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Study of Focused Ions Beam Generated by a Plasma Source through a Series of C- Magnet Configuration

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Abstract

The beam transport system is an essential part of any accelerator. This research investigates how a charged particle beam extracted from a plasma source behaves as it passes through a virtual beam transport system consisting of a series of C-bending magnets. This is done by analyzing the equations of motion of charged particles through this system. In addition, the study investigates the effect of the free drift space regions between these magnets and studies the behavior of charged particles beam passing through the suggested system for both horizontal and vertical planes using a computer program designed for this purpose. The results indicate many focusing regions along the beam path (beam envelop) for both the horizontal and vertical planes. The presence of free drift regions between the magnets strongly affects the beam envelop for both horizontal and vertical planes.

Keywords: Guiding System, Focusing System, Bending magnet, C-magnet.

تبئير حزمة الأيونات المنتجة من مصدر بلازما خلال سلسلة من المغانط بشكل حرف C

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الخلاصة

يعد نظام نقل الحزمة جزءا أساسيا من أي مسرّع. يتضمن هذا البحث دراسة للتحقق من سلوك حزمة الجسيمات المشحونة المستخرجة من مصدر البلازما أثناء مرورها عبر نظام نقل حزمة افتراضي يتكون من سلسلة من المغانط بشكل حرف C من خلال تحليل معادلات حركة الجسيمات المشحونة عبر هذا النظام. اضافة لذلك ، فإنه يتحقق من تأثير مناطق الانجراف الحر بين هذه المغانط ودراسة سلوك حزمة الجسيمات المشحونة المارة عبر النظام المقترح لكل من المستويات الأفقية والعمودية باستخدام برنامج كمبيوتر اعد لهذا الغرض. أاظهرت النتائج وجود العديد من مناطق التركيز (التبئير) على طول مسار الحزمة (غلاف الحزمة) لكل من المستويين الأفقي والعمودي. وجود مناطق الانجراف الحر بين المغانط اثر بشدة على غلاف الحزمة لكل من االمستويات الافقية والعمودية.

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1. Introduction

High energy physics, heavy-ion fusion, warm dense matter physics, ion lithography techniques, and accelerators are essential applications for beam transport systems which require developing high-quality systems for focusing charged particle beams. The beam transport system is a necessary part of any accelerator, whether to transport ion beams from the source to the target with the required properties or inject ions from one system into another [1, 2]. There are large-scale accelerators like high-energy colliders, synchrotron radiation sources, and free electron lasers; on the other, there are portable medical accelerators used to treat cancer patients. In each of these accelerators, a beam of charged particles—including electrons, protons, and ions—is generated from a dependable source such as a plasma source, reaccelerated in (often a chain of) linear or circular accelerators connected by beam transfer lines. Or one can inject these beams of charged particles into a storage ring that reaches an external target by a series of alternating dipole magnets [3]. For all these applications, the ion or charged particle beam must focus on the longitudinal and transverse directions in short pulses and small size spots. Since the beam's power delivered per unit area to the target is inversely proportional to the pulse duration and the square of the beam radius, a small beam size means no energy loss [4]. Studying the motion of charged particles in specific fields is significant because it provides excellent physical insight to understand some of the dynamic processes in the plasma and allows obtaining information about macroscopic phenomena due to the collective behavior of many particles [5]. Transporting charged particles along the required path from one location to another is the primary purpose of beam optics. A magnet lattice is a combination of magnets bent and focused along the ideal path. The optical system comprising the bending and focusing parameters is called a beam transport system [6]. The prominent general components of beam transport systems and particle accelerators supply are the focusing and the beam guidance systems. In most applications, it is preferable to predict and control the path of the beam of charged particles to follow a specific direction along locked orbit circular accelerators closely or a beam transport line. The known Lorentz force (the force exerted on a charged particle moving with velocity through the magnetic and electric fields) is desired to bend and direct the charged particle beam so the plasma, represented by ions, is affected by a magnetic force that bends these ions in a curved path by the influence Lorentz force [7]. Each plasma ion has kinetic energy, a charge, and a mass. Any transport system aims to let these ions take a specific path keeping their concentration through the transport process from the source to the target region. Double focusing is obtained when ions coming from an ion source with expansion in both directions and energy are worthily focused to points in space. Under this condition, the resolving power of the spectrometer of mass can be greater than in single-focusing tools that supply direction-focusing only [8].

