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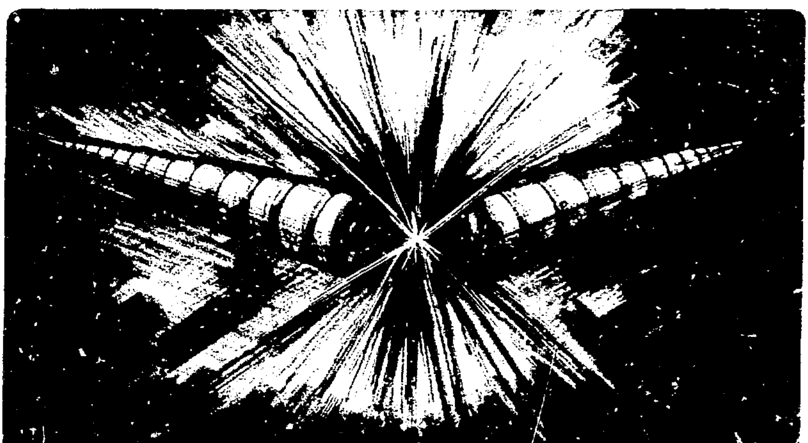

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TRANSPORT OF LOW ENERGY POSITIVE AND NEGATIVE ION BEAM BY PERMANENT MAGNETS*

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Abstract

An experimental investigation of low-energy ion beam guiding by a surface magnetic field generated by samarium cobalt magnets has been performed. It was found that magnets arranged in a multi-ring cusp configuration produced the best beam transport efficiency, in agreement with calculation of the charged particle trajectories for this particular magnet arrangement. This geometry is predicted to yield no distortion in the phase space of the beam. The effect is proportional to charge squared, and is therefore independent of the sign of the charge of the particle being transported.

Introduction

Recently, a dc self-extraction negative-ion source based on surface conversion of positive hydrogen or deuterium ions has been proposed for the production of high power neutral beams.[1] In this type of source, the H^- or D^- ions are formed on a concave, low work-function converter surface. They then accelerate radially across the plasma sheath and are self-focused at the exit aperture of the source. As a result, the H^- or D^- ions form a low energy (≈300 eV) divergent beam. Before these negative ions are accelerated to a much higher energy (>200 keV), some scheme may have to be introduced to transport the beam from the source exit to the accelerator without distorting phase space. Beam guiding by means of axial magnetic fields has been attempted.[2] Current produced cusp and surmac fields have also been proposed for guiding plasmas into confinement devices.[3,4] In this paper, an experimental investigation of beam guiding by permanent magnets is presented. Results show that some magnet arrangements can transport a low-energy divergent hydrogen beam quite efficiently.

1. Single Particle Consideration

Figure 1 shows the trajectory of a positively charged particle which travels with a velocity v from a field-free region into a uniform B-field region. In Figs. 1(a) and (b), the B field is pointing out of the paper (+x direction). The resulting $\vec{v} \times \vec{B}$ force tends to deflect the particle back into the B = 0 region. the distance of penetration into the B-field area increases with an increase of the angle of incidence (which is defined as the angle between v and the boundary of the two regions). If a wall is located at a distance greater than the deepest penetration, which occurs at normal incidence, the particle can return to the field-free region.

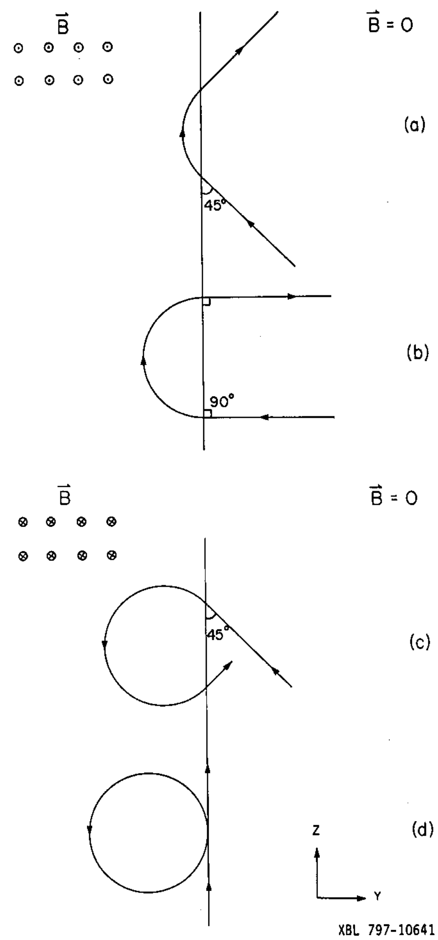

Fig. 1. Reflection of a charged particle by a uniform magnetic field.

