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Effect the Magnetic Field on the Focus of Ion Beam from Plasma Source

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ABSTRACT

One of the main component transport systems is a solenoid magnet, so in this study, a computational study was carried out to calculate some parameters of a solenoidal magnet. The most efficient technique to describe and track the charged particle beam along any optical system (in this example, a plasma source and two drift space areas before and after the solenoid magnet) is by theoretical analysis utilizing matrix representation, which has been provided. The configuration of the ion optical system necessary to create the magnetic identification focus and defocus the ion beam to the target using Matlab computational tools determines many magnet design elements, including magnetic rigidity, magnification, and focusing strength factor. The results demonstrate that a solenoid magnet functions as a convergent lens but can, under some circumstances, transform into a divergent lens. Additionally, changes in the solenoid magnetic field (B) affect the focusing of the beam that passes through the system, as indicated by the magnification values.

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تأثير المجال المغناطيسي على تركيز الشعاع الأيوني من مصدر البلازما

بشرى جوده حسين

قسم الفيزياء/كلية التربية للعلوم الصرفة – أبن الهيثم/جامعة بغداد، بغداد /العراق

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الـــخُـــلاصـــة

أحد المكونات الرئيسية لأنظمة النقل هو المغناطيس ذو الملف اللولبي، لذلك في هذه الدراسة، تم إجراء دراسة حسابية لحساب بعض معلمات المغناطيس ذو الملف اللولبي. التقنية الأكثر فعالية لوصف وتتبع شعاع الجسيمات المشحونة على طول أي نظام بصري (في هذا المثال، مصدر البلازما ومنطقتين للفضاء المنجرف قبل وبعد المغناطيس اللولبي) هي عن طريق التحليل النظري باستخدام تمثيل المصفوفة، والذي تم توفيره. ترتيب النظام البصري الأيوني ضروري لتحديد شعاع مبئر وغير مبئر للهدف باستخدام الادوات الحسابية للماتلاب لتعيين عدد من عناصر تصميم المغناطيس ويشمل الصلادة المغناطيسية، التكبير وعامل شدة التبئير. أظهرت النتائج أن المغناطيس ذو الملف اللولبي يعمل كعدسة محدبة، لكن يمكنه، في بعض الظروف، أن يتحول إلى عدسة مفرقة. بالإضافة إلى ذلك، تغير في المجال المغناطيسي يؤثر على تبئير الحزمة المارة خلال المنظومة، كما هو مبين من خلال قيم التكبير.

1. INTRODUCTION

Numerous scientific investigations focus on the generation, acceleration, and transportation of powerful charged particle beams, which is an ongoing field of research. The necessity for high power and high quality beams for applications like spallation neutron sources, accelerator driven systems, and nuclear waste transmutation has led to a surge in interest in high current accelerators in recent years, particularly linear accelerator (LINAC) and cyclotrons. Understanding how the beam self-field affects the focusing and transmission properties of strong charge particle beams is of increasing interest[1]. A cylindrical area with roughly constant axial magnetic flux density (Bz) is called a solenoid. Solenoids are used in accelerator applications to concentrate or restrict high-current electron beams. Additionally, plasma ion sources employ them. Normal or superconducting coils that carry current produce large-volume solenoid fields.

Because they can focus well, short solenoid lenses have been employed as focusing elements in beam instruments such as electron and ion microscopes for a long time. With caution, solenoids can be used in transport channels to provide a very minor emission increase. Controlling the emittance growth is required to reduce particle losses in high power accelerators, where it is desirable to use smooth, axially symmetrical focusing with a relatively short focusing period [2,3]. These systems are essentially made up of a series of electromagnetic devices that a charged particle beam travels through[4]. Magnetic fields, which deflect particles in accordance with balance of Lorentz force and centrifugal force, are employed in a variety of electromagnetic devices, such as magnets, to direct charged particles along predetermined paths [5]. Magnetic or Electrostatic lenses are needed to retain the diverging ion beam within the vacuum beam tube. This is because the ion beam emerges from the ion source. As a result, the lenses help transport the largest number of charged particles from the source to the rest of the system and prevent collision with the walls of the system [6]. After being separated from the gas discharge plasma by the extraction electrodes, the ions speed up as they enter the vacuum drift tube [7]. In other words, the device that generated an ion beam by ionizing feed material is the ion source [8, 9].