2. Guiding and Focusing System

Any set of lenses forms a focusing and guiding system for charged particles through the recurrence of their motion through the lens field. The beam particles acquire the radial pulse directed to the system's axis. At the lens district, the movement of the beam is resolved by Coulomb's repulsion. As a result, the initially approximate beam is pressed to a certain minimum radius and then starts to prevalence until entering the field of the following lens. Choosing the lens refracting power may provide periodic beam motion and its transfer over a long distance [9]. The fundamental components of a beam transport system are: Quadrupoles, bending magnets, and field-free drift regions. The quadrupole function is to focus, while the electrostatic and magnetic bends function is to provide guiding and focusing [10].

3. C-Magnet Configuration

Bending magnets direct the charged particles beam in the correct direction for transport to the target using a transport system [11]. C-magnet configuration refers to the magnet type used to direct the ion beam. This type produces a homogeneous magnetic field, meaning the magnetic flux is approximately equal along the beam path inside the bending magnet. A uniform magnet with exit pole edges and non-zero angular entrance is considered a bending magnet. The product of the transfer matrices corresponding to each field is used to express the trajectory of the ion beam in the magnetic sector field.

4. Bending Magnet Matrix

An individual particle's behavior in the beam acceleration and transport system is less important than that of a group of particles (the beam), of which the individual particle is a part. This beam is easily defined and controlled using an extension of matrix algebra [12]. The transfer matrix formula describes the effect of ion optical elements and the drifts between them on trajectories by modelling ion-optical transport lines [13]. Transfer matrices theory describes the motion of particles relative to a known central equilibrium orbit. The transfer matrix represents the changes in the transverse position and the particle angle concerning the central beam axis. The first-order transport matrix $\mathbf{M}$ can describe the behaviour of a particle moving through a drift space or a magnetic element. The coordinate's matrix $\mathbf{X}(1)$ for the particle at the end (output) of the element, which is given in terms of the initial (input) coordinate's matrix $\mathbf{X}(0)$ as [14]:

$$\mathbf{X}(\mathbf{1}) = \mathbf{M}\,\mathbf{X}(0) \tag{1}$$

If transverse forces are linear, each element of the cell has a transfer matrix. At the end of n cells (transport element), the orbit vector is [15]:

$$\mathbf{X}(\boldsymbol{n}) = \mathbf{M}^{\boldsymbol{n}} \boldsymbol{X}(0) \tag{2}$$

The dynamics of a charged particle beam propagating along the z-axis are described in a four-dimensional phase space system with two positions Cartesian coordinates (x, y) for the horizontal and vertical plane, respectively, and two angular divergences of the beam (x', y') for the horizontal and vertical plane, respectively [15]. So the phase space at any region can be written as four-row column matrix:

$$\mathbf{X} = \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix} \tag{3}$$

The force on any charged particle moving in a magnetic field is given by the known Lorentz force:

$$\mathbf{F} = \mathrm{q}(\mathbf{v} \times \mathbf{B}) \tag{4}$$

Where: q is the particle charge, $\mathbf{v}$ is the particle velocity, $\mathbf{B}$ is the magnetic flux.
The first order transport matrix $\mathbf{M}$ of the bending magnet at the x-axis is [14, 16]:

$$\mathbf{M}_x = \begin{bmatrix} 1 & 0 \\ \frac{\tan\beta_2}{R} & 1 \end{bmatrix} \begin{bmatrix} \cos k_x l & \frac{1}{k_x}\sin k_x l \\ -k_x \sin k_x l & \cos k_x l \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\tan\beta_1}{R} & 1 \end{bmatrix} \tag{5}$$

and for y-axis is

$$\mathbf{M}_y = \begin{bmatrix} 1 & 0 \\ -\frac{\tan\beta_2}{R} & 1 \end{bmatrix} \begin{bmatrix} \cos k_y l & \frac{1}{k_y}\sin k_y l \\ -k_y \sin k_y l & \cos k_y l \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{\tan\beta_1}{R} & 1 \end{bmatrix} \tag{6}$$

Where: k_x, k_y are the wavenumbers related to the magnetic field index of the bending magnet for the horizontal and vertical oscillations, respectively, β_1 is the entrance angle of the bending magnet, β_2 is the exit angle of the bending magnet, R is the curvature radius of the magnet, and l is the path length inside the magnet.