In Figs. 1(c) and (d), the direction of the B field is reversed (-x direction). The $\vec{v} \times \vec{B}$

force deflects the same charged particle deeper into the B-field region. The distance of penetration is a minimum at normal incidence, but it increases with decreasing angle of incidence. The deepest penetration now occurs during a glancing incidence [Fig. 1(d)], provided that the magnitude of the B field is strong; otherwise the particle will be lost to the wall before it can return to the field-free region. Thus the direction of this B field is not "favorable" for transporting a divergent beam of positive charged prticles propagating in the z direction.

When permanent magnets are used to generate the multi-line-cusp fields along the beam edge, the effect on the motion of a charged particle is difficult to analyze due to the nonuniformity of the B field. However, for some magnet geometries (such as the configuration shown in Fig. 5), it is possible to estimate the maximum distance of penetration of the beam.

If A_z is the z component of the vector potential that characterizes the B field, m and q are respectively the mass and the charge of the particle, and the z axis is the direction of symmetry for the line-cusp fields, then the canonical momentum along this direction $P_z = mv_z + qA_z$ is conserved. In addition, the energy of the particle $E = mv^2/2 + q\phi$ is also a constant of the motion. Assuming the scalar potential $\phi = 0$ everywhere, then a charged particle coming from the B = 0 region with $P_z = 0$ cannot reach regions where $A_z > (2mE)^{1/2}/q$. On the other hand, a particle originating from the field-free region (A_z=0) can have a maximum value of $P_z = mv$. This particle cannot reach regions where $A_z > (8mE)^{1/2}/q$. Therefore, if the vector potential A_z of the given magnet geometry is known, the regions that are accessable to the beam particle can be found.[5]

In some magnet geometries, the line of symmetry is not along the direction of the beam propagation. The reflection of charged particles by the B field can be analyzed only by a computer. The ring-cusp magnet configuration shown in Fig. 8 has been studied in detail by Hooper[6] and Rowlands.[7]

We assume a beam is travelling in the z direction but with a finite divergence in the x direction. Consider the case in which the ring-cusps are generated by wires with currents flowing in alternating directions as shown in Fig. 2. A particle approaching the wires at a glancing angle will experience an alternating magnetic field with amplitude slowing increasing with time. If the field becomes strong enough, the particle will reverse its x direction and return towards the axis. The effect can be considered either as a reflection from a region of high magnetic pressure or as a second-order effect in which the v_xB_z force generates an oscillating v_y. The phase of y is such that the interaction with B_z reverses v_x. The v_zB_x forces alternate rapidly in time as the particle passes many wires, and thus average to zero. For the case of grazing incidence, Rowlands[7] has solved analytically the equation of motion. It was found that under appropriate conditions, the sign of v_x reverses during the interaction, with little exchange of energy between x and z motion. This result is in agreement with computer calculations shown in Fig. 2.[6]

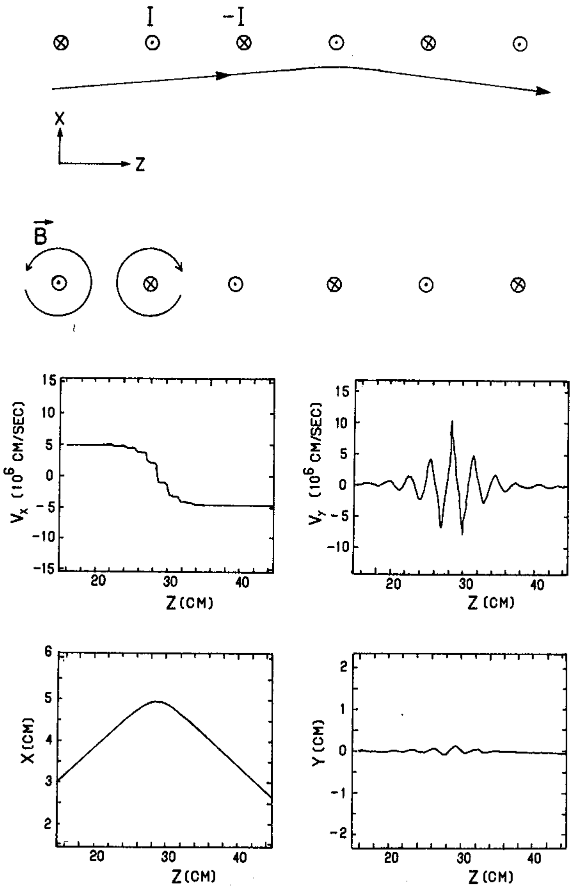

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Figure 2. Particle-wire interaction. The velocities v_x and v_y plotted in the computer output are defined in the top figure. The wires are spaced 1 cm apart in z and 10 cm apart in x.

