PURE ELECTRON PLASMA EXPERIMENTS

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Pure electron plasmas are easily contained in cylindrical geometries similar to EBIS devices.[1–7] The purpose of this talk is to describe a few experimental perspectives and techniques on electron plasma containment which might be relevant to some aspects of EBIS operation.

My remarks will fall into 4 general areas:

(1) The magnetic containment of electrons inside conducting cylindrical tubes is very sensitive to the magnetic alignment, and this property could possibly be utilized to align the various fields in an EBIS;

(2) The ions in a high-field EBIS would be magnetically confined without the electron beam, and the ion plasma containment properties can be estimated by scaling from electron plasma containment properties;

(3) Detection of azimuthally asymmetric waves by wall sectors can be used to diagnose the beam-plasma interaction, and feedback techniques could possibly be used to remove an $l=1$ diocotron mode in the ions;

(4) A magnetically-confined ion plasma in isolation will relax to a confined global equilibrium state which may be manipulated (e.g. cooled) for various purposes.

Magnetic Containment

The simplest cylindrical containment geometry is shown in Figure 1. The entire apparatus is in a uniform magnetic field B_z, and evacuated to about 10^{-10} Torr. The system is repetitively pulsed in the following sequence. Initially cylinders A and B are grounded, and cylinder C is biased strongly negative. Electrons emitted from a negatively biased thermionic source[2,3] then form a column from the source through cylinder B. When cylinder A is biased negative, the electrons are axially trapped by the electrostatic fields. Only the magnetic field gives radial confinement, and some radial transport may occur with time.

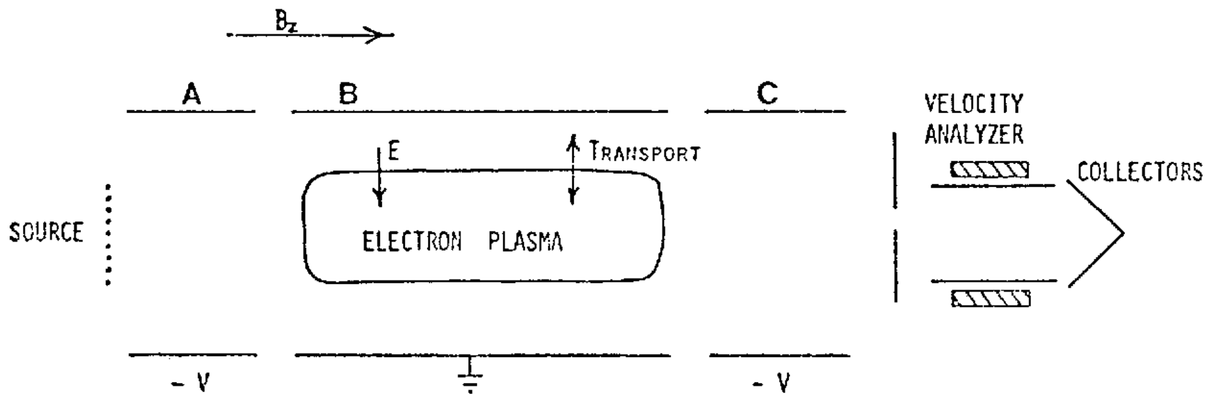

Figure 1. The cylindrical containment geometry.

After a containment time t, cylinder C is pulsed to ground potential, and the electrons stream along field lines to collimators, velocity analyzers, and collectors. Repetition of the cycle many times with different containment times and different collection radii allow us to construct the density and temperature evolutions $n(r,t)$ and $T(r,t)$. A typical density evolution is shown schematically in Figure 2a. Here, we define the time τ_m to be the time required for the central density to decrease a factor of two due to radial expansion.