5. Results and Discussion

In this work, the virtual design of a beam transport system included a series of ten identical C- magnets configurations, each with a radius (R) of 480 mm, and a deflecting angle (φ) of 75^o, while the entrance (β_1) and exit (β_2) angles were 20^o and -10^o, respectively (Figure 1).

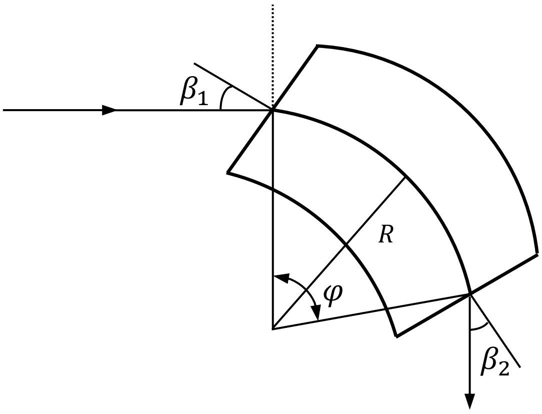

Figure 1: Main parameters of the suggested C- magnet.

The extraction of a charged particle beam from a plasma source of dimension 5mm×10 mm passing through the suggested design involves two cases; the first is when the magnets are arranged so that there is no distance between them (without free drift space), in the second case, with free drift space of 100 mm between one magnet and the next.

In the first case, without free drift space, the beam envelope was as shown in Figure 2. It can be observed from this figure that there are five focusing regions in the horizontal plane which reflects the focusing and defocusing effect of the edge of each magnet in the system. The best focus was 5.4 mm at the end of the fourth magnet.

For more information about the behavior of the beam passing through the designed system, the charged particles distribution in the phase space ellipse (usually have Gaussian distribution) was studied for the selected regions as indicated in Figure 3, (a) at the source region, (b) at the end of the first magnet, (c) at the end of the fifth magnet, (d) at the end of the tenth magnet, and (e) at the end of the beam transport system (target region). The rotation of the phase space ellipse indicates the focusing process in that region.

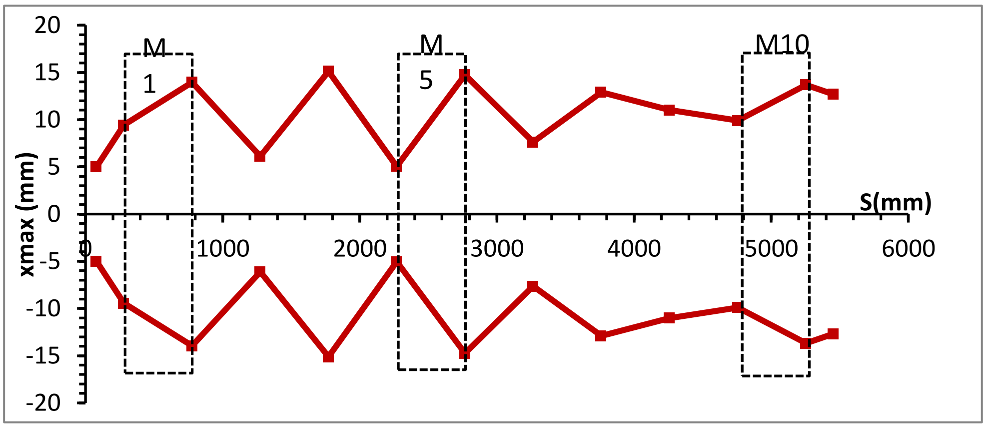

Figure 2: Horizontal beam profile for 10 magnets without free drift space.