For a rectangular array of permanent magnets, the magnetic field can be approximated by that of a line dipole located a distance δ behind the front face. If q and m are the charge and mass of the beam particle, P is the dipole strength, $(d - \delta)$ is the distance from the z-axis to the magnet pole face and L/2 is the cusp spacing, then the maximum x-velocity (on axis) of contained particles, v_c, can be expressed as:

$$v_c^2 = \left(\frac{8\pi qP}{mcL}\right)^2 \sum_{n=0}^{\infty} \left[\frac{1 + 1/2(2n+1)\sinh \frac{4\pi d}{L}}{\sinh^2 (\frac{2\pi d}{L})} \left(e^{-(2n+1)2\pi d/L}\right) \frac{\sinh^2 \left[\frac{(2n+1)2\pi(d-\delta)}{L}\right]}{(2n+1)} \right]^2 \cdot \left[1 + (v_x^o/v_z^o)^2\right]^{-1}$$

For exp $(2\pi d/L) \gg 1$, $$v_c^2 \approx \left(\frac{qP}{mc}\right)^2 \left(\frac{4\pi}{L\delta}\right)\left[1 + (v_x^o/v_z^o)^2\right]^{-1}$$

As an example, if d = 10 cm, L/2 = 5 cm, P = 2260 gauss-cm^2 and δ = 0.64 cm, then for protons, $v_c \approx 3 \times 10^7$ cm/sec corresponding to 480 eV.

II. Experimental Apparatus

A schematic diagram of the experimental arrangement is shown in Fig. 3. The apparatus has three components; an ion source, an extraction system, and a drift pipe. The ion source is a water-cooled cylindrical stainless steel chamber (20-cm diameter by 28 cm long) with the open end enclosed by a three-grid extraction system. The chamber is surrounded externally by 10 columns of samarium cobalt magnets ($B_{max} \approx$ 4 kG) to generate a line-cusp configuration for primary electrons and plasma confinement. A hydrogen plasma is produced by primary ionizing electrons emitted from two 0.05-cm diameter tungsten filaments which are biased at -60 V with respect to the source chamber (anode).

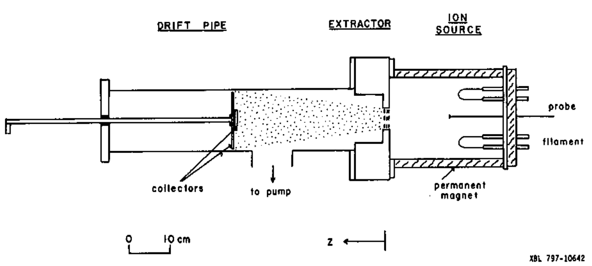

Fig. 3. Schematic diagram of the experimental apparatus.

The ion beam is extracted by means of a standard Berkeley accel-decel electrode system with the first (plasma) grid masked down to an extraction area of 5-cm diameter. This plasma grid is connected to the negative terminal of the filament and the source chamber is biased at a positive potential V_b ($\cong$300 V) relative to ground. The center grid is biased at -60 V to extract the plasma ions and to retard any backstreaming electrons. The outermost grid is electrically grounded.

The drift pipe is a 15-cm diameter and 60 cm long thin-walled stainless steel cylinder. The beam collector is a 14-cm diameter circular copper plate with the center portion (5-cm diameter) covered by a second copper plate. Both copper collectors are mounted on a moveable shaft and are biased at +3 V with respect to the drift pipe (which is at ground potential) to retain the secondary electrons produced by the beam as it bombards the collectors. The beam current at the center or outer collector is measured by a X-Y recorder. The effect on the beam current from mounting samarium cobalt magnets on the external surface of the pipe has been investigated.

