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THE CRYOGENIC PURE ELECTRON PLASMA

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ABSTRACT A pure electron plasma column with a density of $1.8 \times 10^{10} \text{ cm}^{-3}$ is confined longitudinally by electrostatic fields and radially by a 41 kG axial magnetic field. The plasma is cooled by cyclotron radiation and heated by expansion in the large radial electric field due to space charge. Using the measured expansion rate to calculate the heating power and equating the result to the cooling power indicates that the plasma has probably cooled to near the 4°K temperature of its surroundings. At the experimental density and temperature, the correlation parameter, $[\Gamma = (e^2/kT)(4\pi n/3)^{1/3}]$, is approximately 1.2, indicating that the system should be a locally ordered liquid.

An interesting difference between a pure electron plasma (or, more generally, a plasma with a single sign of charge) and a neutral plasma is that a pure electron plasma may be confined forever, at least in theory. Consider the confinement geometry shown in Fig. 1.

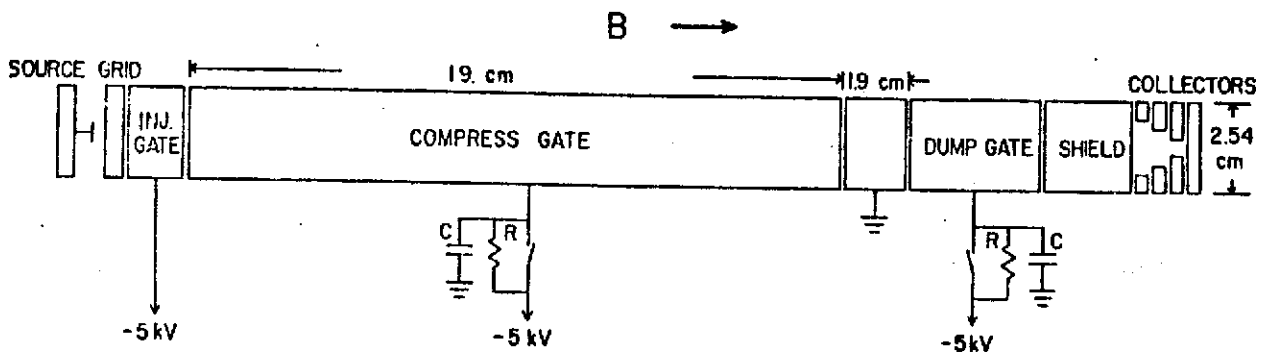


Fig. 1. Confinement Geometry

A set of conducting cylinders are immersed in an uniform axial magnetic field, B . During injection of the electrons all cylinders between the source and the "dump gate" are at ground potential, and the dump gate is biased negatively. Electrons from the source (a negatively biased and heated filament) drift down the magnetic field lines to the region of the dump gate where they are reflected electrostatically. Thus a column of electrons extends from the source to the dump gate. A section of this column is trapped by switching the "injection gate" to negative potential: the electrons are then confined radially by the magnetic field and axially by electrostatic fields. The axial confinement can be guaranteed simply by making the potential on the end cylinders sufficiently negative.

To understand the radial confinement, it is useful to consider the total canonical angular momentum of the electrons

$$P_{\theta} = \sum_j [m v_{\theta j} r_j - (e/c) A_{\theta}(r_j) r_j] \quad , \quad (1)$$

where $v_{\theta j}$ is the θ -component of the velocity of the j^{th} electron and r_j is the radial position of the j^{th} electron. For an uniform axial magnetic field, the θ -component of the vector potential is given by $A_{\theta}(r) = Br/2$. For a sufficiently large magnetic field, the mechanical part of the angular momentum is negligible compared to the vector potential part; so Eq. (1) can be rewritten as

$$P_{\theta} \approx - \sum_j (eB/2c) r_j^2 = - (eB/2c) \sum_j r_j^2 \quad , \quad (2)$$

