Ion Beam Focusing in Solenoid Magnetic Field

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Abstract

The present study investigates the main parameters effect on the solenoid design as converging lens of charged particle beam passing through it. These parameters are solenoid magnetic field (B), solenoid radius (R_o) and the solenoid total length (L). The result indicates that the solenoid system is very sensitive to the change of these parameters. The solenoid acts as converge lens but may convert to diverging lens at some conditions. The best design obtained at (L=1100 mm, B=5000 gauss and R_o=150 mm).

Key words: plasma source, focusing Devices, ions beam, solenoid magnet

Introduction

The beam means a set of particles have about the same kinetic energy and move in about the same direction [1]. In addition, the particle beams can be defined as an ensemble of charged particles moving in a direction approximately parallel to the axis of the motion, which is represented by central trajectory. This axis may be curved if the beam passes through a transverse electric or magnetic field [2]. The behavior of beams can be studied by tracing a large number of individual particles or by studying the transfer properties of curve, which assumed to be bound to the particles contained in the beam [3]. The behavior of many beam transport elements can be obtained to high degree of accuracy by considering, the first order terms in the dynamic. This yields differential equations with linear solutions. This means that the displacement and angular divergence of a particle leaving an element are given in terms of the corresponding input conditions by linear simultaneous equations in which, the coefficients depend on the length and nature of the element [4,5]. Charged particle beams have continually expanding applications in many branches of research and technology, like [1,2]:

1. Thin-Film technology (Ion implantation system).
2. Production of short-lived medical isotopes.
3. Radiation processing of food.
4. Synchrotron light sources.
5. Beam lithography.
6. Recent active areas include flat-screen cathode-ray tubes.
7. Free electron lasers.

To design particle beam transport systems, we therefore adopt some organizing and simplifying requirements on the characteristics of electromagnetic fields used. The general task in beam optics is to transport charged particles from point A to point B along a desired path. We call the collection of bending and focusing magnets installed along this ideal path the magnet lattice and the complete optical system including the bending and focusing parameters a beam transport system [6].

Plasma Ion Source

The ions are extracted from the plasma of gas discharge and then accelerate this ion beam when passes through the extraction electrodes into the vacuum drift tube like figure (1) [7]. That means, the ion source is the tool that produced ion beam by ionized feed material [8,9].
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. The concave shape of the meniscus and the aperture in the source electrode produce a transverse electric field component that results in a converging beam. There are many different types of sources for the various particle species, such as light ions, heavy ions or negative ions. Most of the sources employ magnetic fields to confine the plasma. Some have several electrodes at different potentials to better control the ion beam formation and acceleration process [7]

Beam Guiding and Focusing Devices

Charged particle transport systems are typically designed to guide an input charged particle beam to the exit of the transport system with minimal particle loss and without degradation in beam quality [10].The passage of a trajectory (ray) across an individual element is given by a transformation which yields the output ray directly from the input ray [11]. A different type of focusing device like quadrupole magnets that focus only in one plane and defocus in the other and solenoid magnets that focus in two planes. Guiding particles through appropriate electric or magnetic fields is called particle beam optics or beam dynamics [6].

Particle optical systems are usually comprised of electric and magnetic bending elements like (dipole for magnet), focusing element like (quadrupole and solenoid magnet) and high-order multipoles for correction of aberrations. However, various modern systems for the transport require the detailed treatment of more advanced optical elements [5].

Solenoid Magnet

A solenoid magnet is a cylindrically coiled electromagnet. When current is flowing through the coil, the resulting magnetic field inside the term solenoid to refer to coiled magnets that are long in the axial direction (length >> width), so that the fringe fields at their ends are small compared to the long axial field inside the coil. That means, in a solenoid, the longitudinal magnetic field on the axis is peaked at the center of the solenoid, decreases toward the ends, and approaches zero far away from the solenoid [12], see figure (2) [13]. In contrast, the radial magnetic field is peaked near the ends of the solenoid. In a simple model, the longitudinal magnetic field can be assumed to be zero outside the solenoid and uniforms inside it.

