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# Observation of transverse and longitudinal modes in non-neutral electron clouds confined in a magnetic mirror<sup>a)</sup>

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Electrostatic modes on non-neutral electron clouds confined in a magnetic mirror field have been investigated. The cloud contains  $2 \times 10^{11}$  electrons at an average kinetic energy of 0.3 MeV for a magnetic field with a peak intensity of 9 kG at the midplane. It was found that the cloud is moving azimuthally as well as longitudinally. The azimuthal motion has an  $m = 1$  spatial nature. The longitudinal modes have a more complicated nature, but their frequency equals that of the azimuthal mode.

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The physics of non-neutral plasmas has been investigated lately because of the basic physical phenomena they represent and because of application of such plasmas to collective ion acceleration. An equilibrium of a non-neutral plasma is possible only if some restoring force overcomes the tendency of the plasma to expand by the action of its self-electrostatic field. The restoring force is usually supplied by a magnetic field. Non-neutral plasma equilibria were investigated experimentally and theoretically for straight magnetic fields,<sup>1-2</sup> toroidal magnetic fields,<sup>3-4</sup> and mirror magnetic fields.<sup>5-6</sup>

Levy<sup>7-8</sup> has shown that an infinitely long cylindrically symmetric cold non-neutral electron plasma, confined in a homogeneous magnetic field, will exhibit electrostatic flute-type surface waves which might be stable or unstable. These waves have been observed experimentally by Daugherty *et al.*<sup>3</sup> in a toroidally confined plasma.

In the present experiment a non-neutral electron cloud is injected, trapped, and compressed in a magnetic mirror field. The experiment was described in detail elsewhere<sup>6</sup> and it is shown schematically in Fig. 1. The magnetic mirror field rises in 160  $\mu$ sec from zero to a peak value of 9 kG at the mirror minimum. The field then decays in 1.6 msec. The mirror ratio is 1.1 : 6 on one side and 1.2 : 3 on the other side. The vacuum system has a base pressure of  $5 \times 10^{-8}$  Torr. Inside the glass cylinder is a 10-cm-diam slotted stainless-steel cylinder which enables penetration of the fast magnetic field. The injector has a thermionic electron source and it is usually biased to  $-8$  kV. The emitted current is about 10 A and the injector is pulsed for about 10  $\mu$ sec. The injector is pulsed at the start of the magnetic field and electrons are injected during the first few microseconds of the mirror-field rise.<sup>6</sup> The injector is located between the mirrors close to the high side as indicated in Fig 1.

About  $2 \times 10^{11}$  electrons are trapped under these conditions. They are compressed and accelerated by the increasing magnetic field to a cloud with a radius of about 5 mm<sup>9</sup> and to an average kinetic energy of 0.3 MeV.<sup>6</sup> Firing of the

ejecting coil shown in Fig. 1 pushes the cloud to the left, and when the mirror field becomes flat the self-electrostatic field of the cloud pushes it out of the mirror.

Electrostatic probes<sup>3</sup> (image current probes) are used to detect the modes of the electron cloud. These probes are sensitive to motion of net charges in the system which induces an image current on the probe.<sup>3</sup> Two kinds of electrostatic probes are used: radial probes are placed outside of the glass tube near the slot in the stainless-steel cylinder and they are sensitive mainly to radial or azimuthal motion of the electron cloud; longitudinal probes are placed on axis with their area perpendicular to the axis of the system and they are mainly sensitive to motion of the cloud along the axis. All the radial probes have a width of 2 cm and they are longer than the slot in the metal tube. The longitudinal probes have a shape of a disk with a 10-cm diameter and are located as indicated in Fig. 1.

As reported before,<sup>6</sup> we have measured the frequency of oscillation recorded on radial probes as a function of a few parameters of the experiment. We found that the frequency is independent of the value of the magnetic field and the electron injection energy. We also found that the frequency is proportional to the number of electrons trapped, which

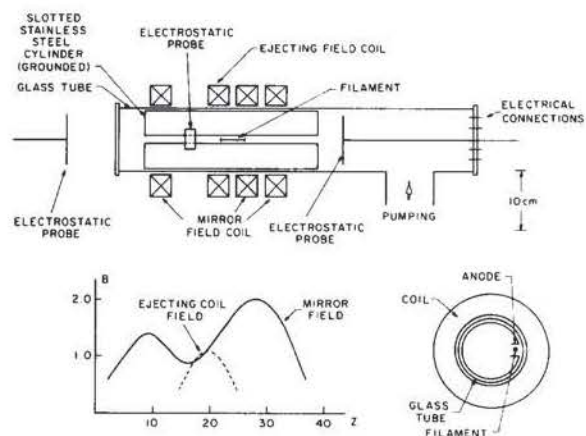


FIG. 1. Schematic diagram of the system. Note the two longitudinal electrostatic probes located on both sides of the system. The location of the radial electrostatic probe along the slot can be changed.