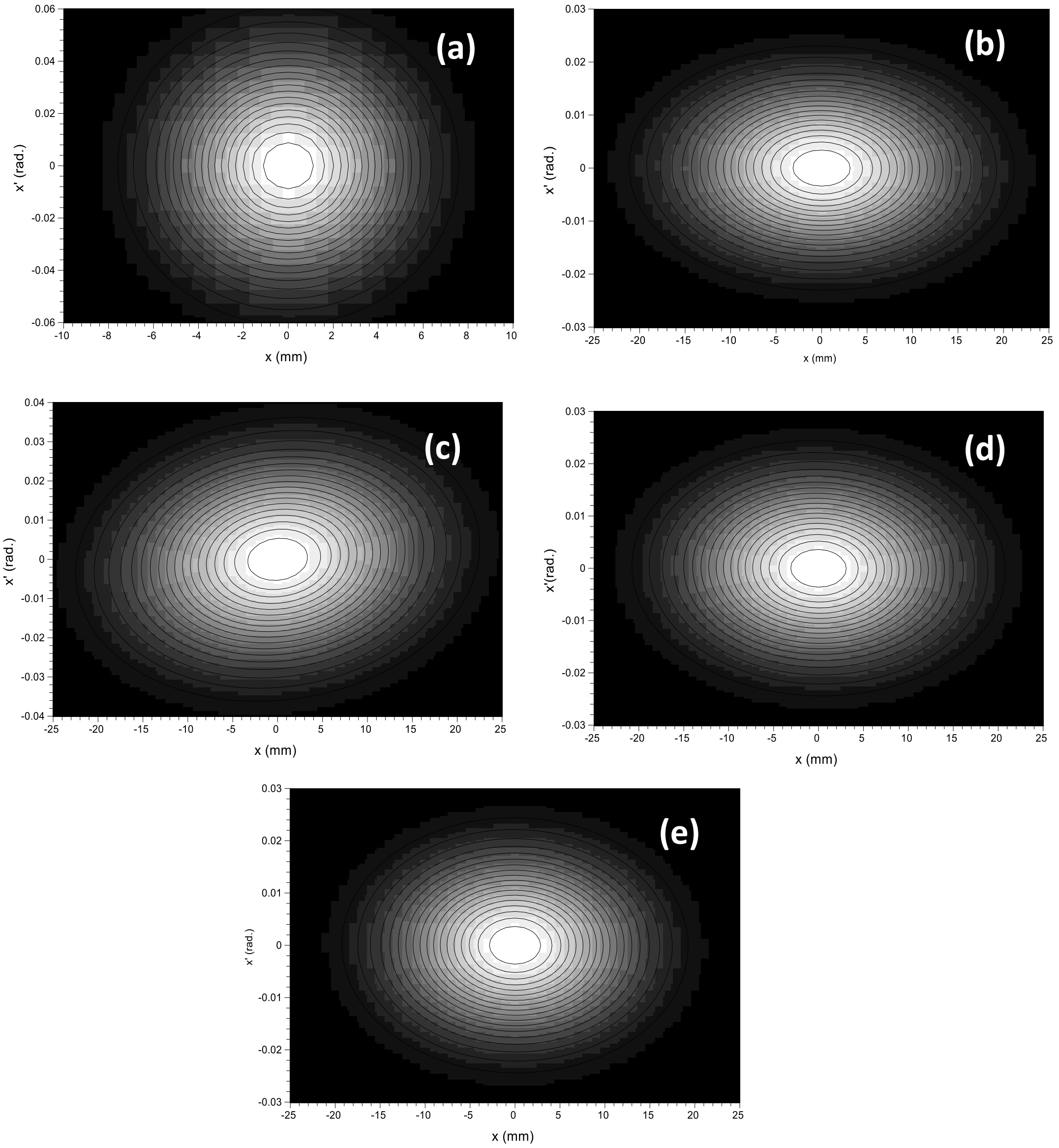

Figure 3: Charged particles beam distribution in phase space ellipse along the beam transport system without free drift space distance for the horizontal plane.

The beam envelope for the vertical plane is indicated in Figure 4. There are only two focusing regions along the beam transport system in the vertical plane. The best focus was 4.9mm at the end of the eighth magnet, reflecting the intense focus in the vertical plane.

The charged particles distribution in the phase space ellipse was studied for the selected regions as indicated in Figure 5, (a) at the source region, (b) at the end of the first magnet, (c) at the end of the fifth magnet, (d) at the end of the tenth magnet, and (e) at the end of the beam transport system (target region). The rotation of the phase space ellipse was more apparent in the vertical plane due to the focusing effect in this plane, as shown in Equation 3.

