# STREAMING PLASMA TRANSPORT AND CUTOFF IN TRANSVERSE MAGNETIC FIELDS*

W. Bernstein, H. S. Ogawa, and J. M. Sellen, Jr.
TRW Systems Group, Redondo Beach, California
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A previous publication[1] has described the penetration of synthesized $Cs^+$ plasma streams through transverse magnetic fields. In those experiments, the observed penetration was attributed to polarization electric fields developed across the plasma density gradients at the plasma-stream boundaries. In the present experiment, the penetration of an annular plasma stream through a radial magnetic field is under study. The new geometry eliminates those boundary effects which caused polarization electric fields observed in the previous configuration. Our preliminary experimental results indicate that electron penetration of the magnetic field ceases as the magnetic field intensity is increased above a critical value where the electron cyclotron frequency $\omega_{ce}$ approaches the electron plasma frequency $\omega_{pe}$. This nonpenetrating regime appears to be stable. For values of magnetic field below the critical value, high-frequency oscillations always, and low-frequency oscillations occasionally, are observed.

The experimental configuration is shown in Fig. 1. The source operating conditions and zero-magnetic-field plasma characteristics are similar to those described previously by Sellen et al.[2] A high-impedance collimator placed in front of the magnetic gap defines the annular plasma stream. Typical plasma densities at the entrance to the field region range from $10^7$ to $10^8$ $cm^{-3}$. For the initial electron temperature of 0.25 eV the Debye lengths lie in the range 0.1-0.035 cm which are small compared with the width of the plasma annulus. The highest ion energy employed to date has been 300 eV corresponding to an ion velocity of $2\times10^6$ cm $sec^{-1}$. The magnetic field intensity can be adjusted from zero to about 1000 G. The radial field geometry results in a $1/R$ falloff in intensity across the gap which for the dimensions chosen represents a 25% decrease across the thickness of the plasma stream. Under certain source conditions, the azimuthally uniform plasma density is also relatively uniform across the gap; under other conditions a density gradient can be generated such that the ratio $n^{1/2}/B$ is relatively constant across the gap.

Only a few diagnostic means have been employed in the study to date. They include the following: (1) a movable Faraday cup to determine the plasma-density profile entering the gap, (2) a movable Langmuir probe for determination of electron temperature in the plasma column, (3) a movable emissive probe for determination of plasma potentials, (4) a movable capacitive probe and rf receiver for detection of electrostatic plasma oscillations, and (5) a movable "floating" collector which terminates the plasma stream and whose floating potential yields a reasonable measure of plasma potential at its location. Measurement of the beam-neutralizer emission current yields the electron flux accompanying the ions to nongrounded surfaces.

One set of observations has been the measure-

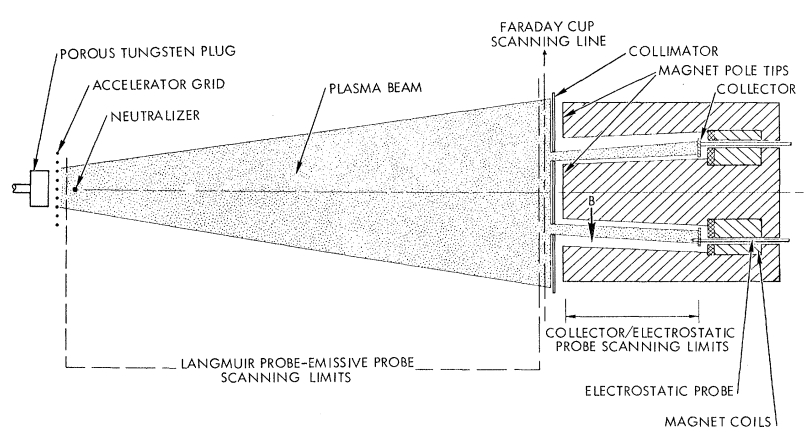


FIG. 1. Schematic of the experimental configuration. The dimensions of the magnet gap are 2 cm in width and 10 cm in depth. The relative length of the plasma column is contracted by a factor of three.