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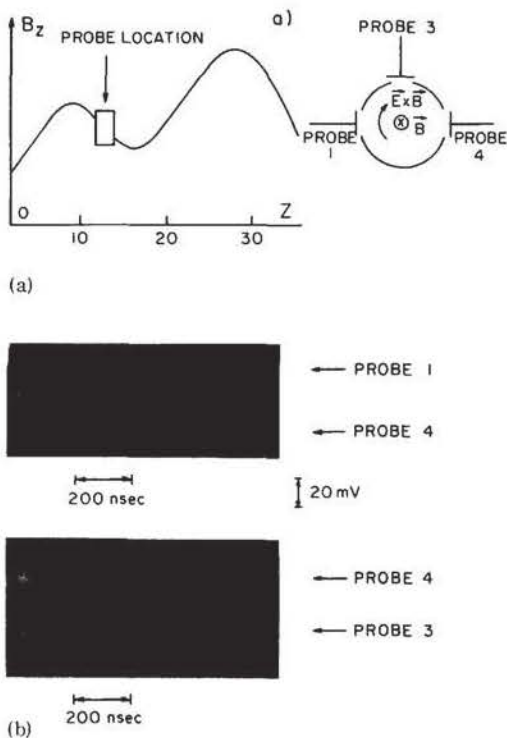


FIG. 2. (a) Schematic diagram of location of radial electrostatic probes around the system with the special slots cut in the stainless-steel cylinder. The location along the axis of the mirror field is also shown. (b) Signals recorded on the three probes. Two dual-beam oscilloscopes were used here.

proves the collective nature of the measured oscillation. In the present study we have been able to increase the number of trapped electrons by a factor of 4 compared to previous results by some changes in the injector<sup>9</sup> and by increasing the mirror ratio. This has, in turn, increased the frequency of the observed oscillations up to about 10 MHz, so that the same dependence between trapped charge and frequency exists for a larger range of charges and frequencies.

The investigation of the spatial nature of these electrostatic oscillations was done by using sets of radial and longitudinal electrostatic probes. A set of four radial probes spread along the slot in the stainless-steel cylinder measured the relative phases along the cloud axis. A zero phase difference between all four probes was found. The meaning of this result is limited since the probes are exposed to the whole length of the cloud and they are not detecting only the oscillation at their location. What can be said safely is that this result is not in contradiction to identifying the mode as a flutelike mode.

The azimuthal mode number was investigated by using three radial probes located around the metal cylinder. To facilitate this, we cut two additional slots in the metal cylinder at angles of 90° and 180° relative to the main slot. The slots were cut to a depth of 5 cm into the metal cylinder and to a width of 3 cm equal to the width of the main slot. The main slot was covered with a grounded metal strip out of the glass cylinder up to 5 cm from the edge so that the three probes detected the induced currents due to the cloud mo-

tion with the same geometry. The geometry of this measurement is shown in Fig. 2(a).

The signals observed on the three probes are shown in Fig. 2(b). The relative phases between the three probes in Fig. 2(b) are equal to their azimuthal shift. This proves that the mode observed is an  $m = 1$  mode. Moreover, from the phase shifts between probes Nos. 3 and 4, the sense in which the disturbance is propagating azimuthally can be deduced and it is found to be clockwise. For the direction of the magnetic field shown in Fig. 2(b), the  $\vec{E}_r \times \vec{B}_z$  drift is also clockwise.

Longitudinal motions of the cloud were detected and investigated using longitudinal probes at both sides of the experiment. We found that the cloud is exhibiting longitudinal oscillatory motion with a frequency that is always equal to the frequency observed on the radial probes. Figure 3(a) shows typical traces of the longitudinal probes on the high and low mirror sides. Usually, the signal of the probe on the higher field side shows more components with higher frequency than the one on the low field side, as is also the case in Fig. 3(a).

