Optimal Parameters of High Energy Ion Microprobe Systems Comprised of Lafayette Lenses

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Abstract. High energy optimal ion microprobes comprised of new compact magnetic quadrupole lenses (Lafayette Quadrupole Lens) are numerically investigated. The smallest beam spot size and appropriate radii of object and divergence slits are presented for different emittances and compared with the corresponding parameters of the Oxford triplet for the same total length. The parameters of the calculated microprobes include demagnification, the magnetic field in the lenses and the coefficients of spherical and chromatic aberrations for several quadrupole system configurations including the doublet, the Lafayette symmetric triplet, the Russian magnetic quadruplets and sextuplets.

Keywords: Ion microprobe; Quadrupole lens; Spherical aberration; Chomatic aberration;Doublet; Triplet; Russian quadruplet.
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INTRODUCTION

In a nuclear microprobe the focusing system is an essential component which determines the beam spot size, i.e. the microprobe resolution, which depends on the spherical and chromatic aberrations. A small beam cross section at the target is the most important of the many conflicting requirements imposed on the beam. Focusing of ion beams of MeV energy is mostly accomplished by magnetic quadrupole lenses in different configurations: doublet, triplet, quadruplet and quintuplet. The most popular systems are the Oxford triplet (OT) and Russian quadruplet (RQ). Using the object and divergence slits we can find for every emittance the optimal size of slits which give the minimum spot size for a given system.

All possible configurations of lenses for the same total length (the distance from the object slit to the target) and for a different length of lenses have different aberrations, demagnifications and magnetic fields on the poles of the quadrupole lenses. In this paper we compare the coefficients of the spherical and chromatic aberrations, demagnifications and magnetic fields for different configurations of quadrupole lenses for two lenses: the Oxford magnetic lens with 0.1 m length and 0.0075 m lens aperture and the Lafayette magnetic lens with 0.04 m length and 0.0035 m lens aperture.

OPTIMIZATION AND NOTATIONS

We have performed the special program of optimizing analytical and numerical calculations to obtain the best design for our system. Beam focusing is understood as the result of non-linear motion of a set of particles [1-3]. As a result of this motion, we have the beam spot on the target. The set has a volume (the phase volume, or emittance). For a given brightness, the phase volume is proportional to the beam current and *vice versa*. The beam has an envelope surface. All particles of the beam are located inside of this surface, inside of this beam envelope. For the same phase volume (or beam current) the shape of the beam envelope can be different. We say the beam envelope is *optimal* if the spot size on the target has a *minimum* value for a given emittance. The beam of a given

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emittance em_{xy} ($em_{xy} \equiv em_x em_y$) is defined by a set of two matching slits: objective and divergence slits. For a given emittance em_{xy}, the shape of the beam envelope is the function of the half-widths r_{1x} and r_{1y} of the objective slit and of the distance l_{12} between two slits. The half-widths r_{2x} and r_{2y} of the second (divergence) slit are determined by the expressions: $r_{2x} \equiv \frac{em_x l_{12}}{r_{1x}}$, $r_{2y} \equiv \frac{em_y l_{12}}{r_{1y}}$. The optimal parameters r_{1x}, r_{1y}, r_{2x}, r_{2y} and l_{12} determine the optimal beam envelope or the optimal matching slits [4].

The probe-forming system consists of two systems: the matching slit system and the focusing system. In many cases the focusing system has two field parameters (two excitations) and several parameters of its geometry. The two conditions of stigmatism determine two excitations as a function of the geometry. For a given geometry and for a given emittance we can find the corresponding optimal matching slits. The geometry, which gives the possibility to obtain a smallest spot size, is the optimal geometry. For this geometry and for the optimal matching slits we find the optimal excitations giving the minimum spot size. The optimal probe-forming system comprises the optimal excitations, optimal matching slits and optimal geometry. For any given emittance we find the parameters of the optimal probe-forming system. We consider the non-linear motion of the beam accurate to terms of 3rd order.

All geometry notations are shown in Fig.1. We use the following notations for the distances in a system of n quadrupole lenses: s_j is the effective spacing between the j-th lens and (j+1)-th lens; l_j is the effective length of the j-th lens; a is the effective object distance (the effective distance between the object slit and the first lens); g is the effective working (or image) distance; l_t is the total length of the system (the distance between the object and the image). The demagnifications in the xoz and yoz planes are d_x and d_y, respectively.

