ELECTRON CONTROLLED TRANSPORT OF INTENSE NEUTRALIZED ION BEAMS

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Abstract

Experimental results are reported for an extended transport channel for long pulse, intense, neutralized ion beams. The transport channel is defined by neutralizing electrons confined by a weak solenoidal magnetic field (ion transit time $<< 2\pi/\omega_{ci}$). Charge separation sheaths which occur when ions expand beyond the confined electron channel reflect the ions. Electrons which diffuse out of the transport region are removed by electrostatic fields. A 10 μs, 28 keV, .17 A beam of singly charged carbon ions is used to investigate the properties of the transport channel. With modest magnetic fields ($<$ 100 G), the ion current incident on a collector .75 m from the ion source is increased a factor of 2.5 over vacuum transport levels. The addition of a small transverse magnetic field, $\leq$ 5 G, decreases the transported ion current. The reduction in current is consistent with the magnetic transport channel model. The scaling of transported ion current with magnetic field strength and sweeping bias is examined. Transport systems of this type may have direct application to both the low velocity initial stages and the high current final focussing region of accelerator inertial fusion drivers.

Introduction

Large radial forces are required for the transverse confinement of high perveance ion beams. Neutralization by electrons greatly reduces the space charge effects. The neutralizing electrons can also increase the effectiveness of applied confinement forces. Robertson[1], has shown that charge separation sheaths which are set up when a neutralized beam is passed through a solenoidal magnetic lens greatly increase the focussing strength of the lens. In this work, charge separation sheaths are employed to confine an intense ion beam in an extended transport channel.

An idealized electron controlled transport system is illustrated in Figure 1. A high current ion beam enters a region with an applied solenoidal magnetic field through a localized electron source. Transverse ion energy causes the ion beam to expand during propagation. The neutralizing electrons are confined by the magnetic field. Ion expansion leaves an excess of electrons in the confinement channel. This sets up a charge separation sheath which returns the ions to the transport channel.

Radial diffusion removes electrons from the transport channel. The population of these untrapped electrons becomes significant for beams longer than the transport channel. When this occurs, the beam expands without generating the confining charge sheaths. To counteract this effect, electron sweeping bias is added to the system. The bias pulls the untrapped electrons from the system along magnetic field lines. If sufficient electron current is present, magnetic streamlines will form surfaces of virtual potential.

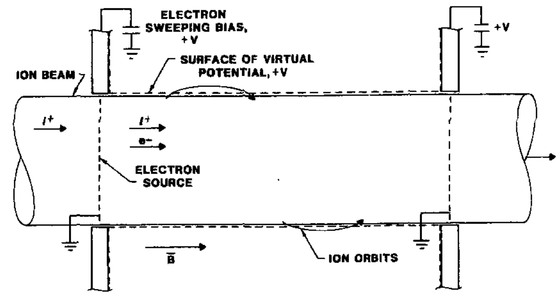

Figure 1. Idealized electron controlled transport system for intense ion beams in a weak solenoidal magnetic field.

A more detailed analysis of the system has been presented by Humphries and Lockner[2]. Included in that analysis are estimates of the sheath thickness. Based on their analysis, a sheath thickness on the order of .1 cm is anticipated for this system with modest magnetic fields ($\sim$ 100 G).

Experimental Apparatus

The experimental system is illustrated in Figure 2. A 28 keV, C^+ beam from a grid controlled ion source[3] is injected into the entrance tube. An 81% transparent mesh (.025 mm diameter stainless steel wires on .25 mm centers) is located 15 cm from the ion source. Neutralizing electrons are emitted from the mesh as needed to maintain the E_z=0 boundary condition. The neutralized ion beam propagates through the 7 cm diameter stainless steel vacuum chamber to an ion collector 75 cm from the ion source. At each end of the system are aluminum rings. Electrons which have diffused out of the transport channel are swept out of the system under the influence of the bias applied to these rings. Each ring can be biased independently. A biased collector plate measures the ion current at the exit of the transport channel. Secondary electrons ejected from the collector add to the ion signal. Therefore, the detector signal is a relative measure of the beam current. A grounded housing shields the beam and transport sheath from the collector bias. The beam enters the housing through a mesh of the type used at the transport entrance.