A solenoid is often used to focus charged particle beams in the low energy section of accelerators and other devices such as in cathode ray tubes, image intensifiers, electron microscopes, ion microprobes and ion beam induced inertial fusion [12]. The solenoid lens is the only possible magnetic lens geometry consistent with cylindrical paraxial beams. Since the magnetic field is static, there is no change of particle energy passing through the lens; therefore, it is possible to perform relativistic derivations without complex mathematics [13].

There are three optically important regions in a solenoid magnet. At the entrance and exit regions the magnetic field has a radial and axial component, except on the magnet axis [10]. The matrices method is best to study these three regions which transfer matrices describe changes in the transverse position and angle of a particle relative to the main beam axis. The transfer matrix description of beam transport in near optical elements facilitates the study of periodic focusing. The matrix description is a mathematical method to organize information about the transverse motions of particles about the main beam axis [16]. Therefore, the transfer matrix (M) of the whole solenoid is the product of three different matrices M_1, M_2 and M_3 corresponding to the entrance fringe field, the constant axial magnetic field and the output fringe field respectively [14,15].

$$M_s = M_1 . M_2 . M_3 \qquad (1)$$

$$M_s=\begin{bmatrix}1&0&0&0\\0&1&\alpha&0\\0&0&1&0\\-\alpha&0&0&1\end{bmatrix}\begin{bmatrix}1&(1/2\alpha)\sin\theta&0&(1/2\alpha)(1-\cos\theta)\\0&\cos\theta&0&\sin\theta\\0&(-1/2\alpha)(1-\cos\theta)&1&(1/2\alpha)\sin\theta\\-\sin\theta&0&0&\cos\theta\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&-\alpha&0\\0&0&1&0\\\alpha&0&0&1\end{bmatrix}$$
(2)

$$M_s=\begin{bmatrix}C^2&CS/\alpha&CS&S^2/\alpha\\-CS\alpha&C^2&-S^2\alpha&CS\\-CS&-S^2/\alpha&C^2&CS/\alpha\\S^2\alpha&-CS&-CS\alpha&C^2\end{bmatrix} \qquad (3)$$

Where: $S=\sin\theta/2$, $C=\cos\theta/2$ and $\alpha=\sqrt{k}$

$\theta=2L\alpha$

$k=(B/(2B_0R_o))^2$

B_oR_o= the magnetic rigidity (in Gauss.mm).

B_o=magnetic field in body magnet region (in Gauss).

R_o = the radius of curvature of the central trajectory (in mm).
B= magnetic field strength (in Gauss).
L=the total length of the solenoid (in mm).

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 [15]:

$$M_s=\begin{bmatrix} 1 & 0 & 0 & 0 \\ -1/f & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1/f & 1 \end{bmatrix} \quad (4)$$

Where f is the focal length given by:

$$1/f = kL = (B/2B_0R_o)^2 L \quad (5)$$

Results and Discussion

The main parameters effect on the behavior of charged particles beam passing through a system of solenoid can be fixed, these parameters are solenoid magnetic field (B), solenoid radius (R_o) and the solenoid total length (L). So any changing in the one of these parameters gives different lens which means new beam profile.

The present system consists of two drift space regions before and after the solenoid and the solenoid ranging in length between 500 and 1500 mm, in magnetic field between 1000 and 6000 Gauss and in radius 150 and 300 mm. Table (1) shows the maximum width obtain at the end of the system for different values of (L, B and R_o). Figure (3) indicates the relation of maximum width obtained at the end of the system versus solenoid magnetic field as function of solenoid radius with constant total length of solenoid (L=700 mm), one could note the reduction of beam width with increasing the solenoid magnetic field for all values of R_o. The best width occurs for low values of R_o which means good focusing properties of solenoid as thin lens.

