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Reduction of radial losses in a pure electron plasma

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A new pure electron-plasma containment apparatus exhibits radial losses approximately 20 times smaller than the prior apparatus. However, the new containment times show the same $(L/B)^{-2}$ scaling with plasma column length and magnetic field as obtained previously. The radial transport is apparently induced by small irregularities that break the cylindrical symmetry of the magnetic and electric containment fields. The fact that the two devices show the same $(L/B)^{-2}$ scaling suggests the dominance of a single generic process, although this process has not yet been identified.

A number of plasma physics and atomic physics experiments are based on confinement of unneutralized electrons or ions in cylindrically symmetric traps.[1–6] For the experiments reported here, a cylindrical column of electrons is confined by an axial magnetic field, and by negative potentials applied to electrodes at the ends of the column. Since the axial confinement is energetically assured, the plasma is lost only by radial transport across the magnetic field. This radial transport is constrained by conservation of the total canonical angular momentum of the particles and fields; the plasma can expand radially only if this angular momentum is changed as a result of external torques acting on the plasma.[7] Electron–neutral collisions can provide a torque and produce plasma expansion, with a rate proportional to the neutral pressure.[8,9] However, for the present experiments, the pressure is sufficiently low that electron–neutral collisions do not significantly contribute to the transport.

Rather, we observe plasma expansion as a result of an "anomalous" transport process that is independent of pressure. This transport is probably caused by small azimuthal asymmetries in the applied magnetic or electric fields. Experiments on a prior apparatus established that the anomalous transport rate depends strongly on the length L of the plasma column, as well as on the magnetic field B. With the magnetic field of the apparatus aligned for maximum cylindrical symmetry, the transport rates were observed to scale as $(L/B)^2$ over more than five decades.[1]

A new apparatus has been constructed, with particular attention given to minimization of construction asymmetries in the electric and magnetic field structures. The magnetic solenoid was wound more accurately, the use of permeable materials was minimized, and the cylindrical containment electrodes were fabricated and aligned to closer tolerances. We find that the anomalous transport rates on the new apparatus show the same $(L/B)^2$ scaling, but with a rate coefficient 20 times smaller. This suggests the dominance of a single transport mechanism in both apparatuses, although this process has not yet been identified. Since all containment devices will have asymmetries, we believe this transport will be generic to all non-neutral-plasma experiments in this geometry. Further, it may have relevance to asymmetry-induced ion transport in neutral devices such as tandem mirrors.[10–12]

The cylindrical containment electrodes for the new apparatus are shown schematically in Fig. 1. There are eight electrically isolated cylinders of radius $R_w = 3.81$ cm; all have length 7.62 cm except for L2, which is 3.81 cm long. One cylinder has four electrically isolated wall sections that can be used to launch and detect waves, but which are connected to a ground for these experiments. The containment electrodes are in a uniform static magnetic field that is varied over the range $33 \leqslant B \leqslant 375$ G. The containment region is evacuated to an operating pressure $P \leqslant 10^{-10}$ Torr.

The system is normally operated in an inject, hold, dump/measure cycle. Electrons emitted from a tungsten filament and grid assembly are trapped within the grounded cylinders between a dump gate (e.g., G2) and an injection gate (e.g., G1) by sequenced application of negative voltages to the dump and injection gates. The length of the trapped plasma column can be varied over the range $4 \leqslant L \leqslant 40$ cm, determined by the cylinders chosen for confinement and by the voltages applied.

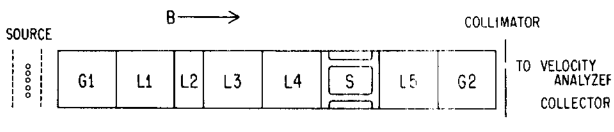

FIG. 1. The cylindrical containment electrodes.