An ion optical system of minimum focal length must be used to obtain a microprobe with maximum decrease of the beam diameter. The lower limit on the focal length is determined by the lowest attainable boundary of working distance g and the smallest possible lens length and probe length. The lower limit on the lens length is determined by the maximum possible magnetic induction at a pole or field strength at an electrode and by the lens construction.

Taking into account chromatic and spherical aberrations, assuming that $r_2 >> r_1$, we can write down an approximate expression for the absolute value of the beam half-width x_e at the target for $y_0 = 0$ and $y'_0 = 0$:

$$|x_e| = \left|\frac{x_{0\max}}{d_x}\right| + |C_{px}||\delta_E||x'_{0\max}| + |C_{sx}|(|x'_{0\max}|)^3$$

(1)

(1)

or

$$|x_e| = \frac{em_x}{|x'_e|} + |c_{px}\delta_E||x'_e| + |c_s||x'_e|^3 \qquad (2)$$

Here

$$c_{px} = C_{px} / d_x, \quad c_{sx} = \frac{C_{sx}}{d_x^3}, \quad x'_e = d_x x'_0, \quad \delta_E = \frac{\Delta E}{E}$$

(3)

We use the following notations:

C_{sx} and C_{sy} are the spherical aberration coefficients in the object space;

C_{px} and C_{py} are the chromatic aberration coefficients in the object space;

em_x and em_y are the emittances of the beam in the x- and y- planes;

c_{px} and c_{py} are the chromatic aberration coefficients in the image space in the x- and y- planes;

c_{sx} and c_{sy} are the spherical aberration coefficients in the image space in the x- and y- planes;

x'_e and y'_e the divergences in the image space.

DIFFERENT TWO PARAMETRIC CONFIGURATIONS OF QUADRUPOLE LENSES

Focusing of ion beams of MeV energy until now is mostly accomplished by magnetic quadrupole lenses in different configurations: doublet, triplet, quadruplet, quintuplet and sextuplet.

In many cases the focusing system has two field parameters (two excitations) – two parametric focusing system. The simplest two parametric quadrupole system is a doublet. The second simplest two parametric focusing system after doublet configuration is a two parametric triplet. There are two different configurations of this triplet.

The first one is the Oxford configuration. In this triplet focusing and defocusing capabilities of the lenses in one plane alternate F-D-F whereas the lens strengths are ordered as A-A-B.

The second two parametric triplet has the Lafayette configuration. In this configuration focusing and defocusing capabilities of the lenses in one plane also alternate F-D-F whereas the lens strengths are ordered as A-B-A. Both configurations are considered with equal lenses ($l_1 = l_2 = l_3 = l$) and drift spaces s_1 and s_2.

The next two parametric focusing system is the Russian quadruplet with $l_3 = l_2$, $l_4 = l_1$, $s_3 = s_1$. In this quadruplet focusing and defocusing capabilities of the lenses in one plane alternate F-D-F-D whereas the lens strengths are ordered as A-B-B-A.

Two triplets form a two parametric Russian sextuplet [5]. In this sextuplet focusing and defocusing capabilities of the lenses in one plane alternate F-D-F-D-F-D whereas the lens strengths are ordered as A-B-A-A-B-A.

NUMERICAL RESULTS

The results of calculations for the main parameters of the doublet (s_1 = 2.5cm), the Lafayette configuration of a nonseparated (s_1 = s_2 =2.5cm) and separated (s_1 = 2.9m, s_2 = 2.5cm) triplet, Russian nonseparated (s_1 = s_2 = s_3 = 2.5cm) and separated (s_1 = s_3 = 2.5cm, s_2 = 5m) quadruplet and separated (s_1 = s_2 = s_4 = s_5= 2.5cm, s_3 = 2.8m) sextuplet comprised from Lafayette lenses are shown in Tables 1, 2 and 3. For the comparison in the Table 1 the same parameters of the Oxford triplet (s_1 = s_2 =6cm) are given. All considered systems have the same total length l_t = 6.25 *m* and the same working distance $g = 0.18\ m$.

From the Table 1 it follows that all coefficients of spherical and chromatic aberrations of all investigated systems comprised from Lafayette lenses are approximately the same and significantly less than the appropriate maximum coefficients of the Oxford triplet.

