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Studies of an unneutral electron cloud confined in a multiple-mirrored toroidal magnetic field^{a)}

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An unneutral electron cloud of 3×10^{13} electrons with a number density of 10^{11} cm^{-3} was compressed and confined by a multiple-mirrored toroidal magnetic field. The radial electric field associated with this electron cloud was about 10^5 V/cm . The electrons, having a large magnetic moment, were confined by the magnetic mirrors. An upper limit of 1 A was set on the induced current when a toroidal electric field of 10 V/cm was applied. This puts a limit $n < 4 \times 10^8 \text{ cm}^{-1}$ on the line density of electrons with perpendicular energy lower than 300 eV.

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The confinement of an unneutral electron cloud in a bumpy toroidal magnetic field is the basis of a scheme for a strong electric focusing ion accelerator.^{1,2} In this scheme, the electrons are adiabatic in the multiple-mirrored toroidal magnetic field, whereas the ions are weakly magnetized. In such a case only ions are accelerated by an induced toroidal electric field. Pursuing this scheme, we present here experimental results on injection and confinement of an unneutral electron cloud in the UCI glass torus.

The glass torus and field coils are shown schematically in Fig. 1. The magnetic field forms 16 mirror cells. Four crossed field injectors are mounted in the ports around the torus. In a previous publication³ we described the behavior of an unneutralized electron cloud in a single magnetic mirror. When the number of injected electrons surpassed the limit that the mirror could hold, the extra electrons were ejected sideways in the toroidal direction. However, owing to the large Larmor radius during injection and the relatively slow rise of the magnetic field, most of the ejected electrons were lost before making a single revolution around the torus. In an attempt to trap the ejected electrons in the side cells,

the magnetic field buildup in these cells was started before activating the coils of the injector cell. By controlling the relative delay between the field start in the side cells and in the injector cells, we could find a setting where electrons were trapped in both types of mirror cells.

Figure 2 presents the observed diocotron frequency in the side cell as a function of injected current into the injector cell. We note that the $l = 1$ diocotron frequency is proportional to the line density of the trapped electrons.^{3,4} The results in Fig. 2 demonstrate that above a certain threshold in injected current electrons are trapped in side cells. The threshold in injected current is due simply to the fact that electrons are first trapped in the injector cell. Using an energy-calibrated x-ray detector collimated to view only radiation emitted from a side cell, we verified that the trapped electrons are indeed relativistic. The maximum electron energy in a side cell was 350 keV. This is lower than the energy of the electrons in the injector cell.³ The observed lower energy is explained by the lower magnetic moment of the electrons streaming sideways from the injector cell. The lower magnetic moment also explains the lower number of trapped electrons in the side cells. A comparison was made between the diocotron frequencies in two side cells of the same injector. It was found that the injector symmetrically filled the two side cells adjacent to the injector cell.

The four mirror cells centered between the four injectors did not trap electrons. Each injector could only fill three mirror cells. For this reason the self-toroidal-electric-field was not eliminated. Yet this electric field was reduced at the

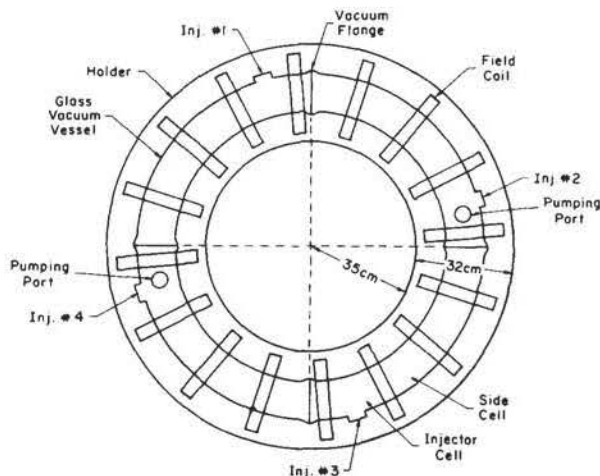


FIG. 1. Schematic diagram of the toroidal experiment.