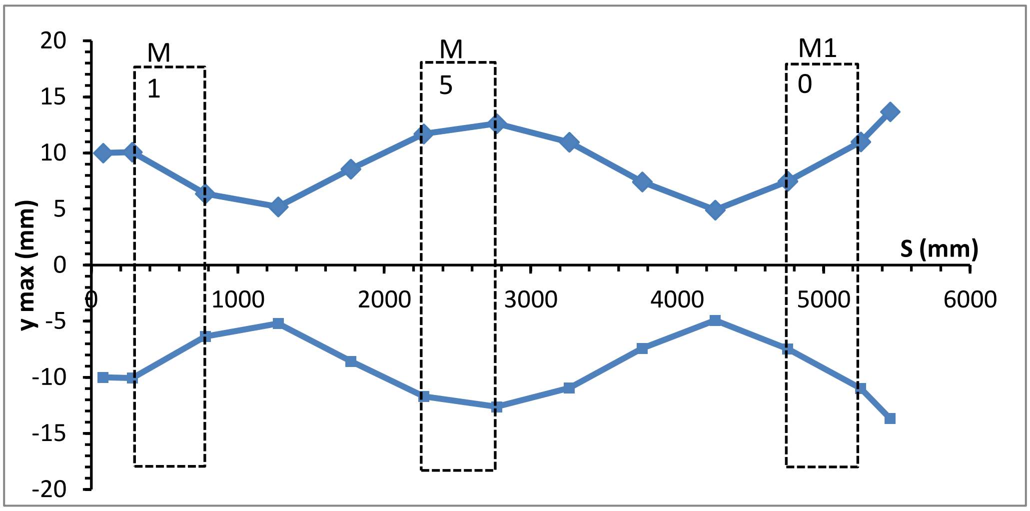

Figure 4: Vertical beam profile for 10 magnets without free drift space.

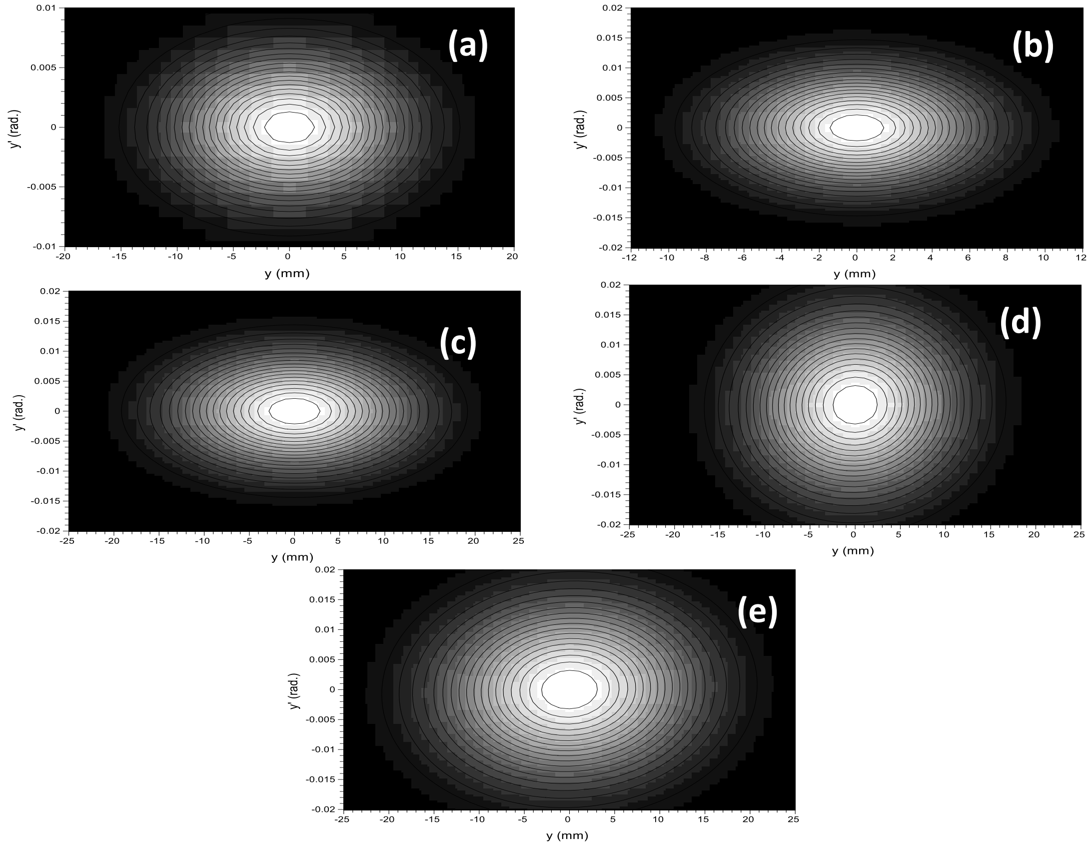

Figure 5: Charged particles beam distribution in phase space ellipse along the beam transport system without free drift space distance for the vertical plane.

