Experiments on Electron Injection into a Toroidal Magnetic Field*

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Electrons have been injected into a toroidal magnetic field to form an electron cloud of approximately uniform density. The injection process was accomplished at magnetic fields of several kilogauss and differs from the inductive charging technique used by previous researchers. Electron densities of $\sim 10^{10}$ cm^{-3} were injected and confined for several hundred microseconds, creating potential wells of ~300 kV. Measurements of the radiated microwave energy from the electron cloud are reported.

The production of magnetically confined electron clouds has previously been investigated for heavy-ion accelerator applications.[1-4] Other researchers have studied the injection of neutralized relativistic electron beams into toroidal magnetic fields.[5,6] Recently, the use of magnetically confined unneutralized high-ν/γ electron beams has been proposed as a means of storing very large electric and magnetic field energy for the production, heating, and confinement of plasmas.[7,8] This has rekindled interest in the production of nonneutral magnetically confined electron clouds and beams. The stability and equilibrium properties of such clouds and beams have been studied theoretically,[9-15] while the injection of low-density ($\sim 8\times10^{8}$ cm^{-3}) unneutralized relativistic electron beams has recently been investigated experimentally.[16] In this paper, we present the results of experiments on the injection of nonneutral electron clouds with density up to $\sim 10^{10}$ cm^{-3} into a toroidal magnetic field. This injection has been accomplished in the presence of magnetic fields of several kilogauss using a technique which differs significantly from that used by previous researchers.

A schematic drawing of the experimental configuration is shown in Fig. 1. A toroidal device (the STP machine) is used to confine electrons injected from a thermionic emitter. The major radius of the device is 50 cm, and the minor radius of the vacuum vessel is ~8.1 cm. The stainless-steel vacuum liner is surrounded by an aluminum shell which is ~2.1 cm thick. An ion pump and titanium sublimation pump provide vacuum in the 10^{-9}-Torr range. An iron-core transformer is available to provide a toroidal electric field. The maximum magnetic field at the minor axis is ~7.8 kG, and the rise time of the magnetic field (zero to peak) can be varied between 2.0 and 3.5 msec. A quasisteady vertical magnetic field can also be applied to provide horizontal positioning of an electron beam formed by accelerating the injected charge.

Electron injection is accomplished by means of a pulsed negatively biased thermionic emitter in conjunction with a curved plate structure. The thermionic element is a directly heated tungsten dispenser cathode which consists of a helical winding of seven turns of 0.64-mm-square cathode material. The cathode helix is 0.64 cm in diameter and ~1.9 cm long. The injector assembly is inserted into the magnetic field near the wall of the vacuum vessel at one toroidal position with the axis of the cathode parallel to the minor axis.

Two different kinds of probes have been used to measure the density of the injected electron cloud. One of these consists of a flat circular stainless-steel disk mounted flush with the vacuum wall, but electrically insulated from it. This disk is connected through a terminated 50-Ω cable to an oscilloscope. This probe provides two separate

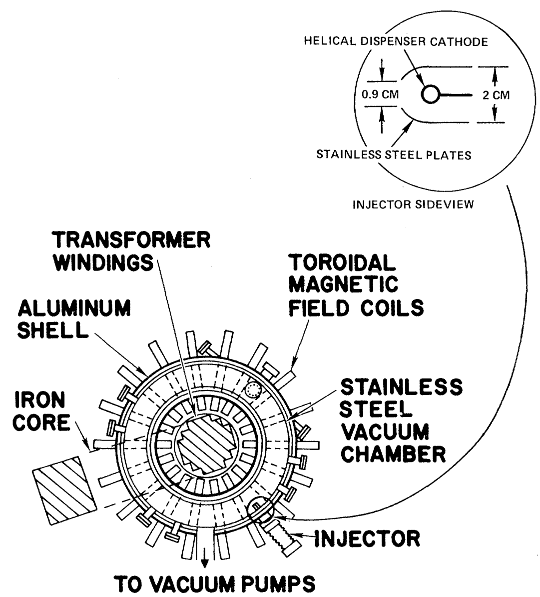

FIG. 1. Schematic drawing of the experimental configuration.

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measurements of the injected charge.[2] First, the image charge induced on the disk produces a voltage at the oscilloscope when it flows to ground. Integrating the probe voltage provides a measure of the injected charge. The disk probe also couples capacitively to the diocotron surface flute modes on the unneutralized electron column. The frequency of these oscillations is given by[2,17] $f \approx Q/8\pi^3 R_0 a^2 \epsilon_0 B_0$, where Q is the injected charge, a is the minor radius of the vacuum vessel, R_0 is the major radius, ϵ_0 is the permittivity of free space, and B_0 is the toroidal magnetic field at the minor axis.

