describes the design of a new probe forming lens system consisting of a high excitation magnetic quadrupole lens quadruplet that incorporates a single magnetic octupole lens. This system achieves both a high demagnification and a low spherical aberration compared to conventional high excitation systems and is intended for deployment for the Harbin 300 MeV proton microprobe for applications in space science and ion beam therapy. This relative simplicity of the ion optical design to include a single octupole lens minimizes the risks associated with the constructional and operational precision usually needed for the probe forming lens system and this system could also be deployed in microprobe systems that operate with less magnetically rigid ions. The design of the new system is validated with reference to two independent ion optical computer codes.

1. Introduction

The 300 MeV proton microprobe system proposed by the Space Environment Simulation Research Infrastructure (SESRI) in Harbin, is under developing for many applications in space science and ion beam therapy. Applications include upset studies in microelectronic devices [1], radiation hazards in space [2], radiation affects in human tissues [3] and other applications where a high energy proton microprobe can be usefully employed [4].

The main challenges of a 300 MeV proton microprobe based on a synchrotron accelerator are [5,6]:

1. Long penetration depth in collimator materials (about 50 mm in tungsten);
2. Plenty of scattered particles and secondary particles;
3. Large beam rigidity (2.7 Tm);
4. Low brightness and large energy spread of the synchrotron beam compared with electrostatic accelerators for MeV ions.

These challenges have been previously addressed [7–9] but further optimization is possible. The first two points require a suitable collimation system to stop scattered protons and secondary particles in order to shape the beam and protect downstream devices. As reported previously [7], Geant4 simulations show a novel collimation system incorporating a bending magnet significantly reduces the downstream scattering of protons and the secondary particles. The last two points require a suitable focusing-lens system, which has a strong focusing ability and large acceptance. Strong focusing can be achieved with a high excitation probe forming lens system in which the ion trajectories have one or more axis cross-overs within the system. In the previous research [8,9], both a separated Oxford triplet system and a separated Russian quadruplet system achieve the goals without using superconducting elements. However, the quality of a nuclear microprobe is also affected by other parameters [10–12] such as intrinsic aberrations and parasitic aberrations. This paper shows a significant further optimization is possible.

There are three main types of aberrations present in a quadrupole focusing system [13]:

1. Chromatic aberration (due to variation in the beam energy);
2. Parasitic aberrations (due to mechanical imperfections in the elements);
3. Spherical aberration (due to off-axis magnetic field effects)

Each of these aberrations are now discussed in turn.

As already pointed out [12] the chromatic aberration of a beam particle is determined by the product of its energy and angular divergences. Hence second-order ion optics calculations that assume a uniform beam phase space will overestimate the chromatic aberration since only a small proportion of the beam particles passing through the

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collimators have both a large angular and energy divergence as is the case for electrostatic accelerators. In the case of a synchrotron accelerator a careful measurement of the beam particle intensity distribution is needed to determine the likely significance of chromatic aberration. It is also possible to correct the chromatic aberration by a sextupole lens or by the use of achromatic quadrupole lenses consisting of superimposed magnetic and electrostatic elements. The latter approach is not suitable for 300 MeV protons because of impractically large electric fields required. However the former approach is being investigated by the present author and the design of an achromatic microprobe system with sextupole lenses is under development and the results will be published in the future.

Parasitic aberrations can also be reduced in principle by careful construction and alignment of the quadrupole lenses [14]. For example the wire-cut, single piece, iron yoke for magnetic quadrupole lenses led to a step-change improvement in current-spot-size performance of microprobe in 1991 [15]. This method of manufacture essentially eliminates the quadrupole lenses from all detectable traces of parasitic multipole fields [16]. In our proposed system, the manufacture of long magnetic quadrupole lenses (length 0.3 m) with very low parasitic fields has not yet been demonstrated. However, provided the usual alignment precision can be achieved, the long magnetic quadrupole lens can be divided into two identical short high precision quadrupole lenses. For example we have demonstrated that two 0.1 m length quadrupole lenses with a drift can replace the 0.3 m quadrupole lens in our proposed 300 MeV proton microprobe system [17].

The spherical aberration is a particular problem for high excitation lens systems such as we propose owing the substantial excursion off axis of the ion trajectories within the lens fields. However spherical aberration can be corrected with three magnetic octupole lenses at the cost of considerable increase in complexity in the fabrication and operation of the system. The operational complexity arises from the need for very precise adjustment of the octupole lens field strengths to correct the aberration. Small errors will introduce very large additional aberration that defeats the purpose of correction. However there are two main motivations to explore a correction of spherical aberration in the 300 MeV proton microprobe system proposed here. First, the separated Russian quadruplet (HIT-4) system, with equal demagnifications in the two mutually perpendicular planes, is limited by a single large spherical aberration coefficient ($< x|\theta^3 >$). This is an unusual attribute compared to other high excitation systems, such as the separated Oxford triplet (HIT-3) system [8] where all three independent spherical aberration coefficients have a similar magnitude. It is therefore possible to employ a single octupole lens to minimize the spherical aberration in the high excitation quadruplet system without the complexity of incorporating three octupole lenses needed to fully correct the spherical aberration. Second, the 300 MeV proton microprobe system can simply increase the demagnification further by reducing the working distance, which usually results in a higher spherical aberration. The correction of spherical aberration can be useful to achieve a smaller spot size when the working distance is reduced.