III. Experimental Results

In the experiment, the source plasma was operated at an overdense condition with V_b = 325 V. As a result, the extracted ion beam had a large angle of divergence. The gas pressure in the system was kept at 1×10^{-4} Torr so that neutralization of the beam in the drift pipe region could be minimized. Figure 4 shows the beam current at the center and outer copper plates as a function of collector position when there were no magnets on the drift pipe. The beam current at the center collector I_{in} drops monotonically as z increases from 8 to 60 cm. However, the current to the outer collector I_{out} goes up as z increases, reaching a maximum at z $\cong$ 22 cm, and then decreases gradually. Since the beam is divergent, I_{out} increases as the outer collector starts to intercept the beam. As soon as the beam strikes the wall of the drift pipe, the beam current received by the outer collector will decrease. The position where I_{out} reaches a maximum then corresponds to the location where the beam starts hitting the wall. In order to study the effect of beam guiding by surface magnetic fields, the permanent magnets are mounted starting z $\cong$ 22 cm on the drift pipe.

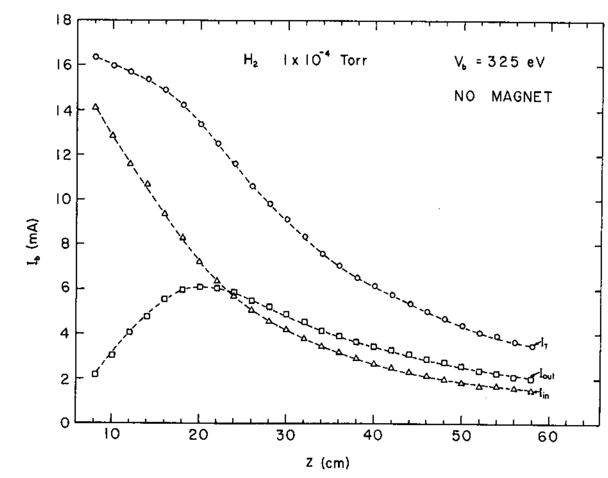

Fig. 4 Ion beam current versus collector position without the presence of permanent magnets on the drift pipe.

Four different magnet configurations have been tested. In the arrangement shown in Fig. 5, six columns of magnets are used to produce

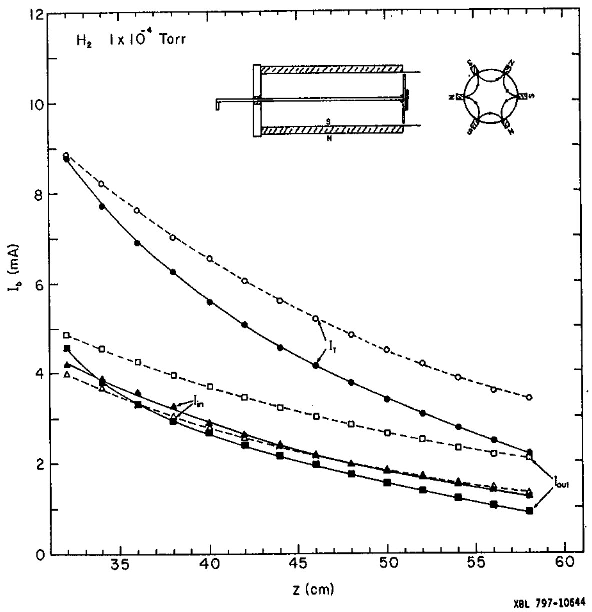

Figure 5. Ion beam current versus collector positoon with (▲■●) and without (△□○) six magnets columns on the drift pipe.

line cusps parallel to the direction of beam propagation. According to the charged particle trajectories shown in Fig. 1, one can conclude that half of the cusp field will tend to deflect the positive ion beam outward to the pipe-wall. The other half of the cusp field will deflect the ions inward. On the average, I_{in} is almost the same for the case with or without magnets. In the region where the outer collector is located, the ions have a larger angle of incidence. The B field with the favorable direction may not be strong enough to turn the ions (B_{max} ≅ 350 G). Consequently,more ions will be lost, resulting in a drop of I_{out}. In fact for this magnet geometry, the total current $I_t = I_{in} + I_{out}$ is less than the case when there are no magnets.

In the arrangement of Fig. 6, 12 line cusps are formed parallel to the beam. The magnitude of the B field with an unfavorable direction is increased to a maximum of 2.5 kG by decreasing the separation between every two other magnet columns. However, the B field with the favorable direction now drops to a maximum of 150 G. The data shows that there is no increase in I_{out}, but I_{in} increases slightly. Overall the total beam current I_t increases by approximately 10% over the case with no magnets.