The magnetic containment of the electron plasma is most readily understood in terms of the total canonical angular momentum, given by[1,5]

$$P_\theta = \sum_j \left[m v_{\theta j} r_j + \frac{q_j}{c} A_\theta(r_j) r_j \right] ,$$

where $A_\theta(r)=Br/2$. The limit of large field is particularly simple, in that the mechanical part of the angular momentum is negligible. Since we have only electrons with $q_j=-e$, we may write

$$P_\theta \approx \frac{-eB}{2c} \sum_j r_j^2 .$$

To the extent that P_θ is conserved, the mean square radius of the plasma cannot change. (In contrast, if there were both positive and negative charges, an oppositely charged pair could move across the field without changing P_θ.)

The plasma can expand only if azimuthally asymmetric forces from outside the plasma act on the particles. The time τ_m thus characterizes the time required for these external torques to decrease the angular momentum of the plasma by about a factor of two.

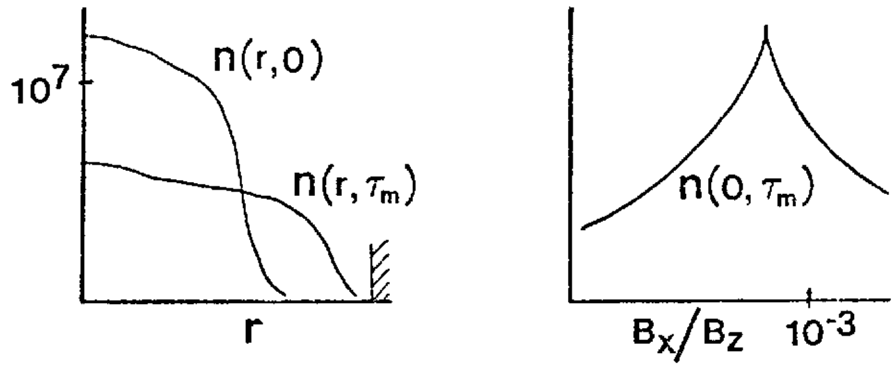

Figure 2. a) Typical density profiles at $t=0$ and $t=\tau_m$;

b) Dependence of central density at $t=\tau_m$ on magnetic alignment.

Alignment

The amount of plasma expansion that will occur in a given time depends strongly on the alignment of the magnetic axis with the axis of the containment cylinders. We can electronically tilt the magnetic axis by creating a secondary B field in $\hat{x}$ or $\hat{y}$ directions: a uniform field B_x effectively tilts the main field B_z by the angle $\theta_x = B_x / B_z$. Figure 2b shows that the plasma density remaining at a particular time is a sharp function of the axis alignment, with a misalignment of 10^{-4} radians being significant. (In this graph, B_y has already been optimized). Once we have determined the optimizing tilts θ_x and θ_y, we can move the mechanical structures to obtain the tilt. Then the secondary B fields are not needed except to null the ambient earth's field. Alternately, the entire alignment could be done by moving the mechanical structures, although this would be somewhat slower.

This alignment procedure completely avoids the problem of mapping the field to determine its axis. Essentially, the contained electrons map the field as they bounce axially, and their radial losses indicate a global average of the magnetic field irregularities and misalignments.

I would like to suggest that this alignment procedure could work equally well on an EBIS, if a very low energy beam is injected so that no ions are formed. The alignment procedure could be especially useful in making two separate magnetic solenoids co-axial: first electrons are contained in one solenoid, and the solenoid is aligned with its internal drift tubes; then the second solenoid is energized and aligned so as to give a minimal degradation in the containment properties.

Other Asymmetry Losses

Even when our apparatus is aligned as well as we can obtain, there are still loss processes. This is shown in Figure 3, where we plot the containment time τ_m versus neutral background pressure P. At high pressures, we find $\tau_m \alpha P^{-1}$, as expected: the stationary neutrals exert a drag on the rotating electron column, decreasing P_θ and allowing expansion.[4,6,8] However, as the pressure is decreased below 10^{-7} Torr, τ_m ceases to increase.

We believe that the loss at low pressures is due to electrostatic or magnetostatic asymmetries in the containment apparatus. Such asymmetries could be due to curvature of the magnetic solenoid, magnetic permeability of irregularly shaped stainless steel parts, or irregularities in the nominally cylindrical containment tubes.