Figure (4). indicates the relation of maximum width obtained at the end of the system versus solenoid magnetic field as function of solenoid total length with constant radius of solenoid (R_o=150 mm), one could note the reduction of beam width with the increase of the solenoid magnetic field for all values of R_o. But this reduction does not continue for all values of B, there is specific value of B break down this reduction in the beam width and cause increasing of beam width. This behavior appears clearly for high values of L, that means the result lens became diverge lens, in other words for each value of B there are optimum values of L to produce converge lens, which means that the solenoid may be behave as diverge lens in some conditions.

Conclusions

Conclusions of the present study can be summarized as follows.

1. The solenoid lens are very sensitive to the change of (L, B and R_o).
2. The solenoid acts as converge lens but may convert to diverging lens at some conditions.
3. The best design obtained at (L=1100 mm, B=5000 gauss and R_o=150 mm).

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Table (1): Maximum width obtain at the end of the system for different values of (L, B and R_o)

Total Length L mm	Magnet field B (Gauss)	R_O= 150 mm		R_O= 200 mm		R_O= 250 mm		R_O= 300 mm	
		X mm	Mag. (X_{out}/X_{in})	X mm	Mag. (X_{out}/X_{in})	X mm	Mag. (X_{out}/X_{in})	X mm	Mag. (X_{out}/X_{in})
500	1000	16.481	3.296	16.604	3.320	16.661	3.332	16.692	3.338
	2000	15.639	3.127	16.130	3.226	16.357	3.271	16.481	3.296
	3000	14.243	2.848	15.341	3.068	15.852	3.170	16.130	3.226
	4000	12.312	2.462	14.243	2.848	15.146	3.029	15.639	3.127
	5000	9.893	1.978	12.843	2.568	14.243	2.848	15.009	3.001
	6000	7.132	1.426	11.158	2.231	13.146	2.629	14.243	2.848
700	1000	16.369	3.273	16.541	3.308	16.621	3.324	16.664	3.332
	2000	15.191	3.038	15.877	3.175	16.195	3.239	16.369	3.273
	3000	13.246	2.649	14.775	2.955	15.488	3.097	15.877	3.175
	4000	10.582	2.116	13.246	2.649	14.503	2.900	15.191	3.038
	5000	7.369	1.473	11.310	2.262	13.246	2.649	14.312	2.862
	6000	4.512	0.902	9.021	1.804	11.728	2.345	13.246	2.649
900	1000	16.256	3.251	16.478	3.295	16.580	3.316	16.636	3.327
	2000	14.744	2.948	15.625	3.125	16.034	3.206	16.256	3.251
	3000	12.257	2.451	14.211	2.842	15.126	3.025	15.625	3.125
	4000	8.906	1.781	12.257	2.451	13.863	2.772	14.744	2.948
	5000	5.261	1.052	9.811	1.962	12.257	2.451	13.619	2.723
	6000	5.000	1.000	7.027	1.405	10.335	2.067	12.257	2.451
1100	1000	16.144	3.228	16.414	3.282	16.540	3.308	16.608	3.321
	2000	14.298	2.859	15.372	3.075	15.872	3.174	16.145	3.228
	3000	11.280	2.256	13.650	2.730	14.764	2.952	15.370	3.074
	4000	7.321	1.464	11.280	2.256	13.226	2.645	14.296	2.859
	5000	4.244	0.849	8.364	1.672	11.280	2.256	12.929	2.585
	6000	8.050	1.610	5.340	1.068	8.980	1.796	11.282	2.256
1300	1000	16.031	3.206	16.351	3.270	16.499	3.299	16.580	3.316
	2000	13.854	2.770	15.121	3.024	15.710	3.142	16.031	3.206
	3000	10.316	2.063	13.091	2.618	14.403	2.880	15.121	3.024
	4000	5.901	1.180	10.316	2.063	12.592	2.518	13.854	2.770
	5000	5.031	1.006	7.001	1.400	10.316	2.063	12.244	2.448
	6000	11.822	2.364	4.331	0.866	7.682	1.536	10.316	2.063
1500	1000	15.919	3.183	16.288	3.257	16.459	3.291	16.551	3.310
	2000	13.411	2.682	14.869	2.974	15.549	3.109	15.919	3.183
	3000	9.370	1.874	12.534	2.506	14.043	2.808	14.869	2.974
	4000	4.796	0.959	9.370	1.874	11.963	2.392	13.411	2.682
	5000	7.040	1.408	5.784	1.156	9.370	1.874	11.563	2.312
	6000	15.807	3.161	4.487	0.897	6.477	1.295	9.370	1.874