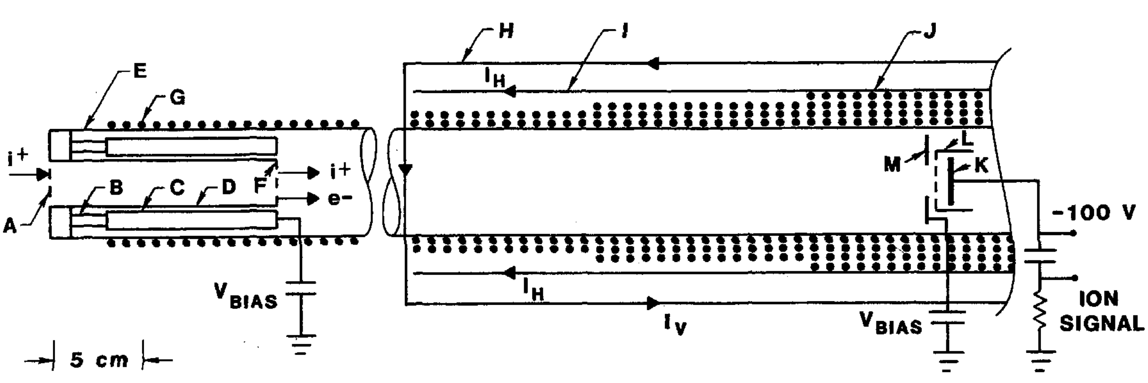

Figure 2. Electron controlled ion transport system: (a) ion injector cathode, (b) insulator, (c) upstream sweeping bias ring, (d) entrance tube, (e) vacuum chamber, (f) entrance mesh, (g) solenoidal windings, (h) vertical deflection windings (1 set of 2), (i) horizontal deflection windings, (j) programmed compression windings, (k) ion collector, (l) collector housing, (m) downstream sweeping bias ring.

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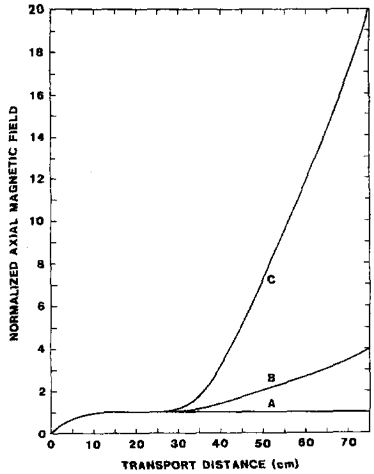


Figure 3. Variation of axial magnetic field strength along the transport channel (field strength normalized to the entrance field value, B_z at z=15 cm): (A) solenoidal field only, compression index = 1, (B) design compression field, compression index = 2, (C) maximum system compression, compression index = 5.

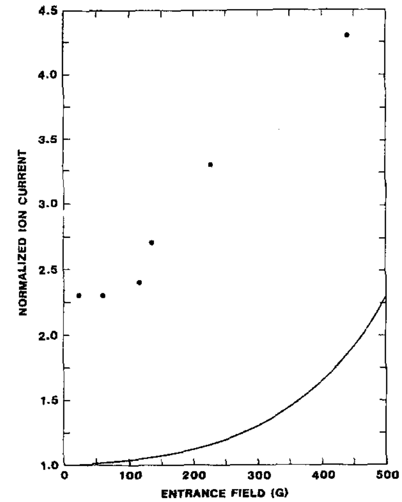


Figure 5. Scaling of transported ion current with magnetic field, compression index = 2, sweeping bias = +200 V (ion current normalized to vacuum transport level). Solid curve: transport enhancement due to solenoidal ion focussing, based on single particle orbits.

Surrounding the transport chamber are four sets of magnetic field windings. The first winding is a solenoid extending the length of the transport region. The maximum pulsed solenoidal field is .5 kG. Halfway down the system a set of programmed compression windings begin. These windings produce a field which increases linearly along the transport channel. A pulsed field of 2 kG can be produced at the location of the ion probe. The range of magnetic field profiles which can be produced by these two sets of windings are displayed in Figure 3. The field profile is described by the magnetic field compression index. The compression index is defined as the square root of the ratio of field strength at the collector to that at the entrance. This quantity expresses the ratio of the radius of a magnetic streamline, and hence the transport channel, at the entrance to its radius at the exit. The final two sets of windings produce magnetic deflection fields in each of the transverse planes. These d.c. driven coils produce a maximum field of 15 G.