ment of collector potential (at a fixed position 5 cm behind the magnetic field entrance) as a function of magnetic field. For magnetic fields below a critical value, the collector potential is relatively constant and is approximately equal to the potential of the plasma stream prior to entrance into the field region. As the magnetic field is increased, there is an abrupt increase in collector potential to a value close to the ion acceleration potential. The rise of collector potential signifies a transition from electron penetration to electron cutoff. Simultaneously, the observed neutralizer emission current decreases by an amount about equal to the ion flux entering the aperture confirming that electrons are no longer accompanying ions to the collector. In the nonpenetrating state both Langmuir probe measurements in the plasma column and the unchanged beam divergence show no evidence of an electron temperature increase which could be attributed to the return of electrons heated in the interaction region.

In Fig. 2, the critical value of field intensity and the corresponding value of $\omega_{ce}$ is plotted as a function of $\sqrt{n}$ (center density) and the corresponding $\omega_{pe}$ for both a uniform density beam and one for which $n^{1/2}/B$ is constant across the gap. The observed differences for these stream configurations are, as yet, unexplained. For all points, $\beta$ defined as $(B^2/8\pi)^{-1}(nMU^2)$ is approximately $10^{-3}$. The insertion of a small obstacle in front of the annulus during nonpenetrating conditions facilitates penetration, probably because it removes the symmetry in the plasma stream and permits azimuthal polarization electric fields to occur. This density perturbation appears to be analogous to the enhanced density spoke described by Janes and Lowder[3] which produced the fast electron diffusion observed in their experiment.

No oscillations are observed once the nonpenetrating condition is achieved. High-frequency oscillations (5-70 MHz) are always observed during penetration. Upon occasion, low-frequency oscillations (50-100 kHz) are observed for weak magnetic fields (2-5 G). As shown in Fig. 3, for magnetic fields less than the critical value, the high-frequency oscillations appear in bands near the electron cyclotron frequency; as the magnetic field is increased to near the critical value, the frequency appears to limit near the electron plasma frequency. Further increases in magnetic field result in the abrupt switch to the nonpenetrating condition and the disappearance of all oscillations.

The absolute values of magnetic field and density for each transition shown in Fig. 2 together with the observed frequencies indicate that the transition occurs for $\omega_{ce} \sim \omega_{pe}$. The possible mechanism of the low-frequency oscillations is unexplained. Two theoretical treatments, one due to Fried and Ossakow[4] which neglects finite temperature effects and the other due to Haeff[5] which includes finite electron temperatures, predict the transport of electrons across a magnetic

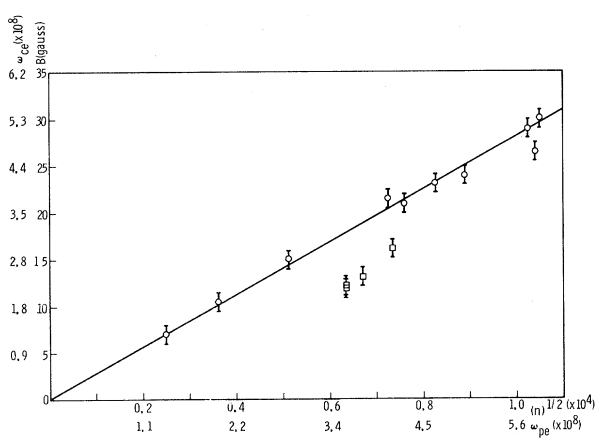


FIG. 2. Dependence of critical magnetic field intensity on plasma density as measured at the collimator; also shown are the corresponding values of $\omega_{ce}$ and $\omega_{pe}$. Experimental points: open circles for a density distribution having $n^{1/2}/B$ constant and open squares for a more uniform density.