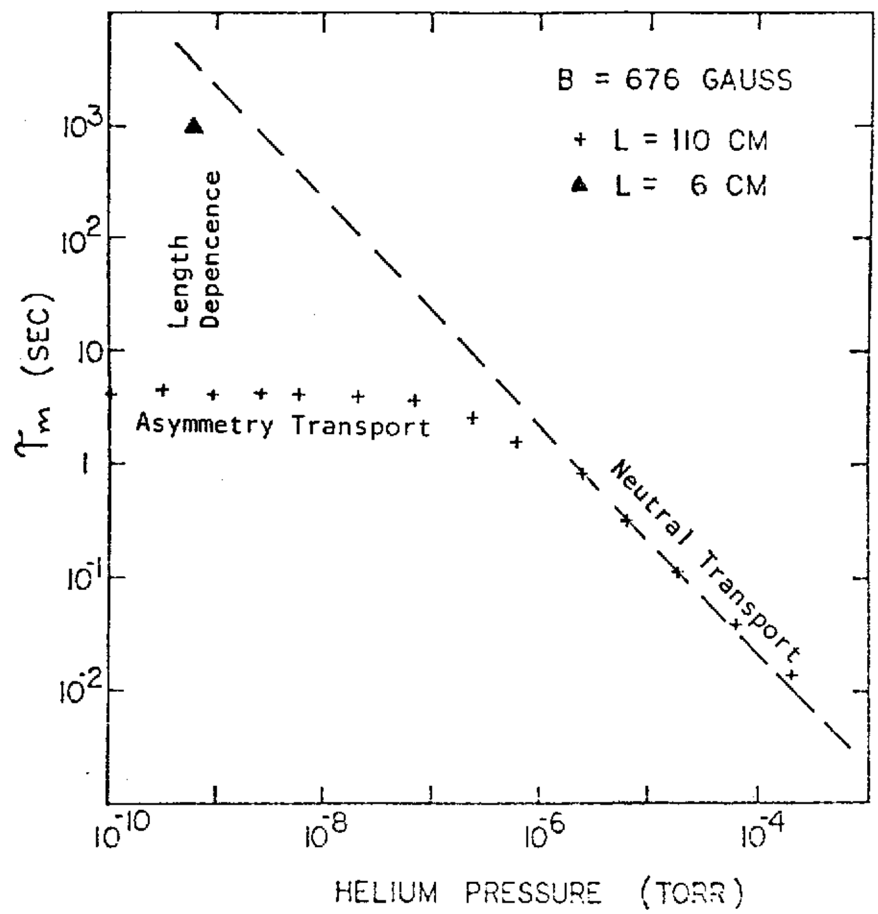

Figure 3. Containment times as a function of neutral pressure.

A striking feature of this asymmetry-induced transport is that it is a strong function of the length L of the contained plasma.[7] As shown in Figure 3, when the length is decreased from 110 cm to 6 cm, τ_m increases from 4 sec to 1000 sec. When we vary both the length and the magnetic field, we find

$$\tau_m = (0.5 \text{ sec})\,(L/100 \text{ cm})^{-2}\,(B/500\ G)^2$$

over a range of 6 decades. Here, $n_0 \approx 10^7 \text{ cm}^{-3}$, $T \approx 1$ eV, $R_{\text{plasma}} \approx 1.5$ cm, $R_{\text{wall}} \approx 3.$ cm.

To characterize the scale of ambient field errors on this device, we note that the magnet bore deviated from straight by about 1 mm over a length of 2 m, and the internal copper containment cylinders were held by stainless steel hangers with permeability $\mu \approx 1.0005$. When we built a new device with a straighter magnetic bore ($\pm$.1 mm) and no internal asymmetric stainless steel, we found improvement in the lifetimes. For the same densities and temperatures, the newer device gives

$$\tau_m = (10 \text{ sec})(L/100 \text{ cm})^{-2}\,(B/500 \text{ G})^2.$$

Electron-Ion Scaling

Much of the physics of pure electron plasmas applies equally well to pure ion plasmas, with a simple scaling between the two. In particular, Newton's equation of motion and Maxwell's equations can be scaled with respect to mass and charge, except for the Maxwell's $\nabla \times b$ equation. Thus, for those ion plasma effects which are electrostatic in nature, electron plasma experiments will give analogous results.

