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THE LBL NEUTRALIZED BEAM FOCUSING EXPERIMENT*

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Summary

An intense neutralized Cs^{+1} beam has been focused by an electrostatic polarization field induced by a solenoidal magnetic field of 10-25 gauss. This report describes the experiment and compares the results with the predictions of an analytic linearized fluid model and a particle-in-cell simulation which treats the motion of the warm electrons in detail.

Introduction

Robertson¹ has pointed out that the focusing strength of a solenoid for positive ions may be enhanced by many orders of magnitude if a co-moving stream of electrons is present. When the two beams enter a solenoid, the electrons are radially compressed; if the densities are sufficiently high, the resulting charge separation creates a large radial electric field which focuses the ions. If successful, such a scheme should find many applications, notably in final transport and focusing of heavy ions as a driver for inertial confinement fusion.

Experimental Arrangement

The experimental configuration is shown in Fig. 1 and the relevant parameters listed in Table 1. The Cs⁺¹ ions produced by contact ionization on a nickel hot plate coated with iridium and extracted at full voltage through a hexcell stainless steel grid 5 mm deep. The small fraction of the ion beam intercepted by the grid generates a sufficient number of electrons to prevent space charge blow up until the beam reaches a hot wire electron source of 7.6 cm radial aperture, where the hot ($_{\sim}$ 100 eV) grid electrons are replaced by cooler (\sim 4 eV) ones.³ The combined beams then enter a solenoid surrounding DT2 (drift tube #2 in Fig. 1) and continue on to the diagnostic tank where the focusing effect is observed.

Diagnostics include Faraday cups for intensity and profile measurements, capacitative probes for measuring

potentials outside the beams and a total current pick-up using DT2.

Table I Experimental Parameters

Ion	Cs ⁺¹
Ion Energy	200-300 keV
Current Density	1.2 mA/cm ² @ 200 keV
Magnetic Field	< 40 G
Source Emittance	4 x 10 ⁻⁷ ,πm rad
Background Pressure	< 2 x 10 ⁰ torr

Neutralization Measurements

An un-neutralized beam characterized in Table 1 expands rapidly; substantial neutralization is required for it to travel to the diagnostic tank and neutralization to better than 99.5% is required to focus the beam. The action of the hot wire source was checked by running with the solenoid off and observing the beam profile at the diagnostic tank and the residual electric field outside the beam in DT2 as functions of wire temperature. At wire temperatures above 2350 K, there was no significant change in the profile and neutralization appeared to be about 99.9%.

Effect of the Magnetic Field

Fig. 2 shows ion current density on axis at the diagnostic tank, as a function of solenoid field strength for the 1.2 mA/cm² beam, at 200 keV. The peak corresponds to a waist in the beam and thus the field strength corresponding to that focal length; a discrepancy of about 30% from Robertson's simple formula is due to electron kinetic effects uncovered in the particle simulation results described in the next section. Faith in this explanation derives largely from the solid curve in Fig. 2, which is the behavior predicted by simulation. Also, the simulation predictions of the potential are in excellent agreement with capacitative probe measurements. The beam energy was varied between 200 and 300 keV and the magnetic field for peak density varied correspondingly.



Fig. 1 Experimental Layout

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Fig. 3 Transverse Beam Profiles at Diagnostic Tank

Fig. 3 shows three beam profiles, one with the solenoid off, one at 20 gauss and one at 20 gauss, but with the hot wire source turned off. The need for good neutralization by low temperature electrons is apparent; with the source off, the beam has expanded. More detailed measurements have shown that, with the source off, some 3% of the electrons from the hexcell structure are reflected at the entrance to the solenoid. The resulting excess positive space charge more than cancels any focusing action. The reflection of hotter electrons is consistent with a theoretical observation that electrons with an initially positive angular momentum have more difficulty in penetrating the magnetic barrier.

Fig. 4 gives the measured line charge excess, $(\lambda_{a} + \lambda_{i})/\lambda_{i}$, as a function of the magnetic field. Simulation comparison curves are also given. The line charge excess does not grow as rapidly as the fluid theory predicts. This observation is consistent with model transverse equilibrium calculations. In these models deviations from the fluid behavior begin when macroscopic charge separation occurs.



Fig. 4. Line Charge Excess vs. Applied Magnetic Field

Computer Simulations

The two and one-half dimensional PIC code MASK was used in a cylindrically symmetric configuration. Poisson's equation is solved at each time step with the electrons treated as rings of charge. The ions are treated as a charged background with the front moving forward in time. The two beams start from an electron emitting surface outside the magnetic field with specified electron temperature and traverse the fringing field of the solenoid and enough of the uniform field region to establish an equilibrium situation. Finally, the radial electric field thus obtained is used to determine the inward deflection of the ions while in the solenoid. At high magnetic field strengths, the deviation between the simulation and experiment in Fig. 2 may be attributed to this thin lens approximation. The single free parameter is the initial electron temperature, which is chosen for a best fit to the experimental results; the best value is close to that inferred from the measured residual lack of neutrality.

Fig. 5 shows a typical scatter plot of v_{θ} vs. r in the uniform field region. The solid line is the rigid rotor prediction of fluid theory. The fact that v_{θ} is less than ideal is substantiated by the argument invoked earlier to account for the reflection of hot electrons.



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Fig. 5 Simulation Scatter Plot for Electrons in the Uniform Field Region

Fig. 6 is a plot of E_r vs. r, together with the straight line predicted by fluid theory. Simulation results are noisy; the curve is obtained by averaging over 30 axial positions and the error bars are two standard deviations wide. The non-linearity of E_r , which is detrimental to the use of such a device as a lens, can be reduced by decreasing the magnetic field or by decreasing the electron thermal velocity relative to the beam longitudinal velocity.

Conclusions

It has been shown that an ion beam can indeed be focused by a 10-25 gauss solenoid with the help of co-moving electrons, that the simplest fluid theoretical description is not wildly in error, and that computer simulation can model the physical processes quite well. Since electrons moving at the same velocity as such a slowly moving ion beam would have a kinetic energy of less than 1 eV, it is not surprising that deleterious thermal effects should be substantial in this experiment. However, the level of agreement between theory and experiment leads us to be optimistic about the usefulness of such a scheme for intense beams of more rapidly moving ions.



Fig. 6 Radial Electric Field Inside the Lens Computed by the Simulation

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