IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

STUDIES OF AN UNNEUTRAL ELECTRON CLOUD IN THE CFIA*

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In the Collective Focusing Ion Accelerator (CFIA) scheme[1], a non-neutral electron cloud is trapped in a multiple mirror toroidal magnetic field. The electrons' radial electrostatic field serves to confine and focus an accelerated ion beam. The ion beam, with a density up to 10% that of the electrons', is accelerated by an induced toroidal electric field. The induced toroidal electric field, however, is not strong enough to overcome the mirror force acting on the electrons. This scheme enables the construction of a very small radius accelerator in the GeV range.

As a first stage in the development of the CFIA, it is necessary to demonstrate trapping and stability of a non-neutral electron cloud over a long time (a few msec). It is also necessary to show that the electron cloud remains confined to the mirror cells when an accelerating toroidal electric field is applied.

The main experimental parameters are summarized in Table I.

TABLE I

Experimental Parameters

Major radius	55 cm
Minor radius	5 cm
Number of Mirrors	16
Number of electron injectors	16
Base pressure	$< 10^{-7}$ Torr
Mirror ratio	1.7
Maximum toroidal magnetic field	17 kG
Energy stored in the toroidal magnetic field	150 kJ
Rise time of the toroidal magnetic field	90 μs
Decay time of the toroidal magnetic field	1.7 ms
Energy stored in the vertical magnetic field	50 kJ
Rise time of the vertical magnetic field	120 μs
Decay time of the vertical magnetic field	1 ms

Based on preliminary experiments,[2] a new glass torus was built, having a port for an electron injector at each mirror cell. Two ion injector ports were also included in the system. A schematic layout of the glass torus and the toroidal field coils is presented in Figure 1.

16 identical electron injectors were built using the same filament and emissive coating. All the injectors could be adjusted under vacuum for a proper filament to anode gap. A schematic diagram of an electron injector is shown in Figure 2.

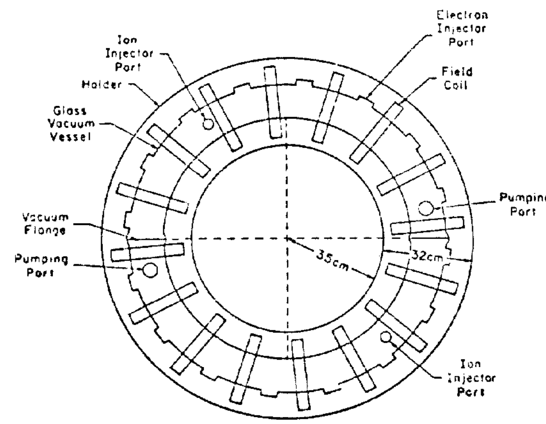

Figure 1. Schematic diagram of the glass torus and the toroidal field coils.

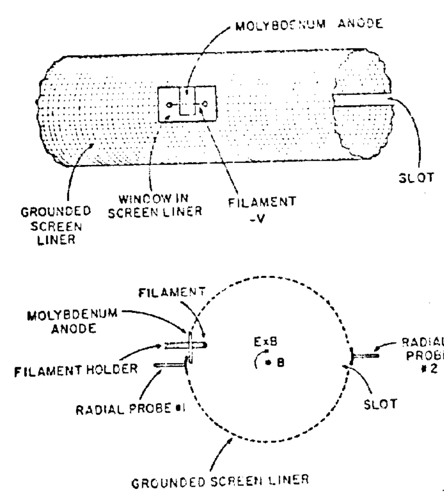

Figure 2. Schematic view of an electron injector.

The filaments of the electron injectors are negatively biased by a pulsed capacitor bank at a voltage range of 7.5 - 15 kV. The electron emission is temperature limited and lasts for about 8 μs, which is the time when the bias voltage is turned on.

The trapping of electrons in each mirror cell was monitored by an electrostatic probe. 16 electrostatic probes were used to verify electron trapping in each mirror cell simultaneously. It was shown previously[3] that the electrostatic oscillations induced on the probes are of the $\ell = 1$ diocotron mode.[4] The frequency of these oscillations is directly proportional to the

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electron line density

$$\omega_{\ell=1} = \frac{2Nec}{BR^2} \quad ,$$

here N is the electron line density, B is the toroidal magnetic field and R is the minor radius. The electron line density in every cell was inferred from the observed diocotron frequency. An efficient trapping of electrons (over 50%) was observed. The torus was filled homogeneously up to a line density of 4×10^{11} electrons/cm. This line density is very close to the electrostatic limit during injection

$$N < \frac{B^2R^2}{8mc^2} \quad .$$

when the magnetic field energy is smaller than the electrostatic field energy. This is not a very serious limitation on the trapped electron charge, since the magnetic field during electron injection can be increased substantially from the current value of about 400 Gauss.