For the second case, with free drift space, the beam envelope is as shown in Figure 6. It can be noted, from this figure, that there are five focusing regions in the horizontal plane, and the best focus is 4.9 mm which appeared at the end of the tenth magnet. This means that the separation between the bending magnets by free drift distance increased the focusing of the beam.

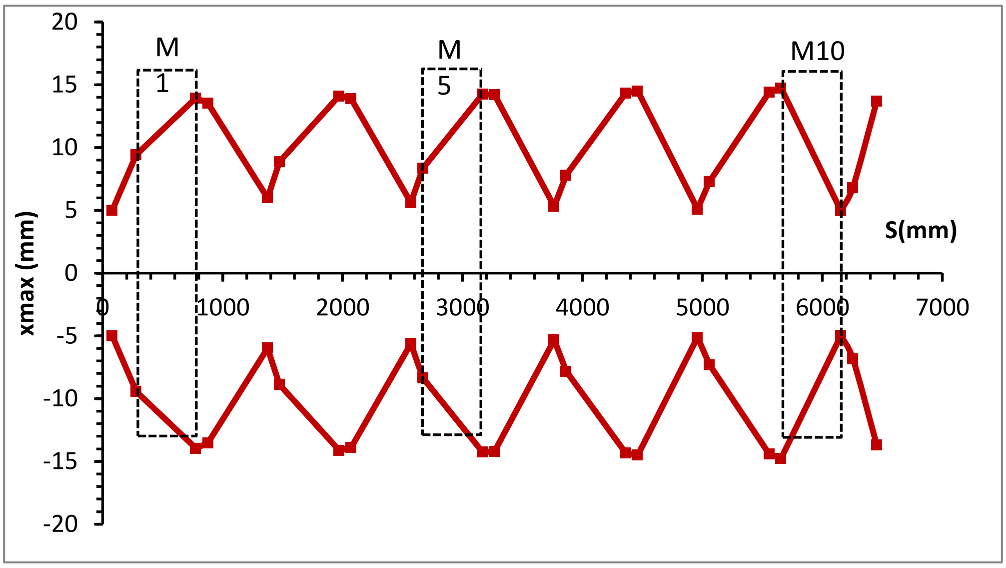

Figure 6: Horizontal beam profile for 10 magnets with free drift space.

The charged particles distribution in the phase space ellipse was studied for the selected regions as indicated in Figure 7, (a) at the source region, (b) at the end of the first magnet, (c) at the end of the fifth magnet, (d) at the end of the tenth magnet, and (e) at the end of the beam transport system (target region). The negative slope of the phase space ellipse was more evident due to the good focusing effect in this case.

The beam envelope for the vertical plane is indicated in Figure 8 for the second case (with 100 mm free drift space); there are only two focusing regions along the beam transport system in the vertical plane. Without free drift space, the best focus is 5.2 mm at the end of the sixth magnet.

The charged particles distribution in the phase space ellipse was studied for the selected regions as indicated in Figure 9, (a) at the source region, (b) at the end of the first magnet, (c) at the end of the fifth magnet, (d) at the end of the tenth magnet, and (e) at the end of the beam transport system (target region). The negative slope of the phase space ellipse was due to the focusing effect.

