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We have shown that the classical theory gives a favorable condition to the possibility of microwave free-electron lasers. Experimental investigation of this possibility is of great significance, not only as a device for the production of high-power coherent radiation, but also as a fundamental process for the interaction of free electrons with coherent radiation, which has attracted a great deal of theoretical interest and attention some years ago.¹⁵

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Radial Distribution of Nonneutral and Neutral Electron Clouds Confined in a Magnetic Mirror

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The radial distribution of a nonneutral electron cloud confined in a magnetic mirror was measured. The cloud is compressed by the magnetic field to a final radius of 4 mm from an initial radius of 4.5 cm with a final kinetic energy of 0.3 MeV and 2×10^{11} electrons. The radial distribution of the cloud is hollow up to 150 μ sec after injection. When the cloud is neutralized by a background plasma, filling in of the center does not occur.

There has been a considerable interest in the last years in the behavior of nonneutral plasmas. Part of this interest comes from the possibility of using the electrostatic fields of these plasmas for collective ion acceleration. Nonneutral electron plasmas confined in magnetic mirror fields were investigated at the University of Maryland¹ for a few years. A few groups around the world have investigated the concept of the electron ring accelerator.²⁻⁵ The use of a toroidal confinement scheme was also investigated for similar purpose^{6,7} and lately, a toroidal collective focusing ion accelerator using a magnetically confined electron cloud has been constructed at the University of California at Irvine.^{8,9}

Levy¹⁰ has shown that an infinitely long, magnetically confined, hollow electron column can be unstable against electrostatic surface waves.

These diocotron¹⁰ oscillations, which are unique to nonneutral plasmas will tend to diffuse the inner and outer boundaries of the hollow column. When this occurs, electrons will effectively cross magnetic field lines. In the present investigation the dynamical behavior of the radial distribution of an electron cloud confined in a magnetic mirror was measured directly for the first time. This was done for neutralized as well as nonneutralized electron clouds.

In the system described here an electron cloud with average electron energy of about 8 keV is injected into a magnetic mirror. Part of the electrons are trapped and then compressed and accelerated by the increasing magnetic field. The magnetic field is then crowbarred and an equilibrium of the nonneutral electron cloud trapped in the magnetic mirror is achieved.

The system was described in detail elsewhere¹¹ and a schematic diagram is shown in Fig. 1. The magnetic mirror field rises in 160 μsec to a peak value at the mirror minimum of 10 kG. The field decays exponentially with a time constant of 1.6 msec. The vacuum system is a glass system with a base pressure of 5×10^{-8} Torr. Inside the glass system is a stainless-steel slotted metal cylinder with a 10-cm diameter. The injector has a thermionic electron source and in most shots it was biased to 8 keV, had a 10-A emission current and the pulse was about 10 μsec wide. The magnetic mirror field has a 1:1.6 mirror ratio on one side and 1:2.3 on the other side. An independent coil creates another magnetic field which is used to make the mirror field flat and electrons are ejected out of the system along field lines by their self-generated electrostatic field.

We have been able to trap up to about 2×10^{11} electrons which have an average kinetic energy of about 0.3 MeV.¹¹ The number of electrons trapped is about a factor of 4 higher than was reported earlier.¹¹ This improvement in trapping was achieved by pushing the filament in the injector 1 mm beyond the anode plate,¹¹ and by increasing the mirror ratio.

The ejection of electron clouds was measured by a Faraday cup and by an x-ray detector which measured bremsstrahlung by ejected electrons. In the present configuration an NE102 plastic scintillator was attached on the end of the system at the low mirror side. Electrons ejected out of the system hit the scintillator and created an image of the electron cloud. The scintillator is 3 mm thick, has a diameter of 10 cm and is located in a point where the magnetic field during ejection equals the field at the midplane.

As was reported earlier the cloud executes electrostatic oscillations which were detected by an external electrostatic probe.¹¹ It was also shown¹¹ that the ejected electron cloud does not create a single pulse but a series of pulses which appeared at a frequency which increases with the number of trapped electrons.

An electronic framing camera was used to record the image of the cloud created on the scintillator. Each frame is 200 nsec wide and the delay between frame is 200 nsec wide and the delay between frames can be changed. The cloud was ejected at different times after injection and its image was photographed.

Figure 2(a) shows three images of the cloud on the left. The cloud was ejected here 110 μsec

FIG. 1. Schematic diagram of the system. Electrons trapped in the mirror are ejected out of the system by the ejecting coil. The electrons are ejected to the left and hit the plastic scintillator.

FIG. 2. (a) Cloud image at a shot in which the cloud is ejected $110 \mu\text{sec}$ after injection. The left part of the picture shows three images of the cloud recorded by the fast framing camera. The lower oscilloscope trace on the right is the signal of the x-ray detector during ejection in the same shot. Each of the positive pulses on the upper trace corresponds to the time at which the camera shutter was open during this shot. (b) Image of the cloud ejected $275 \mu\text{sec}$ after injection. The delay between the openings of the shutter was increased here and it is seen that the image of the cloud is almost solid at the first frame and becomes hollow later. This behavior is seen in other delays too. Note the different time scale and the interchange of the upper and lower traces. (c) Image of the cloud ejected $550 \mu\text{sec}$ after injection. The lower trace on the right is this time an electrostatic probe signal which measures the induced current because of electrons hitting the scintillator. This probe is a metal screen located in front of the scintillator and the cloud image is photographed through it. Note the radial expansion of the cloud. (d) Cloud image for a neutralized cloud. All the three images are hollow. Note the fact that the x-ray pulse is not modulated in this case.