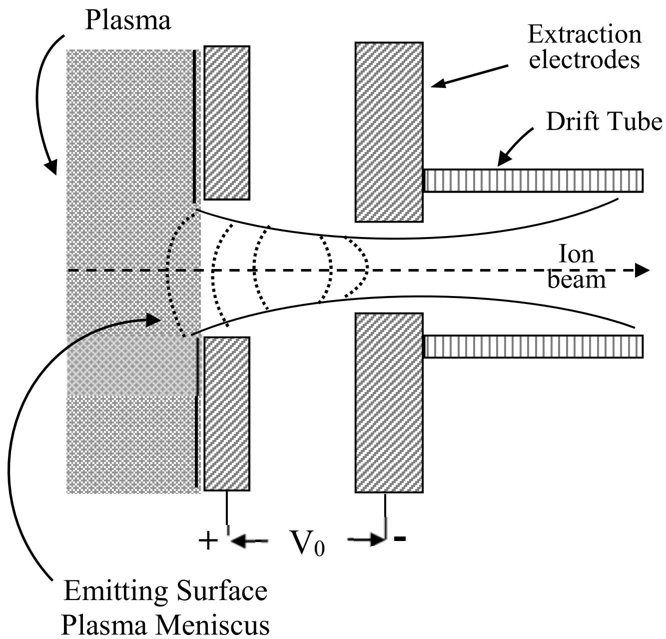

Figure No.(1): Schematic of a plasma ion source [7].

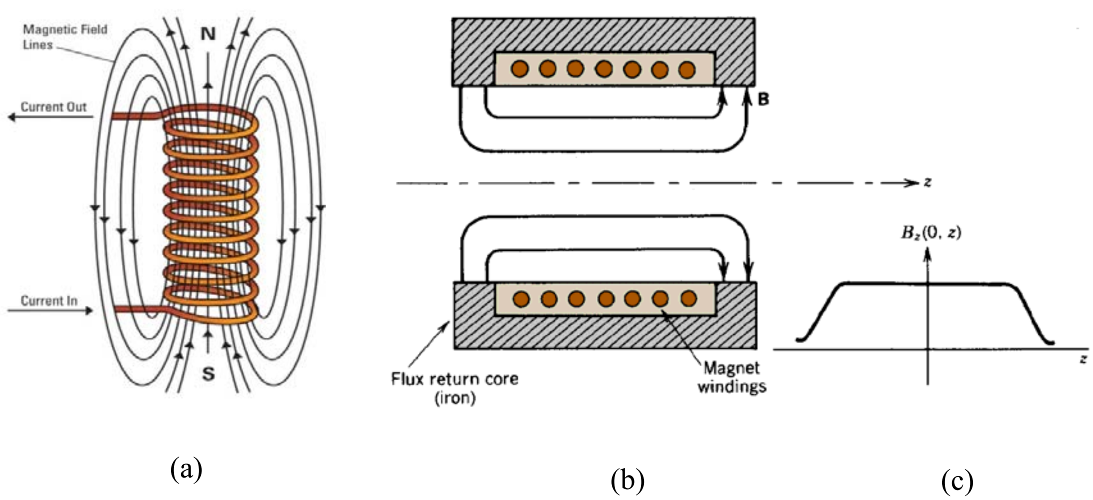

Figure No.(2):Solenoid magnetic (a) Magnetic field lines in a solenoid (b) Geometry and field lines (c) Variation of longitudinal magnetic field on $B_z(0,z)$ [13]