In this paper, we investigated the correction of spherical aberration in both HIT-3 system and HIT-4 system. An improved correction method of spherical aberration was developed to raise the accuracy of calculation. This allowed us to discover a high excitation microprobe system that can be substantially corrected by just one octupole lens.

2. Method

This paper defines that ions move along the z axis (i.e. the beam axis) where x, y and z form a left-handed coordinate system, and θ and φ are the divergences of the ion projected onto the xoz and yoz planes respectively. Spherical aberration is usually characterized by terms of the coefficients $< x|\theta^3 >$, $< x|\theta\varphi^2 >$, $< y|\varphi^3 >$ and $< y|\theta^2\varphi >$ [18]. The spherical aberration coefficients are introduced into the system by multipole fields equivalent to that of an octupole lens [19]. If octupole lenses are present in a focusing-lens system then the spherical aberration coefficients may be written as [14]:

$$\langle x|\theta^3\rangle = \langle x|\theta^3\rangle^q + \langle x|\theta^3\rangle^o$$

$$\langle x|\theta\varphi^2\rangle = \langle x|\theta\varphi^2\rangle^q + \langle x|\theta\varphi^2\rangle^o$$

$$\langle y|\varphi^3\rangle = \langle y|\varphi^3\rangle^q + \langle y|\varphi^3\rangle^o$$

$$\langle y|\theta^2\varphi\rangle = \langle y|\theta^2\varphi\rangle^q + \langle y|\theta^2\varphi\rangle^o$$

where the superscripts *q* and *o* represent coefficients contributed by the quadrupoles and octupoles respectively. Because the cross terms of spherical aberration ($< x|\theta\varphi^2 >$ and $< y|\theta^2\varphi >$) are related in a simple equation in stigmatic quadrupole lens systems, Scherzer showed that three independent octupole lenses are needed to fully correct the spherical aberration of a quadrupole lens system [14].

Correction of spherical aberration in a magnetic quadrupole quadruplet lens system was developed and summarized by Jamieson, including the details of equations and theory about the spherical aberration coefficients contributed by a quadrupole lens, an octupole lens and a system of several lenses derived by Dymnikov [14] in the thin lens model. The equations were incorporated into the matrix method computer program: PRAM (Propagate Rays and Aberrations with Matrices) [20] with the modification that PRAM employs the thick lens focal length instead of the thin lens focal length in Dymnikov's original equations. PRAM also includes an algorithm for numerical optimization of the results calculated by the analytical method. However, the analytical derivation of the equations for the spherical aberration coefficients includes several approximations and in-principle a more accurate numerical calculation can be performed with WinTRAX (raytracing beam optics software for Windows) [21] that avoids the approximations at the cost of greater computational overheads. WinTRAX can also employ an experimental profile for the fringe field of the lenses which is difficult to model analytically. To compare the analytic and numerical approaches, we calculated the spherical aberration coefficient $< x|\theta^3 >$ for two types of quadrupole lenses: Oxford Microbeams OM50 and OM52 with three methods: thin lens model, PRAM and WinTRAX. For these lenses the pole tip field was set to 0.2 T with the object distance at 5 m with a proton beam of energy 3 MeV. The effective length of OM50 is 0.108 m, and the effective length of OM52 is 0.057 m. Further mechanical and other details of the OM50 and OM52 lenses can be found in [22].

The results are shown in Table 1 for the spherical aberration coefficient calculated at the Gaussian image plane in the xoz direction. If we assume the numerical method from WinTRAX has the greatest accuracy then PRAM improves the accuracy of the analytical calculation compared to the thin lens focal model used by Dymnikov in the case of OM50. However, for the actual thin lens OM52 the agreement is worse. The precise reasons for this require further investigation.

To guard against short-comings of our models, we developed an improved correction method of spherical aberration, which combines the efficiency of matrix method and the accuracy of ray-tracing method. The matrix method (PRAM) was used to analyze trends in the spherical aberration as a function of the position and strength of a single octupole correction lens, then the ray-tracing method (WinTRAX) was used to optimize the system.

We first explored the variation of spherical aberration coefficients

Table 1
The spherical aberration coefficient $< x|\theta^3 >$ in the two types of quadrupole lens calculated with the three method. See the details in the text.

	Thin lens model	PRAM	WinTRAX
OM50	−5.62	−3.65	−3.88
OM52	−2.54	−8.04	−3.78

Units: x and y in μm; θ and φ in mrad.