2 - Magnetic Rigidity and Transport Matrix

In order to be able to describe the function of different devices along the path of the beam, general relationships was needed to the motion of charged particles in electromagnetic fields . It is necessary to know the spatial distribution of these fields.

Magnetic rigidity is of great importance in many fields, including beam transmission of charged particles [10,11].

The magnetic Lorentz force in a pure magnetic field always perpendicular to the velocity This indicates that the direction of the velocity varies, for a particle travelling in magnetic field, dm/dt is always zero [6].

$$m\left(\frac{dv}{dt}\right) = qvB \qquad (1)$$

When beam moving with constant value of speed in a circular radius, then the force is given by:

$$F = \frac{mv^2}{R} \qquad (2)$$

Then

$$qvB = \frac{mv^2}{R} \qquad (3)$$

Magnetic rigidity is the effect of particular magnetic fields on the motion of the charged particles, that is a measure of the particle's resistance to deflect in a field [6,12].

$$B_0R_0 = \frac{mv}{q} = \frac{P}{q} = \frac{B}{2\sqrt{k}} \qquad (4)$$

$$k = \left(\frac{B}{2B_0R_0}\right)^2 \qquad (5)$$

Where

$B_o\ R_o$: The Magnetic rigidity (in Gauss.mm).

p: The particle momentum.

q: The particle charge.

B: Magnetic field strength (in Gauss).

k: The solenoid focusing strength

The ratio between momentum and charge of particle refers to magnetic rigidity of the beam, and is seen as a measure of amount of angular deviation that is produced when particles are travels through certain field [13].

A practical way to describe the trajectory of a charged particle is the matrix formalism. It can be derived from the equation of motion of a charged particle in a longitudinal curvilinear and transverse Cartesian coordinate system[14].

We can describe the motion of particles relative to a principal equilibrium orbit by transport matrix theory. Particle orbits are distinguished by their inclination angle and displacement from the main axis. The transverse forces applied by the majority of beam transport systems, including charged particle lenses, solenoid magnets, and bending magnets, are directly proportional to the particle's distance from a desired axis. The axial velocity and main axis position for paraxial motion and linear fields are presumed to be known from an earlier equilibrium calculation. A four-dimensional vector (x, x', y, y') can describe a particle orbit at the same axial location if y and x are the axes normal to z. Stated differently, the particle orbit is specified by four quantities. If transverse velocities are known, the angled numbers y' and x' with respect to the axis are identical to them. Furthermore, it is anticipated that the ion beam optical system is made up of many separates focusing components. The transmission matrix in y or x direction, without acceleration, specified equal unity [15,16].

3 - Solenoid Magnet

A magnet that as a cylindrical coiled electromagnet is called solenoid magnet. Field within the term solenoid refers to long coiled magnets in the axial direction (length >> width), So that at their ends the fringe fields small compared with inside the coil that long axial field. This means, the longitudinal magnetic field decreases toward the ends, and on the shaft peaks at the center of the solenoid approaches zero far away from it [17]. In a simple model, the field uniforms inside the solenoid and assumed to be zero outside it. It used to focus beams into low energy section of accelerators and other devices such as electron microscopes and ion microprobes. The geometry of solenoid lens is compatible with cylindrical coaxial beams. Because static field of magnetic is constant, there is no change in the energy of particles passing through the lens [17,18]. A solenoid magnet has three visually significant zones. With the exception of the magnet axis, the magnetic field at the entrance and exit areas is both radial and axial [19]. These three areas, whose transfer matrices explain changes in a particle's transverse position and angle with respect to the main beam axis, are best studied using the matrix approach. we can facilitate the description of beam transport in nearby optical elements by use transfer matrix. It is a mathematical way of organizing information about the transverse movement of beam about the primary beam axis [20]. So, the transport matrix (M) is product of M1, M2 and M3 respectively to fringe field input, static coaxial magnetic field and fringe field output [21,22].

$$M = M_1 . M_2 . M_3$$

Where:

$$M_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \sqrt{k} & 0 \\ 0 & 0 & 1 & 0 \\ -\sqrt{k} & 0 & 0 & 1 \end{bmatrix}$$

$$M_2 = \begin{bmatrix} 1 & (\frac{1}{2}\sqrt{k})\sin(L\sqrt{k}) & 0 & (\frac{1}{2}\sqrt{k})(1-\cos(L\sqrt{k})) \\ 0 & \cos(L\sqrt{k}) & 0 & \sin(L\sqrt{k}) \\ 0 & (-\frac{1}{2}\sqrt{k})(1-\cos(L\sqrt{k})) & 1 & (\frac{1}{2}\sqrt{k})\sin(L\sqrt{k}) \\ -\sin(L\sqrt{k}) & 0 & 0 & \cos(L\sqrt{k}) \end{bmatrix}$$

$$M_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -\sqrt{k} & 0 \\ 0 & 0 & 1 & 0 \\ \sqrt{k} & 0 & 0 & 1 \end{bmatrix}$$