The scaling requires that the magnetic field for ions is larger by $(m_i/m_e)^{1/2}$, that the containment voltages are larger by the charge ratio Z, and that the initial kinetic energies of the ions are larger by Z^2. The ion dynamics will then be the same as the electron dynamics, except that the ions will evolve slower by a factor of $(m_i/m_e Z^2)^{1/2}$.

For example, a 30 kG EBIS might generate N^{+7} ions with the following parameters: $n_i = 5\times10^8 \text{ cm}^{-3}$, $T_i = 100$ eV, $R_{\text{plasma}} = .05$ cm, $R_{\text{wall}} = 1$ cm, $L = 30$ cm. The containment of these ions after the generating beam is turned off is analogous to the containment of the same size pure electron plasma with the following parameters: $B = 187$ G, $n_e = 5\times10^8 \text{ cm}^{-3}$, $T_e = 2$ eV. We have contained electron plasmas with these parameters in a cryogenic apparatus, and obtain containment times $\tau_m \approx 1$ sec . This suggests that the N^{+7} ions could be magnetically contained for times on the order of 23 sec, presuming it is similar asymmetries which cause losses in both devices.

Of course, the electron and ion systems are not identical. The $\nabla \times b$ Maxwell equation must be included to describe cyclotron radiation, which can be an important cooling mechanism for electrons at high fields,[9] but not for ions.

The most important difference between the electron and ion plasmas results from effects outside the scope of the Newton-Maxwell equations. For example, the collision of an ion with another object must be described by quantum mechanics, and is thus not subject to the above scaling. Indeed, whereas neutral collisions generally cause angular momentum loss and resultant heating of electron plasmas,[6,8] these collisions may result in substantial cooling of ion plasmas.[11,12,14]

Azimuthally Asymmetric Waves

When the ion plasma generated in an EBIS is sufficiently dense that the Debye shielding length λ_D is smaller than the plasma size, collective ion modes become important.[1] In particular, the free energy of the electron beam can couple into these modes and thereby heat the ions. This seems to be a fundamental problem in high density and high Z EBIS operation. Theory predicts that a number of different modes may be unstable[1,15], and experiments detect a wide range of frequencies in the image charge fluctuations on the drift cylinders.[16] These waves are presumably of the form $\exp[ikz + il\theta - i\omega t]$.

The azimuthal mode number l of a wave can be easily determined by detecting the wave with particular azimuthal sections of the cylindrical wall.[4] A complete 360° cylinder detects only $l=0$ modes, i.e. modes with only axial charge variations. In contrast, if the cylinder is split into two 180° sections connected electrically as shown in Figure 4, only $l=1,3,5 \cdots$ modes will be detected.

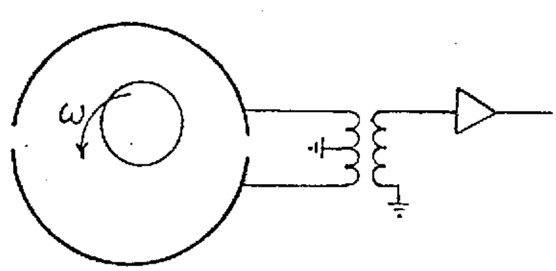

Figure 4. Receiver to detect the $l=1$ diocotron mode.

Modes with $l=0,2,4 \cdots$ will have zero coupling to this antenna. If the cylinder is split into four 90° sectors with diagonally opposite pairs hooked together, only $l=2,6,10 \cdots$ modes will be detected. By taking separate frequency spectra with different antenna configurations, the azimuthal mode numbers of the various spectral components can be identified.