where the last step explicitly involves the fact that the plasma contains only electrons. To the extent that P_{θ} is conserved, there is a constraint on the allowed radial positions of the electrons, $\sum_j r_j^2 = \text{constant}$. As an example, suppose the cylindrical wall is at a radius of 10mm and the electrons are injected at a radius of 1mm; then only one percent of the electrons ever can reach the wall, provided P_{θ} is conserved. This heuristic argument can be made into a formal theorem by considering conservation of energy and conservation of angular momentum for the electron and field system¹. Of course, in the experiments the electrons ultimately do reach the wall, since there are effects that break the cylindrical symmetry and change P_{θ} . Examples of effects that can change P_{θ} are electron-neutral collisions, finite wall resistance and asymmetric field and construction errors. The plasma equilibrium, transport due to neutral collisions, transport due to field asymmetries, and waves in the system have been studied in a series of prior experiments²⁻⁸ and theoretical works⁹⁻¹⁷.

A second difference between a plasma with a single sign of charge and a neutral plasma concerns the consequences of cooling¹⁸. If a pure electron plasma is cooled to a very low temperature, say, to a few °K, there will be no recombination. For $kT < e^2 n^{1/3}$, the electrostatic interactions between the electrons will establish strong correlations. For sufficiently low temperature, these interactions

will establish the short range order characteristic of a liquid, a pure electron liquid. For even lower temperature, the liquid will experience a phase transition to become a pure electron crystal. Of course, the electrostatic interactions conserve P_0 and cannot lead to a loss of electrons.

To obtain a theoretical description of the liquid and crystal states, let us assume the electrons are confined long enough to come into thermal equilibrium with each other. The N-electron thermal distribution is given by $\rho = Z^{-1} \exp[-(H-\omega P_0)/kT]$, where H is the Hamiltonian for the electrons¹⁸. The existence of thermal equilibrium states for which the electrons are confined is another manifestation of the fact that a pure electron plasma can be confined forever. From the distribution, various properties of the system can be calculated^{11,18}. The maximum density that can be confined by a given magnetic field is determined by $\omega_p^2 \leq \Omega^2/2$, where $\omega_p^2 = 4\pi n e^2/m$. This is called the Brillouin limit¹⁹. Correlation effects depend on the parameter $\Gamma = e^2/akT$, where $(4/3)\pi a^3 n = 1$. Note that the usual plasma expansion parameter $g = 1/n\lambda_D^3$ is given by $g = 4\pi/3 \Gamma^{3/2}$. Of course, the plasma state corresponds to weak correlation (i.e. $\Gamma \ll 1$). For $\Gamma \approx 2$, the electron-electron correlation function begins to exhibit oscillations characteristic of a liquid, and, for $\Gamma \approx 155$ the liquid experiences a phase transition to become a crystal. These results are modified by quantum mechanical effects, when $kT < \hbar\omega_p$ or $kT < \hbar\Omega$ ¹⁸.