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The trapped electron plasma initially has an approximately Gaussian radial profile, with central density $n_0 \approx 1.2 \times 10^7$ cm^{-3} and radius $R_p \approx 1.5$ cm, giving a line density of approximately $\pi R_p^2 n_0$ cm^{-1}. The electron space charge is totally unneutralized, so there is a radial electric field that causes the plasma column to rotate about its axis. The electrostatic potential at $r = 0$ is typically 40 V negative with respect to the grounded walls. The initial plasma typically has thermal energy varying between $kT = 0.5$ eV at $r = 0$ and $kT = 1.5$ eV at $r = R_p$, although these temperatures increase substantially (as a result of Joule heating) as the plasma expands radially.

After a chosen confinement time t, the dump gate is pulsed to ground potential, allowing the remaining electrons to stream out axially to the collection electrodes. A collimator singles out the electrons at a particular radial position for density and temperature measurements; the density is obtained directly from the charge collected, whereas the temperature is obtained from electrostatic energy discrimination with and without a mirroring magnetic field.[13] The data from a large number of machine cycles with different confinement times and different collection radii allow us to construct the time evolution of the confined plasma, i.e., $n(r,t)$ and $T(r,t)$.

We characterize the radial transport by the time τ_m required for the density at $r = 0$ to decrease by a factor of 2 as a result of radial expansion by a factor of $\approx\sqrt{2}$. The measured evolution times τ_m depend on both the magnetic field and the plasma length, scaling approximately as $(L/B)^{-2}$. The data from both apparatuses are shown in Fig. 2: the solid symbols are from the new apparatus, while the hollow symbols are from the prior apparatus.[1] A best slope-2 logarithmic fit to the new data gives

$$\tau_m(\text{new}) = 0.32\ (L/B)^{-2}, \qquad (1)$$

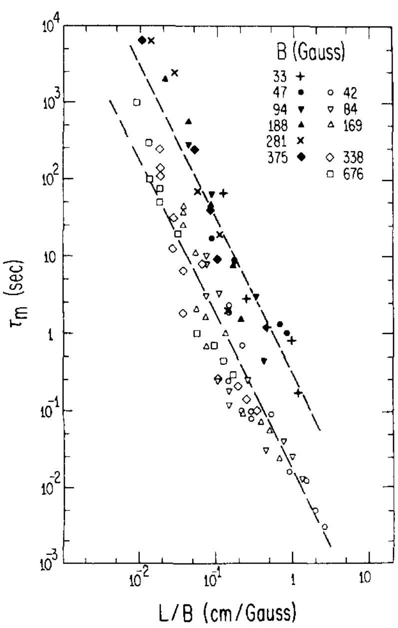

FIG. 2. Measured evolution times τ_m versus plasma length L divided by magnetic field B for the new apparatus (solid symbols) and for the prior apparatus (hollow symbols).

as shown by the upper dashed line. The dashed line shows the fit to the old data, given by $\tau_m(\text{old}) = 0.016\ (L/B)^{-2}$. The same transport process appears to dominate in both apparatuses, with a rate coefficient differing by a factor of 20.

Both data sets in Fig. 2 show approximately a decade of variation around the general scaling lines. These variations are not a result of noise in the system, but rather represent reproducible effects. Different containment regions of equal lengths generally give somewhat different containment times. In addition, there appear to be resonance effects giving degraded confinement at particular magnetic fields; these may be associated with resonances between the stationary asymmetries and doppler-shifted waves in the rotating plasma column.[10,11,14] The longest confinement volume (L1–L5) includes the sectored cylinder S, and confinement times for this volume are generally less than predicted by Eq. (1); this may be associated with the greater misalignment or greater electrical resistance with the wall sections.[15]

It should not be inferred that the data show that the scaling exponents for L and B are identical, or that the exponents are exactly 2. No detailed linear regression fit was performed, and it does not seem warranted for several reasons. The initial plasma density and temperature vary somewhat with L and B, and they vary substantially during the evolution time τ_m. Plasma expansion results in Joule heating of the electrons, but collisions with neutrals may remove a significant amount of this thermal energy.[8,9] Further, electron–electron collisions can cause internal transport of particles and energy (without any bulk radial expansion) on a time scale that is similar to τ_m for the shorter containment volumes.[16,17]