It should be noted that the voltages induced on the wall sectors are themselves asymmetries which can couple back into the plasma.(17) For example, when a 1 $k\Omega$ resistance is connected between wall sectors on electron containment devices, the $l=1$, $k=0$ diocotron mode is observed to grow exponentially on a time scale of 0.1 seconds.(18) (Without the wall resistances, the mode is neutrally stable.) This mode corresponds to a uniform shift of the plasma column off center, with the off-center column rotating about the center of the containment cylinder, as depicted in Figure 4.

Interestingly, the $l=1$ diocotron mode can be made to damp to zero by replacing the wall resistances with feedback amplifiers.(18) If the wave is received on one set of wall probes and then applied to another set 180° out of phase, the off-center plasma column can be moved back on center. In this way, pure electron columns can be moved substantially off-center, then moved back, with no significant spreading of the column.

Launched waves can also cause the diameter of a centered plasma column to decrease. The launched waves should propagate in the $\hat{\theta}$ direction *faster* than the plasma column is rotating. Then absorption of the wave by the plasma will increase the angular momentum of the plasma, causing $<r^2>$ to decrease. (This is essentially the opposite of the effect of collisions with stationary neutral atoms.) Of course, phased launching techniques must be used so that the complementary mode travelling in the $-\hat{\theta}$ direction will not also be launched.

Equilibrium States

Magnetically confined particles all of the same charge sign will come into global thermal equilibrium with themselves.(19) For a single charge species, the equilibrium distribution is

$$f(r,v) = n(r)\exp\left[-\frac{m}{2kT}(v-\omega r\,\hat{\theta})^2\right].$$

This is just a Maxwellian velocity distribution rotating as a rigid rotor. The density profile $n(r)$ is essentially constant out to some radius R_p, and then falls exponentially to zero in a few Debye lengths. Interestingly, the equilibrium for a multi-species ion plasma would exhibit spatial separation of the species.(20)

The time scale to approach equilibrium depends on the dominant interaction mechanism. Like particle collisions result in velocity scatterings which give equilibration on a time scale $[\nu(r_L/\lambda_D)^4]^{-1}$, where ν is the 90° scattering time.[19] Other longer-range interactions may give faster equilibration on a time scale $[\nu(r_L/\lambda_D)^2]^{-1}$.[21] Equilibration times for an ion plasma with $n_i \sim 5\times10^8$, $T_i \sim 100$ eV, $B \sim 30$ kG should be of order 0.1 sec. Of course, the containment system must be sufficiently symmetric that loss processes are small on the time scale for equilibration.

For an isolated system, the initial total number of particles, angular momentum, and energy of the plasma determine the three equilibrium parameters of R_p/λ_D, ω, and T. However, the equilibrium parameters can be manipulated experimentally by any coupling which causes the total energy or total angular momentum of the system to change.

For example, ion plasmas have been cooled to temperatures of a few degrees Kelvin or less using several different techniques. Ion-neutral collisions can cause ion cooling, depending on the neutral energy absorption and momentum transfer cross-sections. Barlow *et al.* [11] report ion plasmas cooling to an estimated 13° K after the ionizing beam is turned off. In this system, selective "evaporation" of the more energetic ions also contributes to ion cooling.

More esoterically, tuned laser-ion interactions can be used to cool the ions as well as to maintain a small radial profile. Bollinger and Wineland report cooling of small collections of 10^2–10^3 ions to temperatures of order 0.1° K.[12] In this system, the absorbed momentum of the laser photon[13] both moves high thermal energy electrons to lower energies, and globally changes the total plasma momentum so as to decrease the mean radius. (This latter effect is similar to the effect of the azimuthally propagating launched waves discussed above.) The atomic properties of the ions can be precisely studied when the thermal energies are minimized.[14]

These and other experiments suggest that in particular EBIS applications one might want to manipulate the magnetically confined ions after the ionizing beam is turned off. It could also be possible to cyclically generate an ion cloud, cool or compress the cloud, then turn the electron beam on for further ionization.

Acknowledgments

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