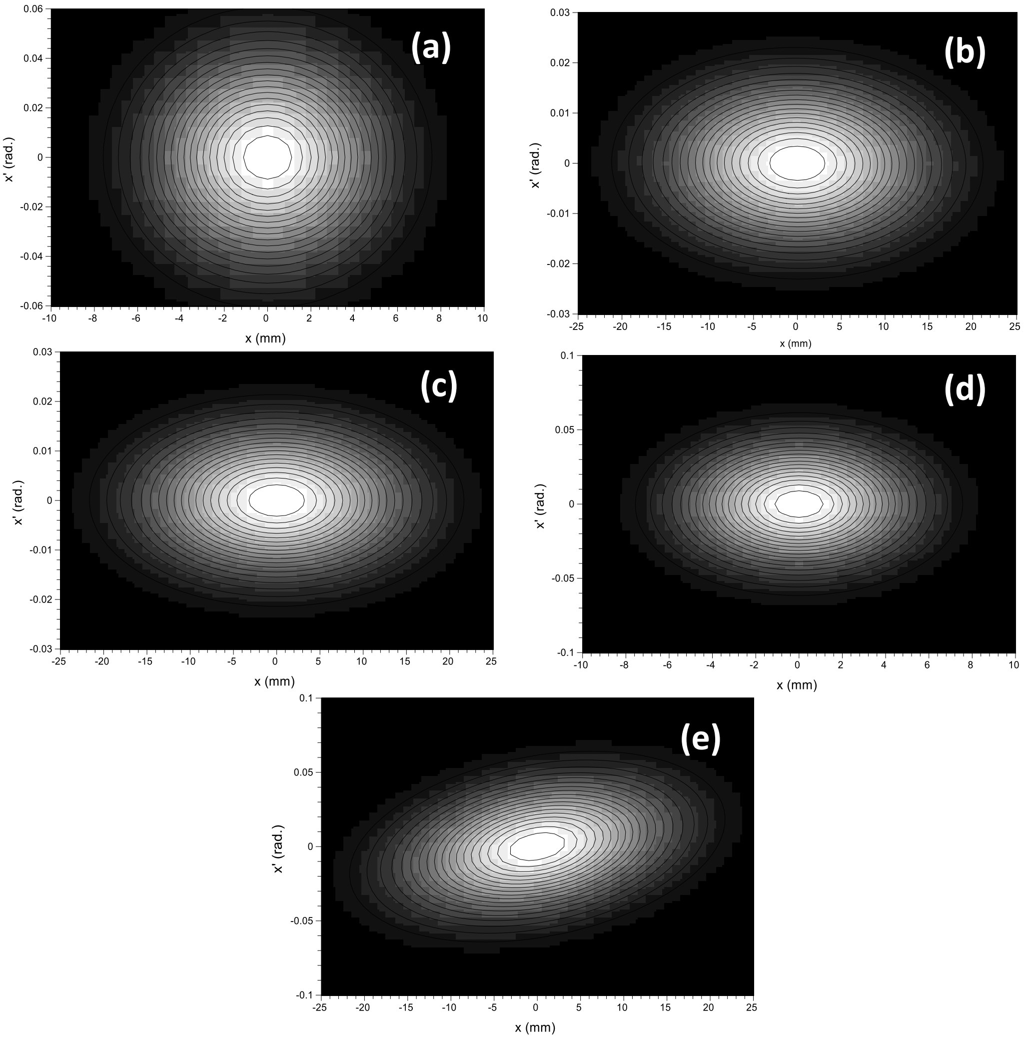

Figure 7: Charged particles beam distribution in phase space ellipse along the beam transport system with free drift space for horizontal plane.

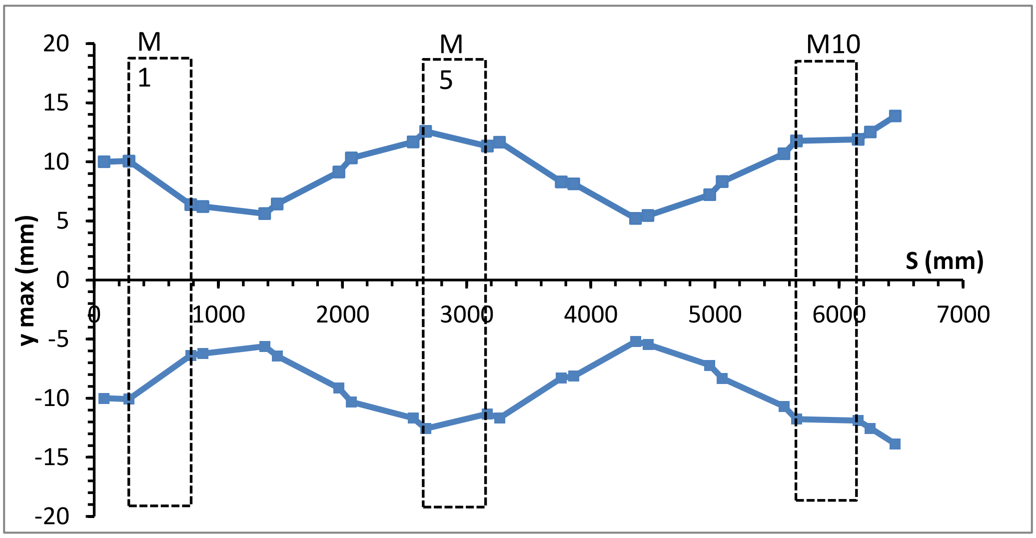

Figure 8: Vertical beam profile for 10 magnets with free drift space.