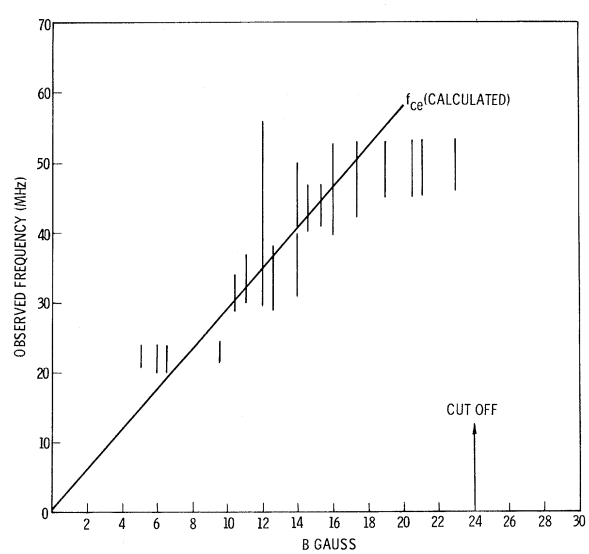


FIG. 3. Frequency dependence of the observed high-frequency oscillations on the applied magnetic field. Also shown are the expected values of the electron cyclotron frequency.

field for $\omega_{ce} < \omega_{pe}$. This mode of transport is inoperative for $\omega_{ce} > \omega_{pe}$, but these treatments do not necessarily predict the existence of the observed stable nonpenetrating state.

The limited diagnostics permit only gross observations of the interaction characteristics. Detailed measurements of the electron temperature, particle trajectories, potential distributions, the dependence of the phenomena on electron temperature and ion energy remain to be done.

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[5]A. V. Haeff, private communication.

## NOTE ON X-RAY SCATTERING BY ARGON

Dominique Levesque and Loup Verlet*
Laboratoire de Physique Théorique et Hautes Energies,† Faculté des Sciences, Orsay, France
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The structure factor measured by x-ray scattering experiments on argon is compared with the same quantities calculated with two different intermolecular potentials. We show that it is not possible to get, from the scattering data, quantitative information concerning the interaction and that the discrepancy between theory and experiment is probably due to a systematic error in the latter.

Mikolaj and Pings have recently studied x-ray scattering by dense argon gas in the vicinity of the critical point.[1] Using those experiments, they have drawn conclusions regarding the interatomic interaction. In particular, assuming that the Percus-Yevick equation can be used in order to obtain a two-body interaction from the experimental structure factor, they show that the effective two-body interaction so derived depends very strongly on the density.[2] The depth of the potential is found to be $-120$°K when the density is as low as 0.280 g/cm$^3$. It rises to $-90$°K when a density of 0.780 g/cm$^3$ is reached (the critical density of argon is 0.536 g/cm$^3$).

It may be thought, at first sight, that this apparent variation of the depth of the potential is due to the failure of the Percus-Yevick equation at those densities. It has been shown elsewhere[3] that this explanation is not tenable: It is possible using molecular dynamics computation to obtain the structure factor of the Lennard-Jones fluid, and to process this structure factor as if it were experimental, using the Percus-Yevick equation. The potential so obtained differs but little from the original Lennard-Jones potential in the density range we are interested in; for the density 0.780 g/cm$^3$, the bowl of the potential differs from the exact one by less than 1 %.

It is therefore tempting to ascribe the apparent change of depth of the potential to the presence of many-body forces. It is generally believed that the "bare" two-body potential, as determined by low-density experiments, resembles a Kihara potential: A depth as large as 163 °K may be necessary[4] in order to explain the behavior of the second virial coefficient at very low temperatures. A Kihara potential with a depth of 143°K fitting rather well the low-density data has been determined by Baker, Fock, and Smith.[5] It leads[6] to a critical temperature which is too large by a factor 1.13. The choice of a deeper potential still increases the discrepancies at the critical point. A Lennard-Jones potential of a depth of 120°K, fitting the second virial coefficient except at very low temperatures, yields critical constants[7] that are clearly better than those obtained from the Kihara potential. In particular, the critical temperature is too high again, but by a factor 1.07 only.

In view of the great success of the Lennard-Jones potential at higher densities, it is tempting to consider it as a good effect interaction