Then the total transfer matrix (M) becomes:

$$M = \begin{bmatrix} (\cos(L\sqrt{k}))^2 & (\cos(L\sqrt{k})\sin(L\sqrt{k}))/\sqrt{k} & \cos(L\sqrt{k})\sin(L\sqrt{k}) & (\sin(L\sqrt{k}))^2/\sqrt{k}) \\ -(\cos(L\sqrt{k})\sin(L\sqrt{k}))\sqrt{k} & (\cos(L\sqrt{k}))^2 & -(\sin(L\sqrt{k}))^2\sqrt{k} & \cos(L\sqrt{k})\sin(L\sqrt{k}) \\ -(\cos(L\sqrt{k})\sin(L\sqrt{k})) & -(\sin(L\sqrt{k}))^2/\sqrt{k} & (\cos(L\sqrt{k}))^2 & (\cos(L\sqrt{k})\sin(L\sqrt{k}))/\sqrt{k} \\ (\sin(L\sqrt{k})^2\sqrt{k} & -(\cos(L\sqrt{k})\sin(L\sqrt{k}) & -(\cos(L\sqrt{k})\sin(L\sqrt{k}))\sqrt{k} & (\cos(L\sqrt{k}))^2 \end{bmatrix}$$

Where *L* the total length of the solenoid (in mm).

4 - RESULTS AND DISCUSSION

The current system composed of a source of plasma and two regions of drift space after and before the body of magnet. Argon gas (Ar) was considered as the ion extracted from plasma source, charged particles are assumed to have passed through the solenoid magnet. Front part of the particle beam source is an incision in parallel with coaxes of the vacuum chamber dimensions (105) mm^2, and beam taken away from this incision at (+35 kV). The influence of primary parameters of charge particle passes through a solenoid system can be repaired, that R_o, field of solenoid magnetic (B) and total length (L) of it. In this study, we made the length of the solenoid is constantly equal to (1000 mm). So any changing in any parameters gives different lens. (Ro) changes in the range (100-550) mm multiplied by Magnetic field in a body magnet region (Bo) that equal to (7000 Gauss) which form the magnetic rigidity, then to calculate solenoid focusing strength (k), all these as in table (1). Any charged particle beam focusing system's primary goal is to produce the lowest possible charged particle beam size, that is, the lowest possible magnification in order to improve standard for some application. Therefore the beam magnification along the system was calculated. In table (1) the magnetic field strength (B) equal to 3000 Gauss. Tables 2 and 3 represent the value of magnetic rigidity, solenoid focusing strength, beam envelop and magnification when we change the magnetic field strength (B) into 4000 and 5000 Gauss respectively. Figure (1) explains the relation between magnetic rigidity and solenoid focusing strength, we noticed from this Figure, the growing in magnetic rigidity causes increasing in focusing strength, that means the magnet act as diverge lens, while it acts as converge lens in the small values of Ro when the magnetic field strength (B) increasing that explain in Tables 1, 2 and 3. Figure (2) ^ represents the relationship between different values of magnification as function of magnetic rigidity, it can be noticed from this Figure, the growing in magnetic rigidity causes increasing in magnification, increasing the magnetic field strength (B) means the magnet act as diverge lens, while it acts as converge lens in the small values of Ro and that are presented in Tables 1, 2 and 3, the behavior of a beam is changed when magnetic field strength (B) increasing to the same reasons of Figure (1). Figure (3) revealed the relationship between the solenoid focusing strength and the magnification of the beam.