The other probe used in the experiment was a high-impedance voltage probe. This probe consists of a 0.5-mm-diam wire covered with an insulating glass sheath except for the tip which is exposed to the electron cloud. This probe can be used to measure the potential well created by the electron cloud from which an estimate of the injected charge can be obtained. The probe is movable so that the radial profile of the potential well can be determined. This type of probe was useful for measuring potentials up to ~100 kV. Above this voltage the probes flashed over along the glass sheath. For potential well depths greater than ~100 kV the probes were used to measure the potential near the edge of the electron cloud from which the potential at the minor axis can be inferred. These results agree with measurements from the disk probes.

Figure 2 shows a typical radial profile of the potential well. The profile is approximately parabolic, indicating that the electron density is nearly uniform across the column. By placing a small disk (1.9 cm diam) at the minor axis and draining the charge at the center through a low impedance, we have also produced hollow annular electron clouds. The radial potential profile under these conditions has the expected flat-top shape.

Under the assumption that the electron density in the cloud is approximately uniform, the injected charge is given by $Q \approx 8\pi^2 R_0 \epsilon_0 V_0$, where V_0 is the potential at the minor axis. Figure 3 shows a plot of the injected charge as determined from both potential probe measurements and diocotron frequency measurements. The results are plotted as a function of the injector cathode bias voltage. The measurements indicate that the injected charge scales linearly with the cathode bias voltage. Potential well depths of up to ~300 kV and injected charge of ~100 μC were achieved with a cathode bias voltage of ~36 kV. The highest charge level corresponds to a uniform electron density of ~10^{10} cm^{-3}.

Measurements of the X-band microwave radiation from the electron ring were made using an X-band wave guide which extended from a glass vacuum view port to a screen room some 15 m away. Figure 4 shows oscilloscope traces of an integrated disk probe signal, a potential probe signal, and detected microwave signals for two different injected charge levels. Electron injec-

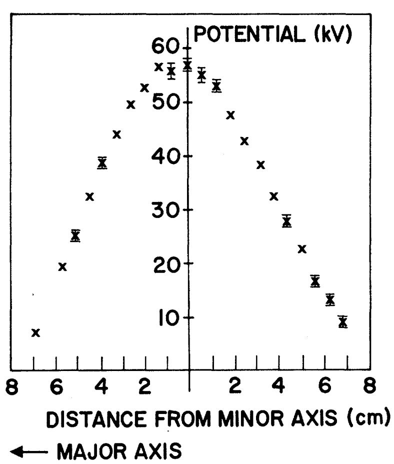

FIG. 2. Radial potential profile measured with a high-impedence potential probe. The cathode bias voltage was 11 kV, the magnetic field rise time was 3500 μsec, and the maximum magnetic field was 5.3 kG. Charge injection was started 2150 μsec after the start of the magnetic field.

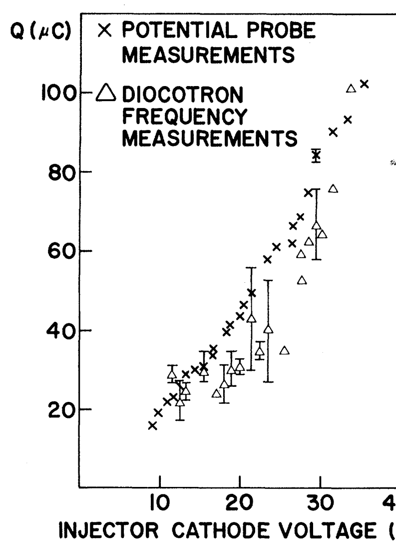

FIG. 3. Charge injected as a function of the injector cathode bias voltage. Injection started 2150 μsec after the start of the magnetic field. The peak magnetic field was 5.3 kG.

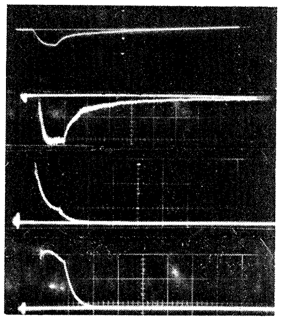

FIG. 4. Oscilloscope traces of probe signals and detected microwave signals. The time scale for all traces is 50 μsec/div. Upper trace: integrated disk probe signal, $RC = 500$ μsec, ~55 μC/div. Second trace: potential probe signal. Third trace: detected microwave signal with injected charge of 42 μC (2 mV/div). Lower trace: detected microwave signal with 81 μC of injected charge (5 mV/div).