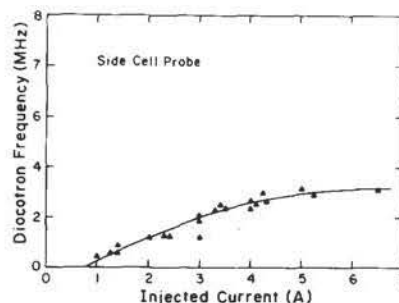


FIG. 2. Diocotron frequency in a side cell as a function of the injected current in the adjacent injector cell.

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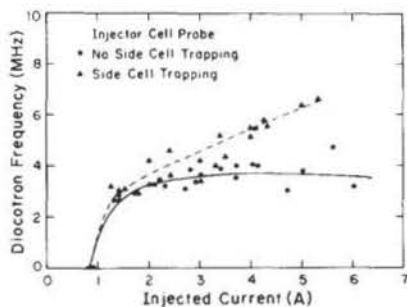


FIG. 3. Diocotron frequency in the injector cell as a function of the injected current into the cell with and without side-cell trapping.

injector cell when the two adjacent cells trapped electrons. One would therefore expect to see an increase in the number of electrons trapped in the injector cell. Figure 3 compares the diocotron frequency in the injector cell with and without trapping in side cells. When trapping in side cells took place the line density in the injector cell was increased up to 3.3×10^{11} electrons/cm. Assuming cloud dimensions similar to those observed in the linear mirror system,⁵ we obtain a number density of 3×10^{11} cm⁻³.

Since each injector could fill three mirror cells with electrons, we reduced the total number of mirror cells to 12. One should note that at this geometry the field coils are widely separated and the resultant magnetic mirror is weak on the outside wall. The injection conditions in this case are far from optimal and the trapping efficiency was poor. Nevertheless, we found a small range of operation parameters where the whole torus was filled with electrons. Eight radial electrostatic probes were used to test the filling of the torus with electrons. Four of the probes were mounted outside the injector cells. Each of the other probes viewed one of the two side cells for each injector. The line density was found to vary considerably along the torus. A very careful adjustment of the resistive shunts on the injectors was needed in order to get all the injectors to operate simultaneously in the same range of parameters. Under the best conditions the line density along the torus was found to be $(1-2) \times 10^{11}$ electrons/cm. The total number of electrons confined in the torus was 3×10^{13} . The maximum radial electric field associated with the observed charge density was 10^5 V/cm.

The signals on the radial electrostatic probes lasted for about 2 ms, which is the decay time of the magnetic field. However, no detailed measurement of electron loss was carried out. The stability of the cloud is currently being investigated.

In single-mirror confinement of a dense electron cloud only electrons with a high magnetic moment can be trapped. Contrary to this, when the whole torus is filled with electrons, one could not rule out trapping of low-magnetic-moment electrons. Such electrons would stream around and be accelerated by an applied toroidal electric field.⁶ For the projected ion accelerator it is important that only a very small fraction of the trapped electrons would have a low magnetic moment. In order to test the fraction of electrons that are free to stream in the torus, we have set up vertical magnetic field coils for driving a toroidal electric field. A 60- μ F capacitor bank was discharged into four loops distributed around the torus. The geometry of the four loops was chosen in a way that minimized the vertical field inside the glass vessel without a considerable loss of flux to drive the toroidal electric field. The oscillation period of the system was 115 μ s. A calibrated Rogowski coil was used to measure the toroidal current. Because of the perturbing field of the primary coils the sensitivity of the Rogowski coil was limited to an electron current of 1 A. Concurrently with the measurement of the induced current, we monitored the eight radial electrostatic probes, thus verifying that the torus was filled with electrons. An induced toroidal electric field of 10 V/cm was applied 150 μ s after the end of the compression of the cloud. No induced current was observed. This puts an upper limit of 4×10^8 electrons/cm having a perpendicular energy of less than 300 eV.

In summary, we have seen that filling cells adjacent to the injector cells with electrons allowed an increase in the number of trapped electrons in the injector cell. This indicates that to this point the number of trapped electrons is limited by the mirror force. Filling the whole torus with electrons did not drastically change the fraction of electron population with low magnetic moment. An upper limit of 0.5% of the trapped electrons could be accelerated by an applied toroidal electric field. Such a small fraction would not pose any problem for the potential use of the device as an ion accelerator.

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