Using 16 electron injectors to fill the torus we observed an increase in electron trapping efficiency by about a factor of two. A total injected current of 3A was enough to fill out the whole torus. Assuming cloud dimensions, after compression similar to those observed in a single mirror experiment,[5] we estimate a maximum radial electric field of 2×10^5 V/cm. This is enough to confine ions of up to 5 MeV.

Some of the parameters of the trapped electrons are summarized in Table II.

TABLE II

Observed Electron Characteristics

W_{inj} = 7.5 - 15 keV

I_{inj} = 1 - 3 A

q_{inj} = 5 - 20 μC

W_{final} = 200 - 500 keV

Cloud radius a = 0.5 - 1 cm

$N = 10^{10} - 4 \times 10^{11}$ cm^{-1}

$\omega_{ce} \sim 1.3 \times 10^{11}$ sec^{-1} at $\gamma = 2$

$\omega_{pe} \sim 6 \times 10^{10}$ sec^{-1}

Radial electrostatic limit $N < \frac{R^2B^2}{8mc^2} \cong 6 \times 10^{11}$ cm^{-1}
(during injection at 400 G)

Diocotron frequency $\omega_{\ell=1} = 5 \times 10^7$ sec^{-1}

Cloud lifetime 1 - 2 ms

The stability of the electron cloud was studied by comparing the diocotron frequency of the same probe at a few different points in time. Figure 3 shows the observed diocotron frequency of one electrostatic probe in one shot, at four different times.

The time delay from the beginning of the electron injection is indicated on the figure, together with the corresponding value of the toroidal magnetic field. Clearly, the observed diocotron frequency increased as the magnetic field decayed. The product of the diocotron frequency f at each time and the toroidal magnetic field strength B at this time, as a function of

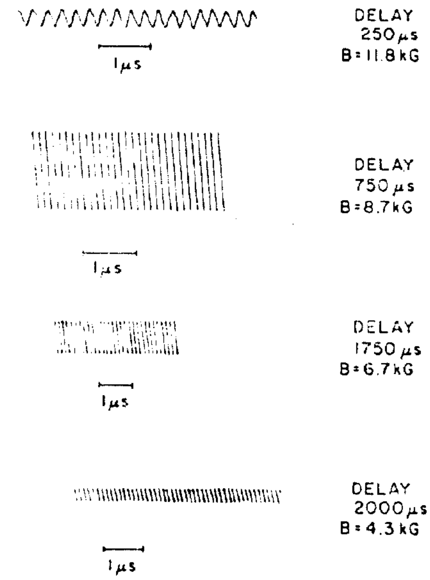

Figure 3. Diocotron oscillations at four different time points on a single shot.

the time from the start of the shot is shown in Figure 4. The product f.B, which is proportional to the line

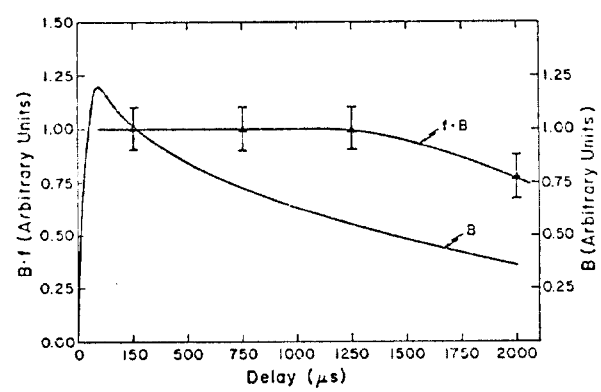

Figure 4. The time dependence of the toroidal magnetic field B and the product of the toroidal magnetic field with the cloud oscillation frequency.

density of the trapped electrons, stays constant for 1.5 ms and indicates no loss of electrons. It seems that the lifetime of the electron cloud is currently limited by the decaying toroidal magnetic field.

Using an induced toroidal field of 10 V/cm and an oscillating period of 115 μs, the induced electron current was measured. If all the electrons, with a line density of 4×10^{11} cm^{-1} were accelerated, there would be a circulating current of about 1 kA. In fact, an upper bound of 1 A was established. This means that at most 0.1% of the trapped electrons are not bound by the mirror force when we apply the accelerating field. This upper limit is low enough to insure no problems during ion acceleration.

In summary we note that a radial electric field of 2×10^5 V/cm was established. This field can confine ions with energy up to 5 MeV. A vertical magnetic field bank of 50 kJ was added to the system. This bank can accelerate protons to a final energy of about 1 MeV. Two ion injectors have been installed and ion acceleration is currently being investigated.

*Work supported by the United States Department of Energy.

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