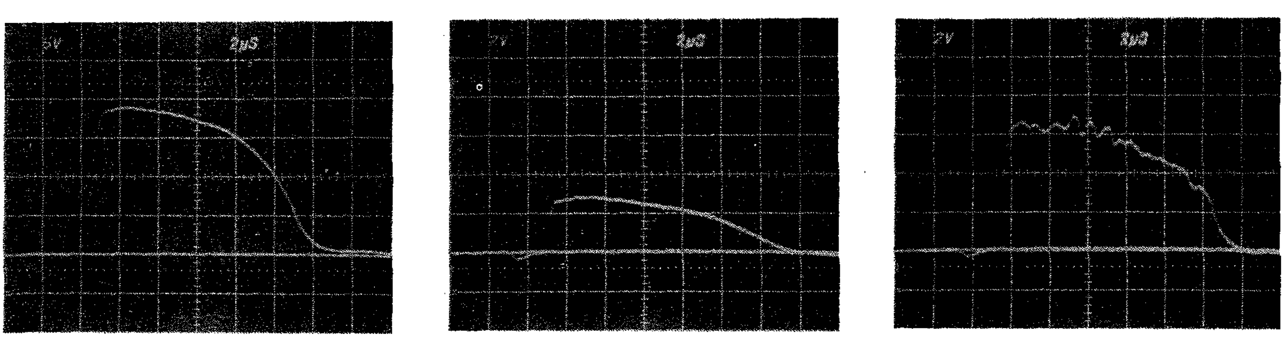
The experimental system was designed for a compression index of two rather than the linear solenoid illustrated in Figure 1. The inner diameter of the downstream bias ring, also the ion probe aperture, is halved when the compression index is increased from one to two. As a result, the ion current collected by the probe is reduced by 75% for vacuum transport. The geometric change does not, however, reduce the current transported to the collector in the electron controlled channel. Therefore, there is a relative increase in transported current with electron control. This increases the sensitivity of the current measurement to the effects of electron control.

Experimental Results

The beam current entering the transport region was measured immediately downstream from the entrance mesh. The ion probe signal at that location is displayed in Figure 4 (a). The current collected by the probe 60 cm downstream, Figure 4 (b), is 13% of the initial beam current. Fields were applied to set up an electron controlled transport channel. The magnetic field was 23 G at the channel entrance and 92 G at the probe. A bias of +200 V, applied to both bias rings, produced the electron sweeping fields. The transported ion current, Figure 4 (c), is more than twice the vacuum transport current.

The scaling of transported ion current with field strength is illustrated in Figure 5. For electron controlled ion transport to be effective the charge separation sheath must be significantly smaller than the beam radius. Based on estimates of this sheath thickness, enhanced ion transport was expected at fields of less than 100 G. The ion source is non-immersed. Therefore, the ions are subject to focussing by the solenoidal field. Single particle calculations indicate that magnetic focussing should become significant when the average solenoidal field is 400 G or more. This average field level is reached when the entrance field is 200 G. Increases in ion current at high magnetic fields are consistent with this model.

The effect of varying the magnetic compression was investigated. The results are summarized in Figure 6. The transport channel was designed for a compression index of 2. For lower compression, one would expect the ion current to be proportional to the square of the compression, proportional to the entrance channel area. Above the design compression, no further increase in current would be expected. The ion current continues to increase with compression beyond the design value. The rate of increase is however, significantly lower than the index squared scaling. The continued increase in transported ion current with compression is



a b c

Figure 4. Comparison of vacuum and electron controlled transport, uncalibrated ion probe: (a) ion current at transport channel entrance (15 cm), (b) vacuum transport, probe at 75 cm, (c) electron controlled transport; entrance field = 23 G, compression index = 2, sweeping bias = +200 V, probe at 75 cm.

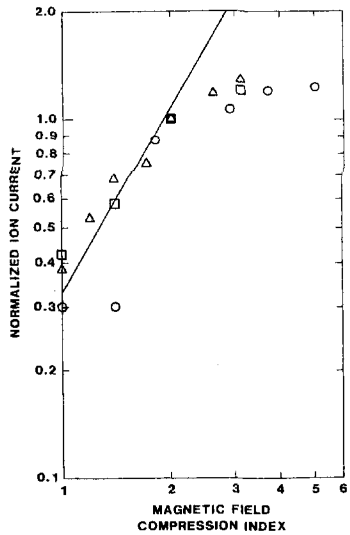


Figure 6. Scaling of transported ion current with magnetic field compression, sweeping bias = +200 V, entrance field: ○, 23 G; □ & △, 230 G (ion current normalized to index = 2 level). Solid curve: compression index squared scaling.

believed to be due to the recapture of ions which had escaped the confinement channel.

