Theoretical Study to Calculate the Focal length of Focusing System from Plasma Source

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Abstract

Optical properties of ion beam passing through the quadruple magnetic lens focusing system are discussed. The study included theoretical analysis using matrices representation to calculate the focal length, lens power, effective length and displacement (the bandwidth envelope) for Horizontal and Vertical plane. Results showed the increasing in effective length caused decreasing in focal length of the system for horizontal and vertical plane, the opposite action appeared with lens power. Furthermore the increasing in effective length caused decreasing in Horizontal displacement (beam envelope) for horizontal plane, the opposite action appeared for vertical plane.

Key Words: Focusing systems, Focal length, Magnetic lens, Quadrupole Magnet

دراسة نظرية لحساب البعد البؤري لمنظومة تبئير من مصدر بلازما

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المستخلص

تمت مناقشة الخصائص البصرية لحزمة ايونات لمنظومة تبئيير عدسة مغناطيسية رباعية. شملت الدراسة التحليل النظري باستخدام تمثيل المصفوفات لحساب البعد البؤري، قدرة العدسة، الطول المؤثر والازاحة (عرض الحزمة) للمستويين الأفقي والعمودي. أظهرت النتائج ان الزيادة في الطول المؤثر يسبب تناقص في البعد البؤري للمستويين العمودي وأفقي، يظهر العكس مع قدرة العدسة. اضافة الى ذلك، زيادة الطول المؤثر يسبب تناقص في الازاحة الافقية (عرض الحزمة) ، يظهر العكس بالنسبة للمستوى العمودي.

Introduction

At the end of nineteenth century, it was found that an axially symmetric magnetic field has a focusing effect on charge particles beam in a cathode ray oscillograph, it acts as a lens. The effect is similar to that of a glass lens on light. This effect was first investigated by Busch in 1926, both theoretically and experimentally by Cosslett [1]. An ion beam transport system consists of focusing, deflection and often additional energy or momentum selection elements. Most often these devices are magnetic elements. To provide focusing in transverse plane quadrupol is used. [2]. A charged particle is an elementary particle or a macroparticle which contains an excess of positive or negative charge. Its motion is determined mainly by interaction with electromagnetic forces [3]. Focusing systems of most installations of particle-beam technology are really intended for beam focusing, that is, obtaining a very small beam cross section (point focusing). While focusing a system of linear beam microwave tubes (klystrons, traveling-wave tubes, etc.) should provide transport of particle beams through extended channels with minimum beam-current loss. In this case their name does not correspond to their function. This is why they also can be named as transport systems, as is commonly done for the accelerator technique [4]. New types of focusing systems, such as quadruple lenses, edge focusing in sector-shaped magnets, alternating gradient focusing, and so on, were invented and contributed to the successful development of plasma physics with steadily increasing energies and improving performance characteristics [5]. Applying the formalism of geometric optics the quadruple magnetic lens can be described as a thin focusing lens [6]. The current research aims to study the focal length of quadrupole magnet system to get the best values that leading to minimum band width or best focusing which is achieved in more control on beam transport systems.

Ion Source

The source consists of the front plate of the ion source, which is known as the plasma electrode, and at least one other electrode, the puller electrode, which provides the electric field for accelerating the charged particles from the ion source to form an ion beam. The ion source voltage is therefore set according to the requirements of the subsequent application. The intensity of the particle beam depends, as a first approximation, on the flux of charged particles hitting the plasma electrode aperture. The emitting plasma surface area has a concave shape, which depends on the plasma density and the strength of the accelerating electric field at the plasma surface [7, 5].

Ion Optical System Focusing

A natural source of ions is considered to be a gas -discharge plasma. An arc type discharge with a hot cathode is usually utilized as the source of ions [4]. The beam behavior and the transformation properties can be described in an analogous way to light optics. As in light optics, a space in which a beam propagates without any forces acting on beam particles, i.e. a field free region is called drift space. In this space, beam particles maintain their direction of motion, i.e. a divergent or parallel beam remains divergent or parallel [8]. Similar to the properties of light rays, particle beams also have a tendency to spread out due to an inherent beam divergence. The characteristic property of such focusing lenses is that a light ray is deflected by an angle proportional to the distance of the ray from the center of the lens. With such a lens a beam of parallel rays can be focused to a point .To keep the particle beam together and to generate specifically desired beam properties at selected points along the beam transport line, focusing devices are required [9]. The most suitable device that provides a material free aperture and the desired focusing field is called a quadrupole magnetic lens [10, 11]. There are two other common terms applied to lenses, the lens power and the focal lengths. The strength of a lens is determined by how much it bends orbits. Shorter focal lengths mean stronger lenses. The lens power P is the inverse of the focal length, P = 1/f. If the focal length is measured in meters, the power is given in m^{-1} or diopters. The focal length is important for describing focusing of nonlaminar beams. It characterizes different optical systems in terms of the minimum focal spot size and maximum achievable particle flux. If the principal planes and focal lengths of a lens are known, the transformation of an orbit between the lenses entrance and exit can be determined [3].

