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Obtaining 1–10 nm optimal beam spot size in the magnetic quadrupole nanoprobe

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ABSTRACT

Focusing of high energy charged particles in an octuplet lens system comprised of two Russian quadruplets, defined as the Lafayette Octuplet, is investigated. This octuplet is a zoom system having the same demagnifications, the same focal lengths, and the same positions of the focal points in *xz* and *yz* planes as the Russian quadruplet.

In this study the matrix method of embedding in the space of the phase moments is used to solve the non-linear equations of motion. With this method all the advantages of the linear differential equations are used, including the independence of the matrizant of the non-linear motion on the choice of the initial point of the phase space. For the same phase volume (or beam current) the spot size is minimized (optimized) by a set of two optimal matching slits: objective and divergence slits. This optimal spot size is a function of the four-dimensional emittance and both geometric and optical parameters of the system. Geometric parameters include total system length, lens lengths, drift spaces, object and working distances, minimum attainable slit openings while optical parameters include demagnifications, spherical and chromatic aberrations. The optimal beam spot size and appropriate optimal slits have been found as functions of the emittance of the system for different geometries. It is shown that the octuplets investigated here allow the possibility to obtain 1–10 nm optimal beam spot sizes. The influence of the beam energy spread on the optimal beam spot size is studied.

1. 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 accomplished by magnetic and electrostatic quadrupole lenses in different configurations: doublet, triplet, quadruplet, quintuplet and sextuplet.

In this paper we consider how to obtain the microprobe nanometer resolution with the quadrupole systems comprised of the Lafayette magnetic lenses with 0.04 m length and 0.0035 m lens aperture.

2. Optimization and notations

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 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.

The probe-forming system with one image 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.

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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.

In this paper two probe-forming systems with two images and with the same working distance g_1 = 18 cm (the distance from the last lens to the position of the image plane) are numerically investigated. Both of them consist of two Russian quadruplets and three slits. The length of each used magnetic lens is the same. In both nanoprobes the first Russian quadruplet and the first two slits are the same. The goal of the first Russian quadruplet and the first two slits is to obtain the first image with the 10 nm spot size at very short first working distance g_{11}, where g_{11} is the distance between the first image plane and the last lens of the first quadruplet. The goal of the second quadruplet in the first probe-forming system is to obtain the second image with the 10 nm spot size at the working distance g_1, where g_1 is the distance between the working plane of the first microprobe and the last lens of the second quadruplet. The goal of the second quadruplet in the second nanoprobe is to obtain the second image with the 1 nm spot size at the same working distance g_1. All geometry notations are shown in Fig. 1. We use the following notations:

l_{12} is the distance between the first and second slits,
s_0 is the effective object distance (the effective distance between the object slit and the first lens);
s_j is the effective spacing between the jth lens and (j + 1)th lens, $j \neq 4$;
l_j is the effective length of the jth lens;
g_1 is the effective first image distance;
s_4 is the effective distance between the plane of the first image and the 5th lens;
l_{34} is the distance between the plane of the first image and the third slit,
g is the effective second image distance or the effective working distance of the nanoprobe;
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;
x'_0 and y'_0 the divergences in the object space;
d_x and d_y are demagnifications in the x- and y-planes respectively;
$\delta_E = \frac{\Delta E}{E}$ is the energy resolution of the beam;
l_t is the total length of the system (the distance between the object and the image).

There are the following relations between some of these values:

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

In our case $l_1 = l_2 = l_3 = l_4 = l_5 = l_6 = l_7 = l_8 = l$ = 4 cm, $s_1 = s_3 = s_5 = s_6 = s_7$. In the first nanoprobe s_4 = g and in the second nanoprobe $s_4 > g$, where $g = 18$ cm.

3. The first quadruplet

The value of the optimal spot size is proportional to the value of the four dimensional emittance. We also must avoid the scattering from the slits. In this paper for $l_{12} = 1.5$ m and $g_1 = 3$ cm we take the following radii of the slits and the corresponding emittance in the first quadruplet:

$$r_{1x} = r_{1y} = 2.56 \text{ mkm}, \quad r_{2x} = 1.64 \text{ mkm}, \quad r_{2y} = 8.43 \text{ mkm}, \quad em_{xy} = 4 \times 10^{-23} \text{ m}^2.$$

As a result we obtain for the energy of particles 3 MeV the radius of the monochromatic beam spot size $r_x \approx r_y \approx 5$ nm at the working distance $g_1 = 3$ cm.

This quadruplet has the following parameters:

$$d_x = d_y = 606.5, \quad C_{px} = -168.6 \text{ m}, \quad C_{py} = -14.77 \text{ m},$$
$$c_{px} = -0.2781 \text{ m}, \quad c_{py} = -0.0244 \text{ m}$$

$$l_t = 4 \text{ m}, \quad c_{sx} = 4.862 \text{ m}, \quad c_{sy} = 0.0355 \text{ m},$$
$$c_{sxy} = c_{syx} = 0.5872 \text{ m}$$

4. The second quadruplet

The image obtained in the first quadruplet is the first image in the nanoprobe which is considered as the object for the second quadruplet. The size of the first image in the nanoprobe is considered as the size of the virtual first slit in the second quadruplet. The third slit of the nanoprobe is the second slit in the second quadruplet. This slit gives the possibility to change the initial four dimensional emittance of the first quadruplet. That means the four dimensional emittance in the nanoprobe in the first and in the second quadruplets is different. The distance between the plane of the first image and the third slit is denoted as l_{34}.

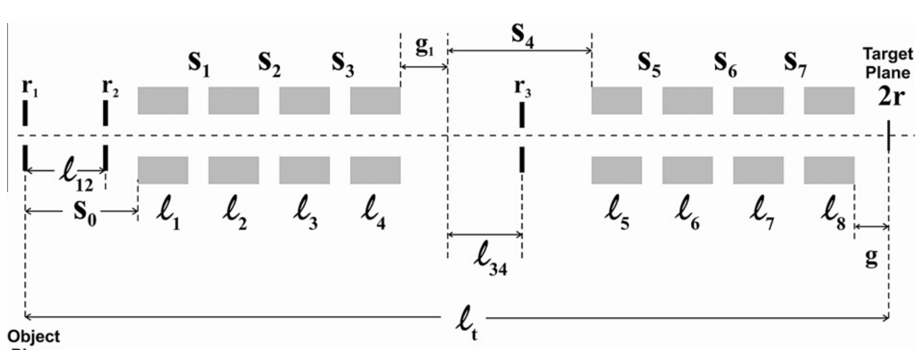

Fig. 1. The geometry notations in the nanoprobe consisting of two different quadruplets.