Table 1: Magnification obtain at the different values of Magnetic rigidity and focusing strength factor for B=3000 Gauss

R_o mm	R_oB (Gauss.mm)*10^5	k (mm^{-2}) *10^{-6}	Magnification (Xout /Xin)
100	7.00	4.59	1.06
150	10.50	2.04	1.49
200	14.00	1.14	1.57
250	17.50	0.73	1.85
300	21.00	0.51	2.07
350	24.50	0.37	2.26
400	28.00	0.28	2.44
450	31.50	0.23	2.65
500	35.00	0.18	2.54

Table 2: Magnification obtain at the different values of Magnetic rigidity and focusing strength factor for B=4000 Gauss

R_o mm	R_oB_o (Gauss.mm)*10^5	k (mm^{-2}) *10^{-6}	Magnification (Xout /Xin)
100	7.00	8.16	1.98
150	10.50	3.62	1.32
200	14.00	2.04	1.05
250	17.50	1.30	1.14
300	21.00	0.91	1.36
350	24.50	0.66	1.60
400	28.00	0.51	1.81
450	31.50	0.40	1.99
500	35.00	0.33	2.16

Table 3: Magnification obtain at the different values of Magnetic rigidity and focusing strength factor for B=5000 Gauss

R_o mm	R_oB_o(Gauss.mm)*10^5	k (mm^{-2}) *10^{-6}	Magnification (Xout /Xin)
100	7.00	10.27	3.15
150	10.50	5.66	2.62
200	14.00	3.18	1.98
250	17.50	2.04	1.41
300	21.00	1.42	1.10
350	24.50	1.04	1.06
400	28.00	0.79	1.29
450	31.50	0.63	1.59
500	35.00	0.51	1.77

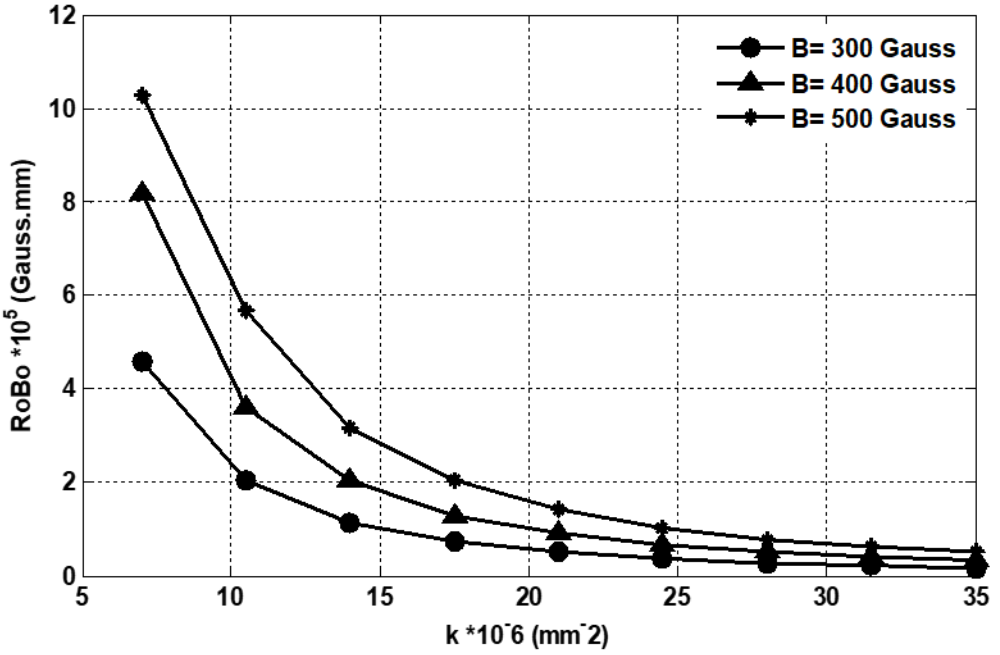

Fig. 1: The magnetic rigidity versus focusing strength factor with different magnetic field