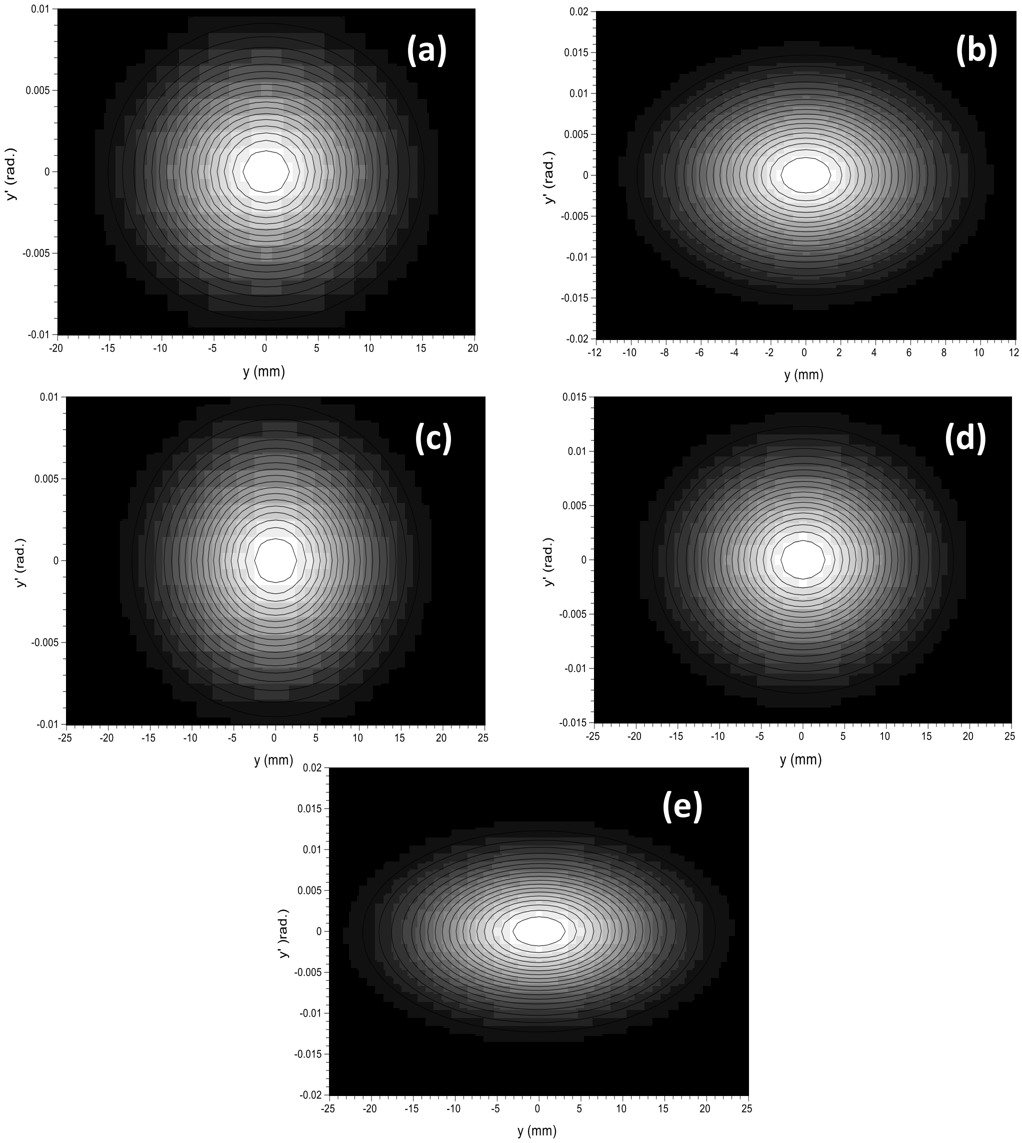

Figure 9: Charged particles beam distribution in phase space ellipse along the beam transport system with free drift space for vertical plane.

6. Conclusions

The results indicated that charged particle beam focus varies with the system configuration for horizontal and vertical planes. Multi-magnets lead to multi-good focusing regions; the number of focus areas changes with if it is a horizontal or vertical plane. Separating the magnets by significant free drift distance leads to defocusing beam at the target for the current system design. So for applications requiring a small beam spot on the target, minimizing the distance between the magnets in the transport system is recommended. This is suitable for small accelerators of medical use that require concentration in the charged particles beam, in addition to the small space it requires to suit the places of service.

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