Optimal slits and appropriate spot size for a few systems and for the emittance $em_{xy} = 10^{-18}\ m^2$ are given in the Table2.

In the Table 3 optimal slits and appropriate spot size for a few systems are given for the emittances at which the minimum width of one of the object slits is approximately 1 μm.

TABLE 1. Demagnifications, coefficients of spherical and chromatic aberration and magnetic fields on the poles of lenses for the focusing systems comprised from Lafayette magnetic quadrupole lenses

Systems	d_x	d_y	c_{sx} [m]	c_{sy} [m]	c_{px} [m]	c_{py} [m]	B_1 [kgs]	B_2 [kgs]
Oxford triplet	68.81	-20.24	0.5846	130.75	-0.218	-1.894	1.818	1.925
Focusing systems comprised from Lafayette magnetic quadrupole lenses.								
Doublet	-13.82	-49.01	20.95	1.468	-0.460	-0.125	1.801	2.379
Nonseparated Lafayette triplet	-18.87	-24.59	5.966	20.35	-0.218	-0.344	1.488	2.698
Separated Lafayette triplet	783.1	-287.7	1.503	22.44	-0.129	-0.482	2.420	1.850
Nonseparated Russian quadruplet	-19.48	-19.48	13.34	22.96	-0.275	-0.331	0.878	2.341
Separated Russian quadruplet.	65.15	65.15	21.33	1.478	-0.467	-0.128	2.391	1.812
Separated Russian sextuplet	106.6	106.6	22.10	6.004	-0.368	-0.229	1.543	2.773

TABLE 2. Focusing systems comprised from Lafayette magnetic quadrupole lenses. Slits and spot size for $em_{xy} = 10^{-18}$ m^2.

Systems	r_{1x} [µm]	r_{1y} [µm]	r_{2x} [µm]	r_{2y} [µm]	$\left\|x'_{e\max}\right\|$ [mrad]	$\left\|y'_{e\max}\right\|$ [mrad]	r_x [µm]	r_y [µm]
Doublet	4.962	17.60	133.3	91.11	1.788	4.336	0.42	0.60
Nonseparated Lafayette triplet	8.047	10.48	157.1	80.08	2.877	1.912	0.55	0.50
Nonseparated Russian quadruplet	9.326	9.326	120.9	100.9	2.287	1.908	0.58	0.60
Separated Russian quadruplet.	23.5	23.5	28.13	68.48	1.779	4.331	0.60	0.70

TABLE 3. Focusing systems comprised from Lafayette magnetic quadrupole lenses. Slits and spot size.

Systems	r_{1x} [µm]	r_{1y} [µm]	r_{2x} [µm]	r_{2y} [µm]	$\left\|x'_{e\max}\right\|$ [mrad]	$\left\|y'_{e\max}\right\|$ [mrad]	r_x [nm]	r_y [nm]
Doublet, $em_{xy} =$ $= 2.2\ 10^{-21}$	0.5001	1.774	62.03	42.41	0.832	2.018	58	50
Nonseparated Lafayette triplet, $em_{xy} = 10^{-21}$	0.6034	0.7861	66.23	33.77	1.213	0.806	40	40
Separated Lafayette triplet, $em_{xy} = 10^{-24}$	1.600	0.588	1.010	1.117	0.768	0.312	7.0	3.0
Nonseparated Russian quadruplet, $em_{xy} = 10^{-21}$	0.699	0.699	50.98	42.55	0.964	0.805	45	45
Separated Russian quadruplet. $em_{xy} =$ $= 3.5\ 10^{-23}$	0.501	0.501	7.801	18.99	0.493	1.201	9.0	12
Separated Russian sextuplet, $em_{xy} =$ $= 6\ 10^{-24}$	0.506	0.506	4.011	6.193	0.415	0.641	6.0	6.0

CONCLUSIONS

The smallest beam spot size and appropriate radii of object and divergence slits of high energy ion microprobe systems comprised of Lafayette lenses are obtained for different emittances and compared with the corresponding parameters of the Oxford triplet for the same total length.

Separated Lafayette triplet and separated Russian quadruplet and sextuplet must be used if we want to obtain spot size less in the range 100nm×100nm – 15nm×15nm.

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