Quadrupole Magnet Lenses

A magnetic lens is a device for the focusing or deflection of moving charged particles, such as electrons or ions. Its strength can often be varied by usage of electromagnets. Magnetic lenses are used in diverse applications, from cathode ray tubes over electron microscopy to particle accelerators. A magnetic lens typically consists of several electromagnets arranged in a quadrupole, sextuple, or higher format, the electromagnetic coils are placed at the vertices of a square or another regular polygon. From this configuration a customized magnetic field can be formed to manipulate the particle beam [12]. Magnetic lenses are widely used to control beams of charged particle with various energy and directions in several fields. Therefore their focal properties have been extensively studied theoretically and also experimentally. The simplest magnetic lens is a donut-shaped coil through which the beam passes, preferably along the axis of the coil [1, 13]. A quadrupole is a magnetic element that has four poles, two norths and two souths. They are symmetrically arranged around the centre of the magnet. There is no magnetic field along the central axis [14]. These magnets are used to focus the particle beam. In quadrupole magnet the field lines all cancel each other out at the centre of the quadrupole so a particles beam feels no force as it passes through the centre. It can be seen that while the particles beam is being focused in the vertical direction it is simultaneously being defocused in the horizontal direction [5, 9]. Consequently two different types of quadrupole have to be used, first type in (horizontal – vertical) plane and the other is the same thing rotated through (90 degree). This rotated version will cause the particles beam to be focused in the horizontal plane and defocused in the vertical plan. When arranged correctly a series of quadrupole can lead to net focusing in both planes [15]. Generally, quadrupoles, which focus in the horizontal plane are often referred to as focusing quadrupoles (QF) whereas quadrupoles which focus in the vertical plane are often referred to as defocusing quadrupoles (QD) [14]. Its field, concentrated between the four magnetic poles. In order to keep the beam confined in both transverse planes, it is necessary to have a sequence of quadrupoles with alternate polarity [16]. The quadrupole magnet lens converts the orbit vector ui = (x_i, x_i') into the vector u_f = (x_f, x_f'). The components of u_f are linear combinations of the components of ui. The operation can be written in matrix notation $u_f = A_F\, u_i$ [3]; if A_F is taken as:

$$A_F = \begin{bmatrix} \cos(L\sqrt{k}) & \sin(L\sqrt{k})/\sqrt{k} \\ -\sqrt{k}\sin(L\sqrt{k}) & \cos(L\sqrt{k}) \end{bmatrix} \qquad \text{...........(1)}$$

where the subscript F denotes the focusing direction.

If the poles of quadrupole magnet are rotated 90^{o}, the lens defocuses in the other direction. The transfer matrix in this case is:

$$A_D = \begin{bmatrix} \cosh(L\sqrt{k}) & \sinh(L\sqrt{k})/\sqrt{k} \\ -\sqrt{k}\sinh(L\sqrt{k}) & \cosh(L\sqrt{k}) \end{bmatrix} \qquad \text{..............(2)}$$

where the subscript D denotes the defocusing.

The two main parameters that show in equation (2) are *k* and *L*, where *L* represented the effective length of quadrupole magnet (in metre) and *k* represented the strength focusing factor (in m^{-2}) [15, 17]. The thin lens approximation is done by making the (kL) small and by keeping the first term of Taylor series for the cosine and sine. The matrix then takes the form

$$A_q = \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \qquad \text{………… (3)}$$

Where f is the focal length, in case of quadruple given by [9, 18]

$$1/f = kL \qquad \text{……….. (4)}$$

Results and Discussion

In this study Matlab program build to study the effect of main parameter of quadrupole magnet lens. The main parameters effect on the behavior of charged particles beam passing through a system of quadrupole magnet can be fixed, these parameters are k (strength focusing factor), and the effective length (L) which the product of these two parameter gives us the inverted focal length of the lens magnetic. So any changing in the one of these parameters gives different lens which means new beam profile. In this study the action of quadrpole magnet lens as focusing or defocusing elements in horizontal plane or in vertical plane this effect was calculated using a computer program that has been built for this purpose (see table 1) which indicates the focal length, lens power and displacement for horizontal and in vertical axis for different values of effective length we note in it when the increasing in effective length causes decreasing in focal length for horizontal and vertical plane, the opposite action appears with lens power.