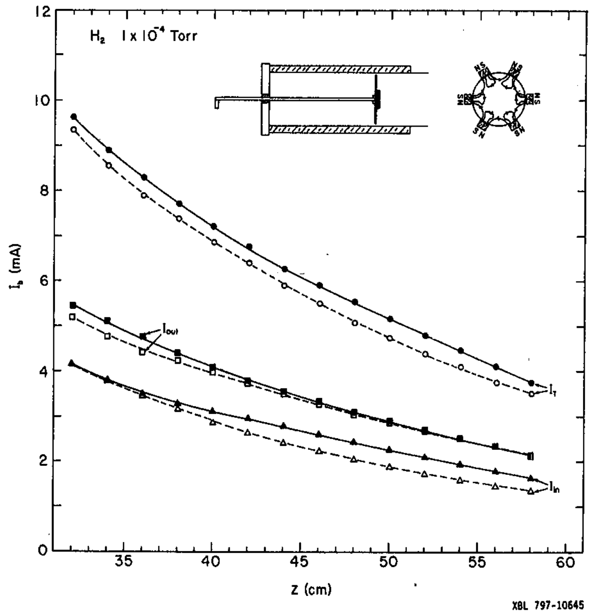

Figure 6. Ion beam current versus collector position with (▲■●) and without (△□○) 12 magnet columns on the drift pipe.

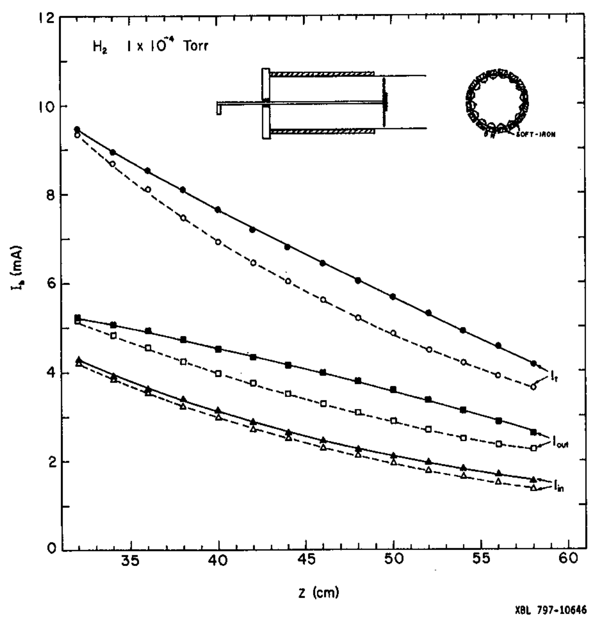

Figure 7. Ion beam curreent versus collector position with (▲■●) and without (△□○) 16 magnet columns on the drift pipe.

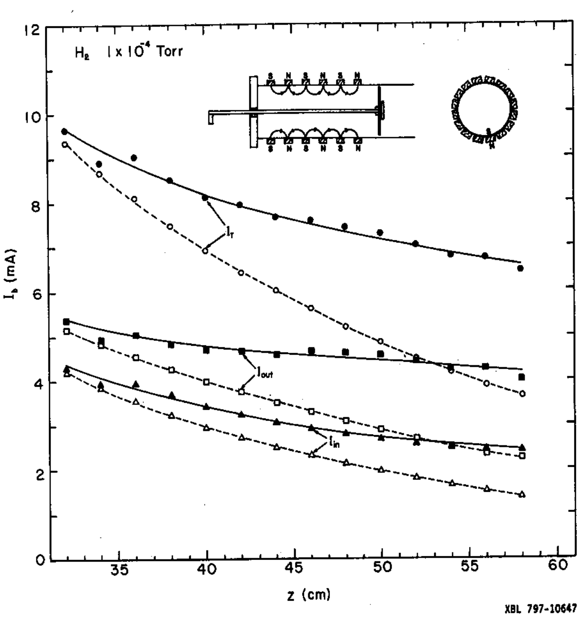

Figure 8. ion beam current versus collector position with (▲■●) and without (△□○) six rings of permanent magnets on the drift pipe.