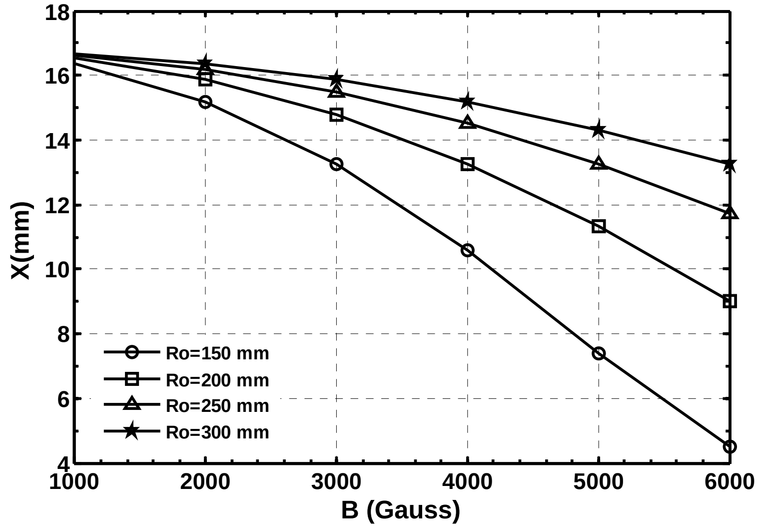

Figure No.(3): The relation of maximum width obtained at the end of the system versus B as function R_o with (L=700 mm)

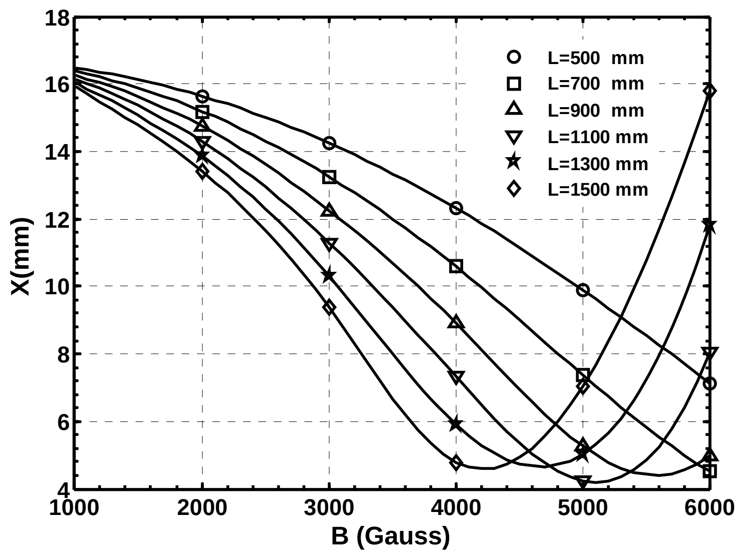

Figure No. (4): The relation of maximum width obtained at the end of the system versus B as function L with (R_o =150 mm)

تبئير حزمة ايونات في مجال مغناطيسي لولبي

بشرى جودة حسين
قسم الفيزياء/ كلية التربية للعلوم الصرفة (ابن الهيثم)/ جامعة بغداد
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الخلاصة

الدراسة الحالية تفسر تأثير المعلمات الاساسية في تصميم الملف اللولبي الحلزوني بوصفها عدسة لامة لحزمة الجسيمات المشحونة المارة خلالها. هذه المعلمات تتمثل في شدة المجال المغناطيسي للملف اللولبي (B) ونصف القطر (R) والطول الكلي للملف (L). بينت النتائج أن منظومة المغناطيس اللولبي تكون حساسة جدا لتغيير هذه المعلمات.كما يعمل الملف اللولبي عدسة لامة، لكن يتحول الى عدسة مفرقة عند بعض الشروط. أنسب تصميم نحصل عليه عندما يكون (L=1100 mm, B=5000 gauss and R_o=150 mm)

الكلمات المفتاحية: مصدر البلازما، نبائط التبئير، حزمة ايونات، المغناطيس اللولبي