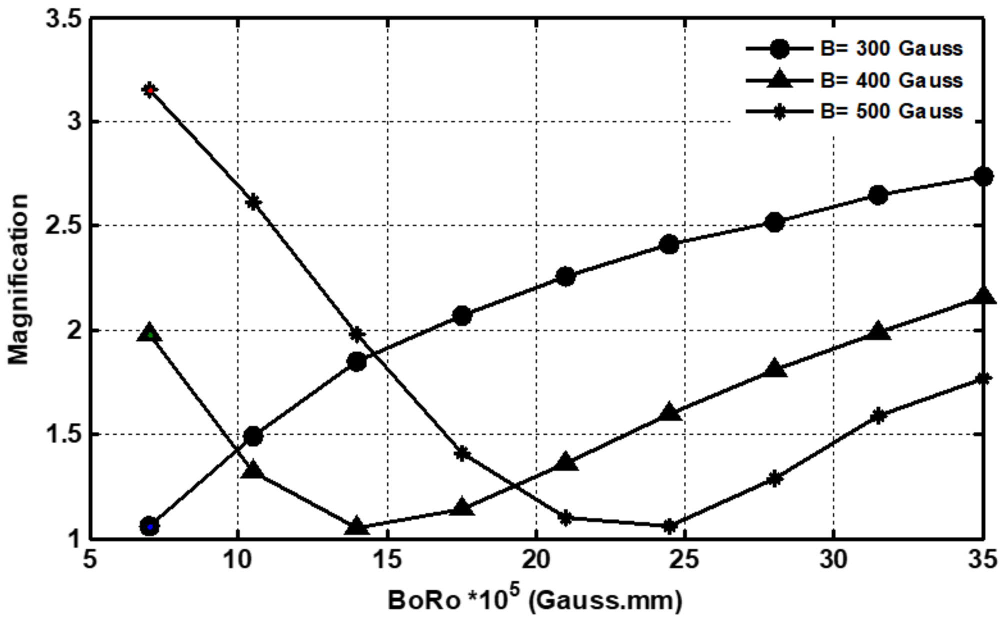

Fig. 2: The magnification as function of the magnetic rigidity with different magnetic field (B)

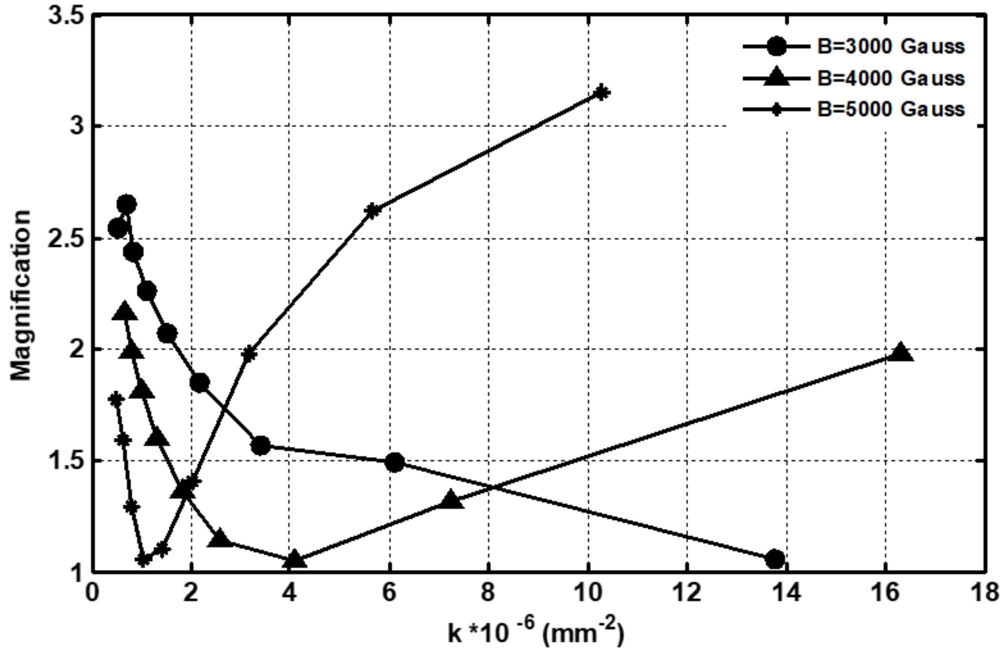

Fig. 3: The magnification versus focusing strength factor with different magnetic field

5 - CONCLUSIONS

In this study, the solenoidal magnetic lens is seen to be sensitive to changes in magnetic rigidity and the focusing strength. Furthermore, it acts as a converging lens but may become divergent in some circumstances. The focusing of the beam traveling through the system changes due to variations in the solenoid magnetic field (B), which are described by changes in magnification values. This allows it to be used for low-energy sections of accelerators and the design of vacuum pipes. The relationship between the magnetic rigidity and focusing strength factor was a uniformly decreasing relationship. As for the relationship of magnification to magnetic rigidity, its behavior was more apparent at high magnetic fields (4000 and 5000 Gauss), where the most appropriate value of magnification (1.05) with the value of magnetic rigidity ($14*10^5$ Gauss. mm) was at the value (4000 Gauss) of the magnetic field strength. In the case of the field (5000 Gauss), only the values were ($24.5*10^5$ Gauss. mm) and (1.06) For both magnification and magnetic rigidity, respectively. In addition, the relationship between magnification and the focusing strength factor was inverse up to a specific value and became an increasing relationship for high values of magnetic fields. This means that increasing the intensity of the magnetic field affects the concentration coefficients of ionizing radiation. Several studies have explained this relationship, including (23, 24).