We believe the significance of the data to be in the suggestion that a simple L and B scaling may be generic to these cylindrical containment apparatuses, since all devices will have construction asymmetries. The two apparatuses considered here are similar in that each uses gold-plated copper containment electrodes in a stainless steel ultra-high-vacuum system, inside a magnetic solenoid with approximately 1500 turns. The two apparatuses differ mainly in the design and fabrication efforts to reduce the electric and magnetic asymmetries. Electric asymmetries were reduced by making the containment cylinders thicker (0.38 vs 0.13 cm) so they would remain cylindrical under assembly stresses, and by improving the alignment of one cylinder with another (± 10 vs ± 50 μm). The magnetic asymmetries seem in retrospect to have been more significantly reduced. The new solenoid maintains much closer tolerances on the placement of the wires (± 0.01 vs ± 0.1 cm) by elminating curvature and sag from the inner structural tube. Magnetic irregularities were further reduced by eliminating the internal stainless steel ($\mu \approx 1.003$) support rails and hangars used to position the copper electrodes in the older device, and by machining the stainless steel vacuum tube to be straight and uniform. The magnetic asymmetries were thus probably reduced on both the long and short spatial scales.

The observed transport scaling can be considered from the perspective of perturbations to single-particle trajectories. The theory of single-particle resonant transport has been extensively developed for application to ion transport in neutral-plasma devices such as tandem mirrors.[12] This theory considers the enhanced radial drifts that occur when a particle remains in phase with an asymmetry as the particle bounces axially and drifts azimuthally. In the simplest case, this happens when the bounce time equals the rotation time. In our device, a thermal particle bounces axially in a time $\tau_b = 2L/\bar{v}$, and drifts around the axis in a time $\tau_r = 2\pi rB/cE(r)$. For $kT = 1$ eV and $n = 1.2\times 10^7$ cm^{-3}, we obtain $\tau_b/\tau_r = 8(L/B)$. Our data, with $10^{-2} < L/B < 1$, thus span a range around $\tau_b = \tau_r$. However, no global signature of this resonance is seen in the data of Fig. 2.

Experiments are currently in progress to measure the transport induced by intentionally applied electric and magnetic field pertubations.[10] In these experiments, it has become apparent that one must consider the collective response of the plasma in order to obtain the perturbation fields inside the plasma. Since the plasma is rotating, even zero-frequency perturbations can linearly excite plasma modes.[14] Furthermore, various nonlinear couplings have been considered theoretically, by which static asymmetry fields can transfer angular momentum to plasma modes and particles.[11] While some correspondence between theory and experiment has been seen, no explanation for the $(L/B)^2$ scaling has as yet been developed.

In summary, we have observed radial loss rates scaling approximately as $(L/B)^2$ on two electron-plasma containment apparatuses. We believe this radial transport is induced by small azimuthal asymmetries in the electric or magnetic containment fields. The mechanism by which asymmetries couple angular momentum into the plasma and thereby induce radial transport is not yet understood. More care was taken to reduce these asymmetries in construction of the second apparatus, and loss rates were reduced by a factor of 20.

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Pinch dynamics in thin foil relativistic electron beam diodes

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Time-resolved K_α emission from targets struck by relativistic electrons is used as a diagnostic of the electron flow in pinch relativistic electron beam diodes. Pinch dynamics in thin foil anode diodes are studied. A transition from a regime of reflexing pinch to a regime of flow dominated by ion emission from the anode is observed. Current fluctuations in the pinch region are also detected.

The pinch flow of electrons in diodes generating intense beams of either electrons or ions is important in the study of various problems of high-energy density physics. In this Brief Communication we report on the study of some properties of this flow, using time-resolved K_α spectroscopy diagnostics. In this method we study the K_α x-ray lines produced by the beam in several foil targets, allowing space- and time-resolved observations.

The flow of electrons in large aspect ratio diodes using thin foil anodes is of practical interest because such diodes are used for generating intense ion beams[1] and microwaves.[2] A point of interest is that the electron pinch mechanism in these diodes is different from that in diodes using thick anodes. As was shown in experiments and simulations,[3] the pinch process in thin foil anode diodes with hollow cathodes has three stages. First, the anode area opposite the emission area of the cathode is heated by the reflexing motion of the electrons. At this stage a small fraction of the current

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