For an equilibrium transport channel, electrons which diffuse out of the confinement channel must be removed. Electrostatic sweeping fields to remove diffusing electrons are produced when positive bias is applied to the rings at each end of the system. Removal of this bias significantly reduces the effectiveness of the transport system, as illustrated in Figure 7. Negative bias further decreases the transported ion current. The effect of the sweeping fields saturates at +200 V bias. At the saturation bias, the magnitude of the electron current collected by the bias rings is 40% of the original ion current. Of that current, 95% is collected by the downstream ring. Grounding of the upstream ring produced no change in the performance of the transport system. This indicates that the electron sweeping fields are not set up in the upstream portion of the transport channel. This is consistent with the loss of a significant portion of the original

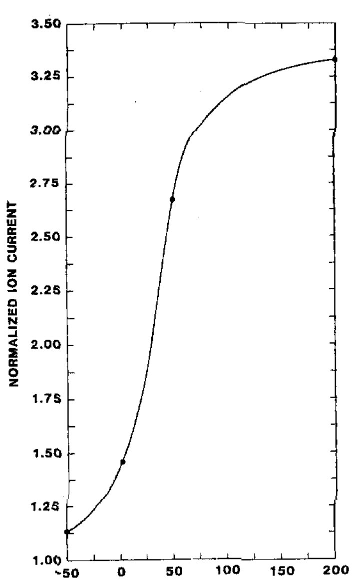


Figure 7. Scaling of transported ion current with electron sweeping bias, entrance field = 230 G, compression index = 2 (ion current normalized to vacuum transport level).

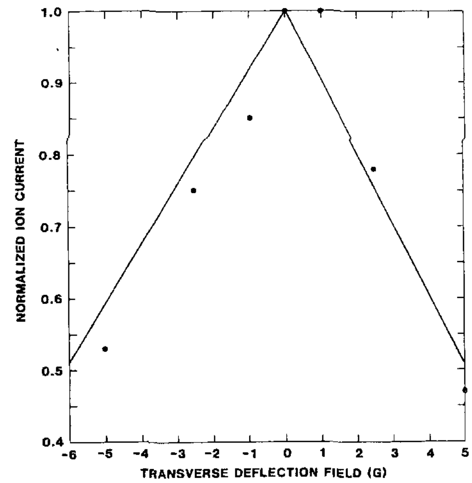


Figure 8. Scaling of transported ion current with vertical deflection field, entrance field = 23 G, sweeping bias = +200 V, compression index = 2 (ion current normalized to non-deflected level). Solid curve: predicted scaling biased on axial field deflection.

beam, which indicates that the diffusing electrons are removed over only a portion of the channel length.

The effect of transverse magnetic fields was examined. Vertical deflection fields up to 5 G were applied to the final 30 cm of the transport channel. The normalized ion current collected at the probe is plotted against the deflection field strength in Figure 8. A reduction in ion current occurred with both polarities of magnetic field. Similar results were obtained for deflection in the other transverse plane. Direct magnetic deflection of the ions would be on the order of .1 cm which would not account for the observed results. The effect of the deflection field may be modeled as a transverse displacement of the axial field, and hence the transport channel, upstream from the collector. Therefore, as the beam enters the transport region it is offset from the transport channel. The overlap in beam and channel inlet area determines the current transported to the probe. This overlap is a function of channel displacement and beam radius. The channel displacement is $(B_t/B_z)Z$, where B_t and B_z are the transverse and axial fields and Z is the distance over which the deflection field is applied, 30 cm. The beam area was left as a free parameter to fit the model to the data. The fit shown in the figure required a beam radius of 3.5 cm. This is the radius of the transport chamber wall. Ineffective removal of diffusing electrons in the upstream portion of the transport channel would account for the substantial beam expansion.

Conclusions

The present experiment demonstrates the feasibility of electron controlled equilibrium transport for intense, neutralized ion beams. Magnetic fields of less than 100 G and sweeping biases on the order of +100 V are sufficient to create a confined electron transport channel. The experimental results are consistent with the formation of such a channel. Radial diffusion of electrons, which results in beam expansion, is believed to be the primary cause of ion loss in this system. Improved removal of these electrons should significantly increase the effectiveness of this transport system. Future work will concentrate on alternative geometries which will more effectively apply electron sweeping fields.

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References

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