after injection. The lower oscilloscope trace shows the modulated x-ray signal, while the three positive pulses on the upper trace correspond to the time at which the shutter is open. As can be seen the cloud image is hollow at the

FIG. 3. Dependence of cloud diameter on the time at which the cloud is ejected after injection. Each point is an average of three images like the ones shown in Fig. 2. The $B^{-1/2}$ curve is normalized to give the best fit to the measured points. The decrease in the $B^{-1/2}$ curve corresponds to the compression stage of the cloud and the increase in $B^{-1/2}$ is due to the decay of the magnetic field. The rate of the cloud expansion is faster than the $B^{-1/2}$ increase.

center. This hollowness of the cloud during the whole ejection time is observed for ejection times of up to about $150 \mu\text{sec}$ after injection.

Figure 2(b) is similar to Fig. 2(a), but this time the cloud is ejected after $275 \mu\text{sec}$. What is seen is that the earlier parts of the ejected pulses form a solid image while the later parts form a hollow one. Figure 2(c) shows a typical image of the cloud that was ejected $550 \mu\text{sec}$ after injection. All the images seen on this picture are solid, although the image of the one or two last pulses that are ejected are found to be hollow at this delay time. When the cloud is ejected at 1 msec after injection, all images of the cloud are found to be solid. The radial expansion of the cloud is clearly seen in Fig. 2(c).

Figure 2(d) is again a similar figure, however, this time the cloud is neutralized because of the plasma that was injected into the system because of a short circuit on the injector. What is seen in this case is that all the images are hollow. In these cases of neutralized clouds no signals are observed on the electrostatic probes and the ejected electron cloud is not modulated but continuous as can be seen on the x-ray detector signal. We had shots up to about 0.5 msec after injection in which the neutralized cloud remained hollow in contrast to the case of nonneutralized clouds.

Figure 3 shows the dependence of average cloud diameter measured from the three exposures in each shot on the ejection delay time. The $B^{-1/2}$ curve is calculated from the known time dependence of the magnetic field. As can be seen from Fig. 3 the cloud has a diameter of less than 1 cm at peak compression. The initial diameter of the cloud, which is fixed by the injector location, is about 9 cm. The $B^{-1/2}$ curve is normalized in order to get the best fit for the experimental points. If the cloud behaves in an adiabatic way then one would expect a $B^{-1/2}$ dependence. But as can be seen from Fig. 3 the expansion of the cloud in the decaying magnetic field is faster.

The expansion of the cloud beyond the $B^{-1/2}$ dependence and the filling in of the center are both nonadiabatic processes and they are connected to the fact that the plasma is not neutral. As was shown earlier,¹¹ the cloud executes electrostatic oscillations which are similar in their nature to the diocotron oscillations.¹⁰ These oscillations were always observed when the cloud was not neutralized and were never observed for neutralized clouds. As we described earlier the diocotron oscillations are surface modes which will tend to diffuse the surfaces of the cloud. It seems very reasonable, therefore, that the filling in of the center and the faster-than-adiabatic radial expansion are a result of these electrostatic oscillations. Filling in of the center is not occurring when the cloud is neutralized since these electrostatic modes do not exist for a neutralized cloud. This set of

measurements represents an indirect evidence that one mechanism for a cross-field diffusion process in a nonneutral plasma is through the electrostatic oscillations of the plasma.

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Hydrogen-Pellet Fueling Experiments on the ISX-A Tokamak

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We report the results of experiments on the ISX-A (impurity-study experiment) tokamak that demonstrate the technique of plasma fueling by solid-hydrogen-pellet injection. The results show that density increases of up to 30% or more can be realized without apparent deleterious effects on plasma stability and confinement.

Considerable attention has been given lately to the concept of proposed refueling tokamak fusion power reactors by injecting solid hydrogen pellets into the reacting plasma. The principal

advantage claimed for this technique is that a moving pellet will traverse the confining magnetic fields and thereby carry fresh fuel to the hot central plasma core. For this technique to prove

FIG. 2. (a) Cloud image at a shot in which the cloud is ejected $110 \mu\text{sec}$ after injection. The left part of the picture shows three images of the cloud recorded by the fast framing camera. The lower oscilloscope trace on the right is the signal of the x-ray detector during ejection in the same shot. Each of the positive pulses on the upper trace corresponds to the time at which the camera shutter was open during this shot. (b) Image of the cloud ejected $275 \mu\text{sec}$ after injection. The delay between the openings of the shutter was increased here and it is seen that the image of the cloud is almost solid at the first frame and becomes hollow later. This behavior is seen in other delays too. Note the different time scale and the interchange of the upper and lower traces. (c) Image of the cloud ejected $550 \mu\text{sec}$ after injection. The lower trace on the right is this time an electrostatic probe signal which measures the induced current because of electrons hitting the scintillator. This probe is a metal screen located in front of the scintillator and the cloud image is photographed through it. Note the radial expansion of the cloud. (d) Cloud image for a neutralized cloud. All the three images are hollow. Note the fact that the x-ray pulse is not modulated in this case.