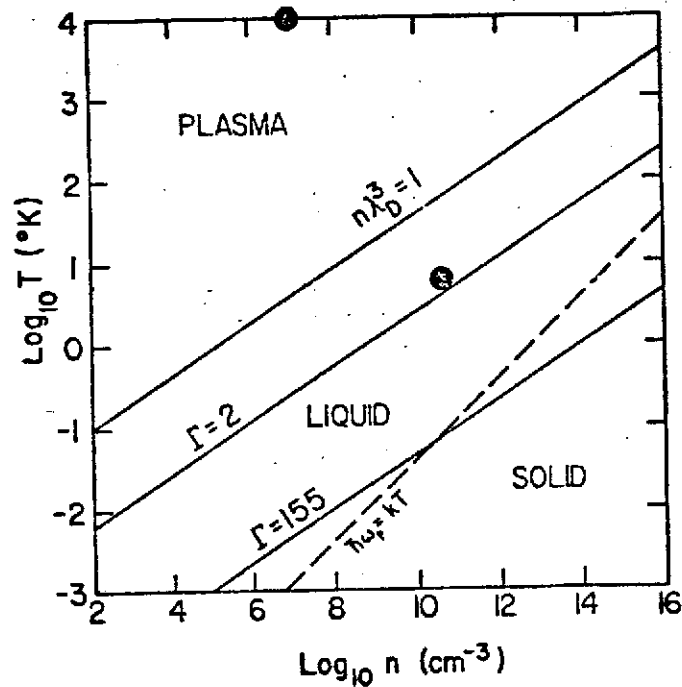


Fig. 2. Parameter Space

It is instructive to collect these criteria on a single graph. In Fig. 2 the ordinate is $\log_{10}(T)$, where T is measured in °K. The abscissa is $\log_{10}(n)$, where n is measured in electrons per cubic centimeter. The various stages of increasing correlations are indicated by lines at $n\lambda_D^3 = 1$, $\Gamma = 2$ and $\Gamma = 155$. The onset of quantum behavior is indicated by the line at $\hbar\omega_p = kT$. The Brillouin limit for a magnetic field of 41 KG is 8.2×10^{13} electrons/cm³. The temperature of a heat reservoir may be reduced to 4°K with liquid helium and to 10^{-2} °K with a dilution refrigerator. Of course, the real question is whether or not the electrons can be cooled to the temperature of the heat reservoir.

One method of cooling is to let the electrons lose energy by cyclotron radiation. A single electron executing classical cyclotron motion in unbounded space radiates energy at the rate $dW/dt = -2e^2 v_{\perp}^2 \Omega^2 / 3c^3$, where v_{\perp} is the magnitude of the electron velocity perpendicular to the magnetic field. This rate also describes the radiation of an elec-

tron in an optically thin plasma bounded by a large and lossy cavity²⁰. If electrostatic interactions between the electrons keep the electrons near thermal equilibrium the cooling power per electron is

$$P_c = \left[\frac{2e^2}{3c^3} \right] \Omega^2 \left[\frac{2kT_{\perp}}{m_e} \right] R(T, T_w, \Omega) \quad (3)$$

where the factor R is a correction for the non-zero temperature of the cavity, T_w , and for possible quantization of the cyclotron orbits.

$$R(T, T_w, \Omega) = \left(\frac{\hbar\Omega}{kT_{\perp}} \right) \frac{\exp\left(\frac{\hbar\Omega}{kT_w} - \frac{\hbar\Omega}{kT_{\perp}}\right) - 1}{\left[\exp\left(\frac{\hbar\Omega}{kT_w}\right) - 1\right]\left[1 - \exp\left(\frac{\hbar\Omega}{kT_{\perp}}\right)\right]} \quad (4)$$

There will also be unwanted mechanisms heating the plasma. We believe that the dominate heating mechanism is associated with the large amount of electrostatic energy that can be liberated by imperfections in the confinement. Radial expansion in the large radial space charge field may lead to joule heating of the plasma. For the preliminary experiment reported here, we have measured the radial expansion rate and assumed that all of the released power, P_H , goes to heat the plasma. Equating $P_H = P_c$ allows us to deduce an upper limit on the plasma temperature.

For the present experiment, the entire containment system, shown schematically in Figure 1, is sealed inside a brass vacuum vessel, evacuated, and immersed in liquid helium. Thus the cavity temperature, T_w , is 4.2°K. Residual gas in the vacuum chamber freezes out on the walls and the vacuum attained is sufficiently good that transport due to electron-neutral collisions is negligible. The magnetic field is produced by a superconducting solenoid, also in the liquid helium. We compress the plasma after injection to increase its density. Referring again to Figure 1, we inject a continuous beam of electrons which is reflected by the -5kV potential of the dump gate. The inject gate is then closed by lowering its potential to -5kV, thus capturing the electrons. The compress gate potential is then lowered to -5kV, axially compressing the column into the 1.9cm long final confinement cylinder. The magnetic field, which was 1kG at the injection time is then slowly ramped to 40.8 kG, radially compressing the column to its final density.

A radial histogram of plasma density may be measured at any time by pulsing the potential of the dump gate to ground; the electrons escape longitudinally along B and are collected by the set of ring electrodes shown in Figure 1. The shot to shot reproducibility of the system is very good so we can construct the radial evolution of the plasma in time by injecting the plasma repeatedly

and dumping it after various delay times. Typically, at 40.8 kG almost all of the electrons are at a smaller radius than the 1.27mm radius of the smallest collector plate hole. Hence we improve the radial resolution of the profile by ramping the magnetic field down to some intermediate value be-

fore dumping and then calculating the radius before ramp down. This was done for the data reported here. We always make the most pessimistic assumption about this process when deducing the plasma size for the heating calculation; namely, that the plasma goes out at least as fast as the magnetic field lines. While the plasma is being held, the low frequency filters on the - 5kV containment voltage lines are switched in to prevent possible heating of the plasma by noise from these circuits.