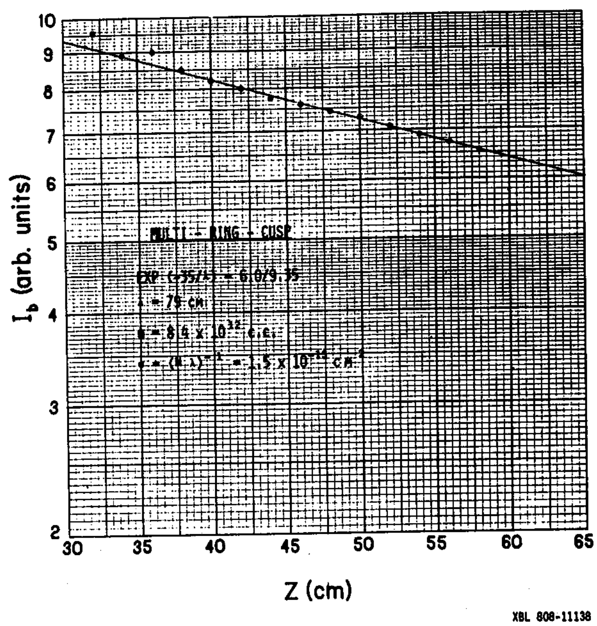

Fig. 9. A semi-log plot of the total beam current versus the axial distance for the magnet configuration in Fig. 8.

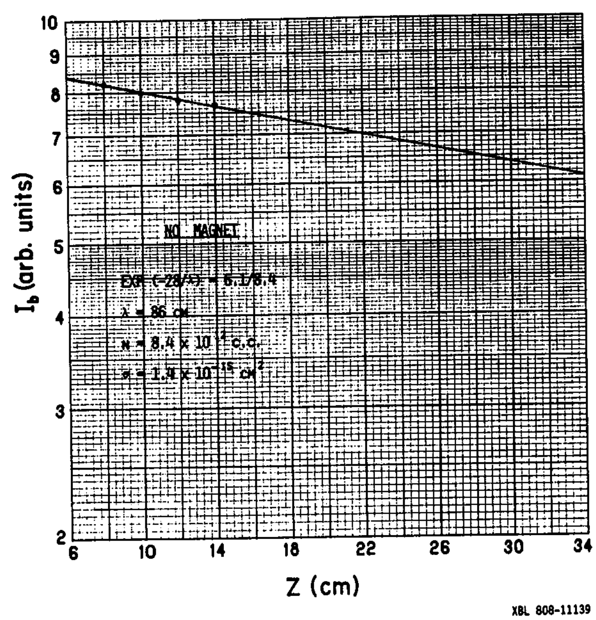

Fig. 10. A semi-log plot of the beam current versus the axial distance for z < 18 cm when there is no magnet.

In Fig. 7, the magnet columns are oriented with opposite polarity facing one another. The unfavorable B field that exists between two magnets is short-circuited through a strip of soft iron. Only the B field that has the favorable direction extends into the drift pipe. However, this B field does not penetrate very far and its magnitude is only 120 G at the wall. As a result, there is no improvement on I_{in}. But I_{out} in this case exceeds that when there are no magnets. An average increase of approximately 16% in I_t is observed with this geometry.

Figure 8 shows six rings of permanent magnets mounted normal to the beam in alternating polarity with a cusp spacing ≈ 5 cm. In this configuration, both I_{in} and I_{out} are found to be higher than when no magnets are used. In fact, a distance of 58 cm from the extraction grids, an increase of 75 in I_t is obtained. In fact, the exponential decrease in I_t as z increases (in Figs. 8 and for z < 18 cm in Fig. 4) is found to have a mean free path $\lambda \approx 80$ cm as shown in Figs. 9 and 10. This corresponds to a cross section of 1.5×10^{-15} cm^2 which is approximately equal to that of the charge exchange reaction $H_2^+ + H_2 \rightarrow H_2 + H_2^+$. Thus the total beam current I_t corrected for charge exchange, is constant, in agreement with the numerical computation of charged particle trajectories described above. In order to show that this magnet arrangement yields no distortion in the phase space of the beam, further experimental investigation of the emittance of the beam will need to be conducted.

In conclusion, the effect on the beam current from mounting samarium cobalt magnets in different geometries on the external surface of the drift pipe has been studied. It was found that magnets arranged in a multi-ring-cusp configuration (Fig. 8) produced the best beam transport efficiency. Instead of mounting the magnets on the surface of the drift pipe, they can also be assembled to form an open system to allow pumping of gas from the beam line.

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