Figure 1 illustrate the focal length as a function of effective length for horizontal and vertical axis, the best focus occurs for high values of L which means good focusing properties of quadruple magnet as thin lens where shorter focal lengths mean stronger lenses [3]. While Figure 2 notes that the relationship is extrusive, an increase of effective length value increases the power of the lens because the lens power is the inverse of the focal length. Figure 3 and 4 indicate the relation of horizontal and vertical displacement as a function of focal length respectively. In two forms note that the horizontal displacement (beam envelop) increases with increased focal length, that means there is a focusing for charged particle beam in horizontal plane while opposite action appears in vertical plane.

Table (1): The Focal Length, Lens power and displacement for x and y axis for different values of Effective Length

Effective Length L mm	Focal Length for x-axis f_x mm	lens power for x-axis P_x mm^{-1}	Focal Length for y-axis f_y mm	Lens power for y-axis P_y mm^{-1}	Horizontal displacement x mm	Vertical displacement y mm
100	2.40	0.41	10.00	0.10	17.42	10.69
200	1.22	0.83	5.03	0.19	15.74	11.23
300	0.83	1.20	3.12	0.32	12.95	11.90
400	0.61	1.63	2.40	0.41	11.87	12.72
500	0.50	2.01	2.00	0.50	10.99	13.68
600	0.42	2.45	1.51	0.66	9.46	14.79
700	0.35	2.83	1.43	0.69	8.96	16.06
800	0.31	3.20	1.26	0.78	6.86	17.49
900	0.27	3.61	1.11	0.90	4.17	19.11
1000	0.25	4.09	1.00	1.00	3.90	20.92
1100	0.22	4.44	0.91	1.09	2.64	22.95
1200	0.20	4.82	0.82	1.22	1.93	25.21
1300	0.19	5.24	0.77	1.29	1.29	27.72
1400	0.17	5.61	0.71	1.40	0.98	30.52
1500	0.16	6.08	0.67	1.49	0.52	33.62

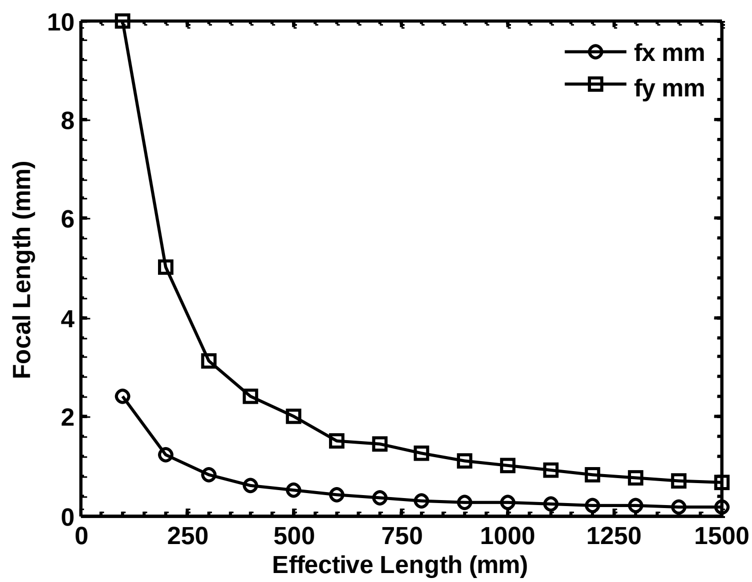

Figure 1: Variation of focal length as function effective length for x and y axis