The results of a containment experiment are shown in Figure 3. First the plasma is created by the injection, compression, and ramping sequence and the radial profile measured after holding a few seconds at 40.8 kG. This procedure is repeated several times to establish reproducibility. Then we measure $n(r)$ with the plasma held an extra 6000 seconds at 40.8 kG. We have analysed the data assuming the radial density profile is the shape given by the histogram. Of course, the actual shape is some unknown smooth curve, but a series of numerical tests has shown that the difference does not qualitatively change our result. The captured plasma is approximately 18mm long and 1mm in radius. The mean radius expands by about 0.1mm in 6000 seconds. The total number of electrons is 9.6×10^8 and the central electron density, averaged over a 0.8mm radius is $1.8 \times 10^{10}/\text{cm}^3$. Since the unneutralized electron density is known, the potential as a function of radius is also known, and the difference in total electrostatic energy for the two histograms shown in Figure 3, ΔU , may be calculated by elementary methods. The heating power per electron is $P_H = -\frac{1}{N} \left(\frac{\Delta U}{\Delta t} \right)$.

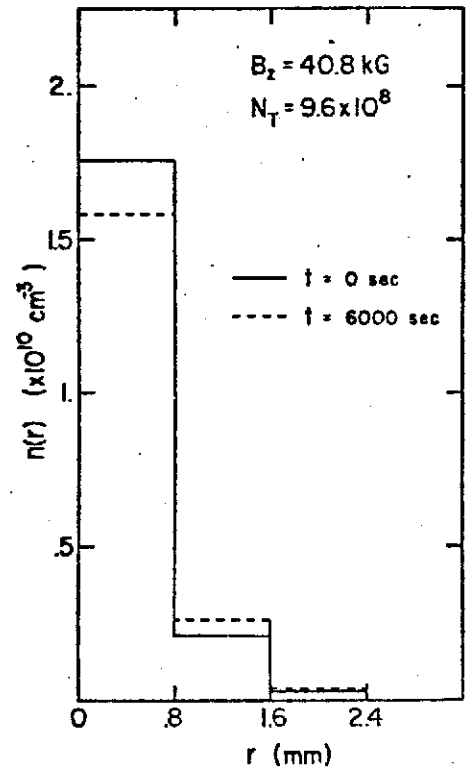


Fig. 3. $n(r)$ vs r

Equating this to the cooling power (Eq. 3) obtains $RT_{\perp} = 1.6^{\circ}\text{K}$.

Inserting R , calculated from equation 4, obtains $T_{\perp} = 6.0^{\circ}\text{K}$. At

40.8 kG, $\Omega_c = 5.5^{\circ}\text{K}$, and quantization of the cyclotron orbits and the 4.2°K cavity temperature are both important. In this peculiar parameter regime, the parallel energy of the electrons is partially decoupled from the perpendicular energy²¹, but for our experiment the two energies should be almost the same on the time scale of interest. Assuming $T_{\perp} = T_{\parallel}$, the experimental values of T_{\perp} and n give $\Gamma = 1.2$. This point is shown as the lower solid dot on Figure 2. The upper solid dot corresponds approximately to the $T = 1 \text{ eV}$, $n = 10^7 \text{ cm}^{-3}$ plasma originally injected, before compression and cooling.

In summary, a pure electron plasma column with central density $1.8 \times 10^{10} \text{ cm}^{-3}$ has been contained under conditions such that it has probably cooled to approximately 6°K and has a correlation parameter, Γ , of approximately 1.2, which is close to the theoretical value necessary for the system to become a locally ordered liquid.

ACKNOWLEDGEMENTS

This work is based on research supported by the National Science Foundation under Grant No. PHY80-09326.

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