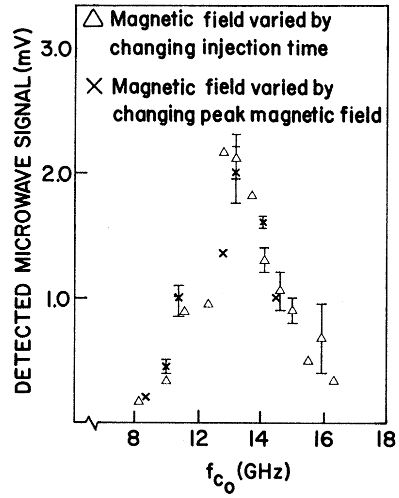

FIG. 5. A plot of the detected microwave signal as a function of the cyclotron frequency for an electron at the minor axis.

tion for these shots occurred over 50 μsec starting ~2150 μsec after the beginning of the magnetic field. The magnetic field rose to a peak of 5.3 kG in 3500 μsec. Under these conditions the potential created by the injected charge lasts ~200 μsec, after which oscillations are observed in the unintegrated disk probe signals. These oscillations probably correspond to the ion resonance instability discussed by Levy, Daugherty, and Buneman.[12] Although the amplitude and the shape of the microwave signal change as the amount of injected charge varies, the emission is normally strongest near the beginning of the injection period before the electron density has reached its peak. We assume that this early peak is due to a collective radiation mechanism driven by the injection process.

In Figure 5, the amplitude of the detected microwave signal is plotted against the cyclotron frequency for an electron at the minor axis (f_{c_0}) as the magnetic field is varied. By changing the magnetic field at injection time, f_{c_0} is swept across the pass band of the lowest-order (TE_{10}) wave-guide mode. The magnetic field was varied both by adjusting the peak magnetic field and by changing the time during the rise of the field at which injection occurred. Both methods of changing the magnetic field at injection time gave the same variation in the detected microwave signal, indicating that the emission depends on the magnetic field and suggesting that it occurs at the cyclotron frequency.

The electron injection technique described here differs significantly from the inductive charging process reported previously.[1-3] The charge injection in the present experiments occurred in much more slowly rising magnetic fields and at field strengths considerably in excess of the critical magnetic field above which inductive charging ceases. We speculate that the observed charge injection may be due to the creation of a diocotron resulting from an initial annular electron cloud profile. Such an instability would saturate by filling the center of the cloud. Another possible explanation involves electron transport across magnetic field lines due to the anomalous noise and electron stream behavior discussed previously.[18-20] The existence of charge in the center of the machine has been verified by means of voltage probes operated in a low-impedance mode (50 Ω) to collect charge. Such probes typically collect currents of ~1 A within a few microseconds after injection has been started, indicating rapid transport of the electrons into the center of the machine. Typically, approximately half the current leaving the injector goes into the electron cloud. Depending on the injector voltage and geometry, the emitted current can vary from ~1 A to more than 20 A.

Preliminary experiments have been conducted using the transformer which produces a toroidal electric field of about 0.5 V/cm. Under these conditions the toroidal current was only 50 A instead of ~10 kA corresponding to 100 μC. The application of a vertical magnetic field of up to ~50 G (of either polarity) had no significant effect on the current or the equilibrium of the electron cloud. On the basis of these observations, we conclude that almost all of the electrons are in trapped orbits between magnetic mirrors. The toroidal magnetic field varies by ~1% on the minor axis and ~0.3% on the inner wall of the torus over a distance of $L=17$ cm (the distance between coils). If $E_\varphi < (mv_\perp^2/2Be)\Delta B/L$, the toroidal electric field E_φ would be insufficient to overcome the magnetic mirror effect. With $E_\varphi = 0.5$ V/cm and $100\Delta B/B = 0.3-1$, the electrons would remain trapped if $mv_\perp^2/2 = 2.8-0.85$ keV. The drift kinetic energy of electrons at the periphery of the torus is $(m/2)(cE_r/B_z)^2 = 0.6$ keV which is insufficient to produce trapping. However, the injector has applied voltages of ~35 kV so that it is quite likely that $mv_\perp^2/2$ is approximately several keV, which is sufficient for trapping.

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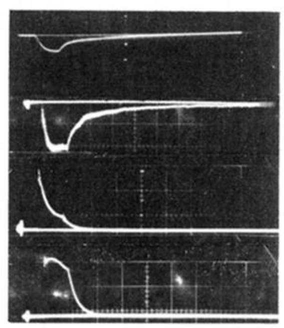

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