6 - REFERENCE

1. A. Goswamt, Studies of space charge dominated beam in the spiral inflector and central region of cyclotron, Bhabha Atomic Research Centre Mumbai-400085, India, September, 2012.
2. S. Humphries, Designing permanent-magnet solenoids, Ph.D., Field Precision Albuquerque, NM 87192 U.S.A, Copyright 2009.
3. G. Davis, V. V. Kashikhin, T. Page, I. Terechkine, J. Tompkins and T. Wokas, Designing Focusing Solenoids for Superconducting RF Accelerators, Fermi National Accelerator Laboratory , FERMILAB-CONF-06-290-TD, Work supported by US DOE under contract No. DE-AC02-76CH03000, August 28, 2006.
4. H. Wiedemann, Particle Accelerator Physics, Third Edition Springer-Verlag Berlin Heidelberg, 2007.
5. J. T. Urban, An Optimized Super ferric Wiggler Design for the International Linear Collider Damping Rings, Cornell University 2007.
6. F. W. Abdelsalam, M. M. Abdelrahman and B. A. Soliman," An electrostatic lens system for the deceleration of high intensity heavy ion beams", Vol. 9(8), pp. 199-207, April, 2014
7. M. Reiser, Theory and Design of Charged Particle Beams, WILEY-VCH Veriag Gmbh and Co. KGaA, Weinheim, Printed in the Federal Republic of Germany, 2004.
8. J. H. Keller, Beam Optics Design for Ion Implantation, Nuclear Instruments and Methods, 1981, **189**, 7-14.
9. M.M. Abdelrahman, " Ion Beam Simulation Using a Lens System for Acceleration and Deceleration of Low Energy Ion Beam". J Nucl Ene Sci Power Generat Technol.,Vo.2(2), 2013.
10. J. Holmes, S. Henderson and Y. Zhang, Magnetic Fields and Magnet Design, US Particle Accelerator School, Vanderbilt, January, 2009.
11. R. Blush, Magnetic Rigidity\, University College Cork, 2008.
12. M. Fraser, A discussion on solenoid focusing, BE-RF-BR (CERN), March 2012.
13. U. Barletta, Overview on Magnetic Fields, US Particle Accelerator School, USPAS, 2012.
14. M. Hachmann, Transverse emittance measurement at REGAE via a solenoid scan, Diploma thesis, Institute Experimental physics University of Hamburg, November 2012.
15. H. Wiedemann, Particle Accelerator Physics, Third Edition Springer- Verlag Berlin Heidelberg, 2007.
16. S. Humphries, Charged Particle Beams, Albuquerque, New Mexico, Department of Electrical and Computer Engineering University of New Mexico, 2002.
17. V. Kumar, Understanding the Focusing of Charged Particle Beam in a Solenoid Magnetic Field. Am. J. Phys., 2009, **77** , 737-741.
18. S. Humphries, Principles of Charged Particle Acceleration. Published by Jon Wiley and Sons. University of New Mexico, Copyright, 1999.
19. K. Dehnel, and M. Dehnel, Using Beamline Simulator V1.3. Published by accelso Inc., Del Mar, California, U.S. printing, June, 2002.
20. E. Regenstreif, Focusing with Quadrupoles, Doblets, and Triplets in Focusing of Charged Particles, edited by A. Septier. 1, Academic Press INC., 1967, 353-410.
21. A. M. Lombardi, Beam Lines, CERN Accelerator School, CERN-320 Copies Print September 2006.
22. Ph. Royer, Solenoidal Optics. European Organization for Nuclear Research, CERN- PS Division Geneva, Switzerland 1999.

23. H. S. Hasan, A. A. Abbas, M. S. Erhayief, M.J. Yaseen, Theoretical Investigation of Spherical Aberration Coefficient Solenoid Magnetic Lens, Journal of Physics: Conference Series IOP Publishing, 1530 (2020) 012151.
24. S. Y. Lu†, T. N. Hu, X. D. Tu, Y. Q. Xiong, P. Yang, G. Y. Feng, Designing of a solenoid lens for the application to a compact electron beam testing bench, 10th Int. Particle Accelerator Conf., IPAC2019, JACoW Publishing, Melbourne, Australia, 2019.