This situation changes if we inject and trap only a small number of electrons. Figure 3(b) shows the traces of the two longitudinal probes for a shot in which only about  $5 \times 10^{10}$  electrons were trapped. What is seen very clearly in this case

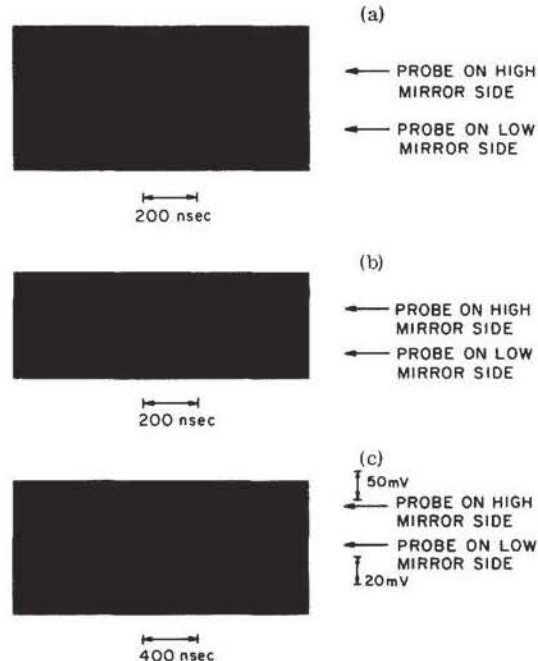


FIG. 3. (a) Typical signals on the two longitudinal electrostatic probes note the higher harmonics observed on the probe on the high mirror side. (b) The same as (a), but here a smaller number of electrons is trapped. Note the phase relation between the probes. Note also the decrease in the oscillation frequency when a smaller number of electrons is trapped. (c) Signals observed on the two longitudinal electrostatic probes during ejection. The signal on the probe on the high mirror side is because of electrons hitting it directly. The probe on the low mirror side detects electrons hitting the end flange of the system through their induced charge. Note the phase difference.

is that the two probes show basically the same signal shape and that they are out of phase by  $180^\circ$ .

A similar picture about the cloud longitudinal motion is observed during its ejection. As was reported earlier,<sup>6</sup> the electron cloud is not ejected continuously, but in a series of pulses that appear at an almost constant frequency. Since the ejecting coil is located near the high side of the mirror (Fig. 1), the electrons are expected to be ejected along the low side of the mirror. However, about 5% of the total number of trapped electrons are ejected through the high side of the mirror and are detected by the electrostatic probe located inside the vacuum system. Most of the electrons are ejected to the low mirror side and hit the flat edge of the glass tube which is insulated. The net charge of these electrons induces a net charge in the longitudinal electrostatic probe which is located in the low mirror side out of the vacuum system. Figure 3(c) shows the traces of the two longitudinal probes during ejection. What is seen is that a phase difference close to  $180^\circ$  exists between the two probe signals. This indicates that during ejection the electrons in the cloud are oscillating longitudinally in unison in accordance with the observation of Fig. 3(b). Each time the oscillation reaches one of the mirrors, part of the electrons are ejected.

A possible interpretation of the observed mode on the radial probe is that it originates from a bunch of electrons rotating on the surface of the cloud. The frequency of rotation on the cloud-surface is given by  $\omega = 2N_e c / a^2 B$ , where the cloud radius is  $a$  (cm), it has  $N$  electrons/cm,  $B$  is the magnetic field,  $-e$  is the charge of the electron, and  $c$  is the velocity of light. This is the rotation frequency obtained by calculating the  $\vec{E} \times \vec{B}$  drift velocity originating from the radial component of the self-electrostatic field crossed with the  $z$  component of the magnetic field.

We have proved experimentally,<sup>9</sup> by measuring the radial distribution of the cloud that the cloud behaves roughly adiabatically so that  $a^2 \propto B^{-1}$ . This explains why the observed frequency is independent of the magnetic field. For the cloud

in our experiment the numerical value of  $\omega$  is about a factor of 5 higher than the value observed experimentally. This is obtained assuming a cloud length of 5 cm and  $a = 0.5$  cm for  $B = 10$  kG.<sup>9</sup>

The frequency of the  $\vec{E} \times \vec{B}$  drift rotation equals the  $m = 2$  diocotron mode frequency for an infinite cylindrical column. However, our observed mode has an  $m = 1$  spatial nature and it cannot be identified as this mode. The physical nature of the two phenomena is still very similar. The observed mode cannot be identified as the  $m = 1$  diocotron mode either, since for that mode  $\omega_1 = 2N_e c / R^2 B$ , where  $R$  is the radius of the cylindrical conductor. The frequency of this mode is inversely proportional to the strength of the magnetic field, in contrast to the experimental observations.<sup>6</sup>

The fact that the longitudinal and transverse modes have the same frequency proves that they are coupled. A possible coupling mechanism can be through the  $\theta$ -component of the electrostatic field which is caused by the azimuthal mode. This field crossed with the radial component of the mirror magnetic field causes an axial oscillatory drift which will have the same frequency as the azimuthal mode. The coupling may also happen because of the fact that the axis of the metal cylinder and the axis of the magnetic field are unparallel. The azimuthal motion will then cause an oscillating component of the electric field in the  $z$  direction.

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