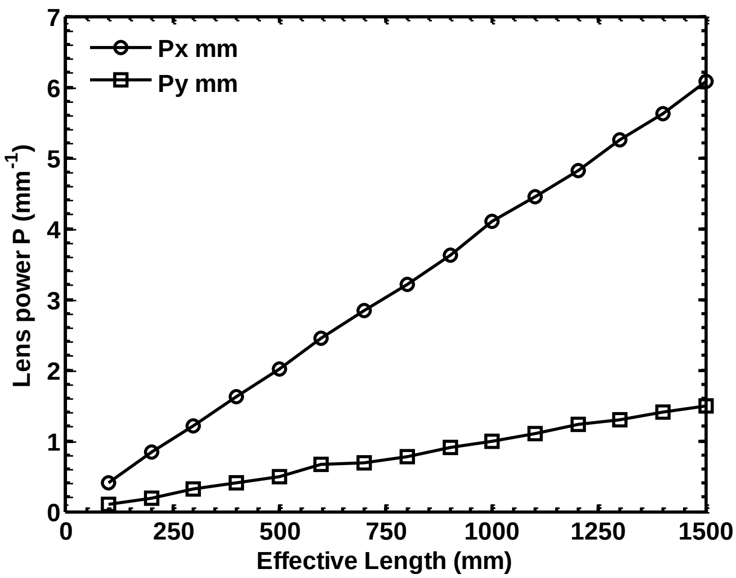

Figure 2: Variation of Lens power as function Effective Length for x and y axis

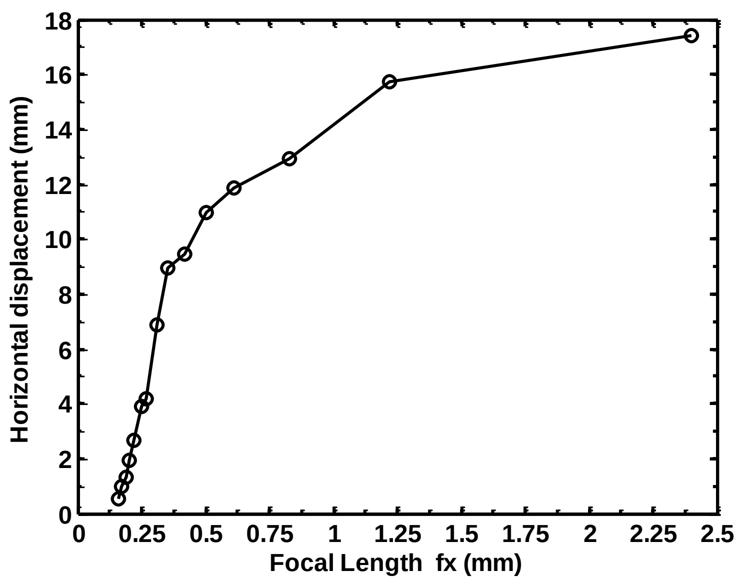

Figure 3: Variation of horizontal displacement with focal length for x-axis

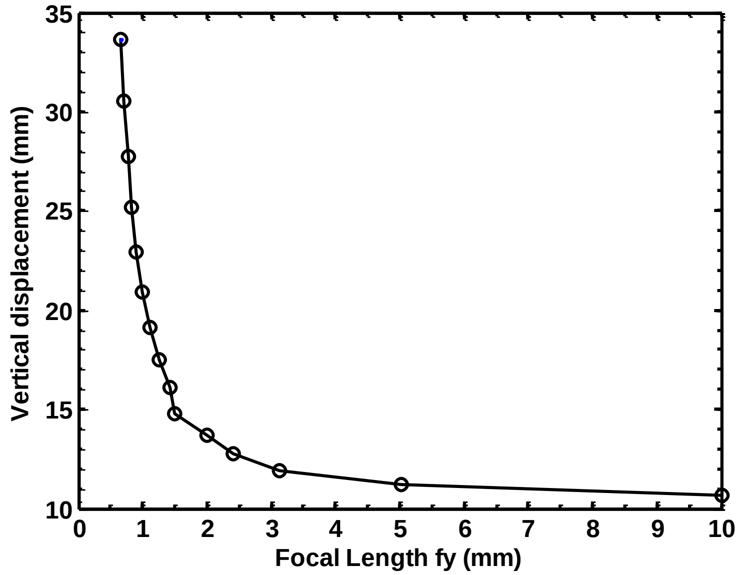

Figure 4: Variation of vertical displacement with focal length for y-axis

Conclusions

The results have shown that quadrupole magnet acts as focusing element for the horizontal plane while acts as defocusing element for vertical plane. The increasing in effective length causes decreasing in focal length for horizontal and vertical plane, the opposite action appears with lens power. Furthermore the increasing in effective length causes decreasing in horizontal displacement (beam envelope) for horizontal plane, the opposite action appears for vertical plane.

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