FORMATION AND CONFINEMENT OF NON-NEUTRAL ELECTRON PLASMAS IN A MULTI-RING ELECTRODES TRAP USING WITH A FIELD EMITTER ARRAY CATHODE

H. Tanaka, T. Sodekoda, T. Maekawa, S. Yamaguchi†, T. Nagatomo†, M. Asakawa†, Y. Terumichi† and A. Mohri‡

Graduate School of Energy Science, Kyoto University
† Faculty of Science, Kyoto University
‡ Faculty of Integrated Human Studies, Kyoto University
Sakyo-ku, Kitashirakawa Oiwake-cho, Kyoto 606-8502, Japan

Abstract

A Field Emitter Array (FEA) cathode is used to form a non-neutral electron plasma in a multi-ring electrodes trap by the multi-pulse stacking method. The time evolution of the accumulation is investigated. When a $m = 1$ or 2 rotating electric field at frequency range of the electrostatic mode is applied, the plasma radius decreases and the confinement time becomes one order of magnitude longer.

1. Introduction

Conventionally, nonneutral electron plasmas are formed with a spiral hot tungsten cathode in order to give the hyperbolic potential distribution for a constant-density electron column [1]. One the other hand, recent experiments for production of nonneutral anti-matter plasmas are performed using isotopes or accelerators combined with some moderators. In such cases, the spatial energy distribution of the particles can not be controlled. And in order to increase the trapped number of particles, multi-pulsed beams are used [2].

Aim of this paper is to demonstrate to form nonneutral electron plasmas by trapping multi-pulsed electron beams emitted from the equipotential surface. A Field Emitter Array (FEA) cathode is used as an electron source. It is not only because the emitters are equipotential, but it has several benefits such as low outgas level, easy handling, and wide controlabillity. For trapping and confinement, a multi-ring electrodes trap is used. This trap enable us to confine long spheroidal nonneutral plasmas [3], and it is very important for trapping multi-pulsed beams.

Furthermore, we report preliminary results of long time confinement using a rotating electric field with frequencies of the electrostatic modes. These results differ from the case reported for the cold nonneutral ion plasmas [4].

2. Experimental Setup

The apparatus is shown schematically in Fig. 1. The FEA cathode is consist of 9 chips, each chip size is 4 mm $\times$ 4 mm and 6800 emitters/chip are etched. The size of the one emitter is about 2 μm. The gates of each three chips are electrically connected to apply voltages separately.

The multi-ring electrodes trap (2L = 78 cm) has 41 ring electrodes made of aluminium alloy with 9 cm inside diameter and 1.5 cm length. They are accurately aligned in the aluminium alloy vacuum chamber, insulated each other with ceramic supports. In order to produce a hyperboloidal electrostatic potential well, different voltages are applied to each ring electrode as $V(z_j) = V_{well} z_j^2/L^2$, where z_j is the position of the j-th ring electrode and $z_{21} = 0$. The trap is placed in a long solenoidal coil that provides a uniform magnetic field up to 510 G. The chamber is evacuated by a turbo-molecular pump and a cryogenic pump and the base pressure is about 1×10^{-7} Pa. Three ring-electrode (EL18, EL21 and EL24) are devided into eight sectors respectively and insulated each other electrically. In this experiment, a rotating electric field is applied to the central section (EL21) such that $V_k(t) = V_0 \cos(2\pi f_{rot} t - m\pi k/4)$, $(k = 0, \cdots, 7)$ for $m = 1$ or $m = 2$.

The radial profile of density distribution is measured by destroying the well and dumping plasmas to a 19 ch Faraday cup, whose spatial resolution is 3 mm.

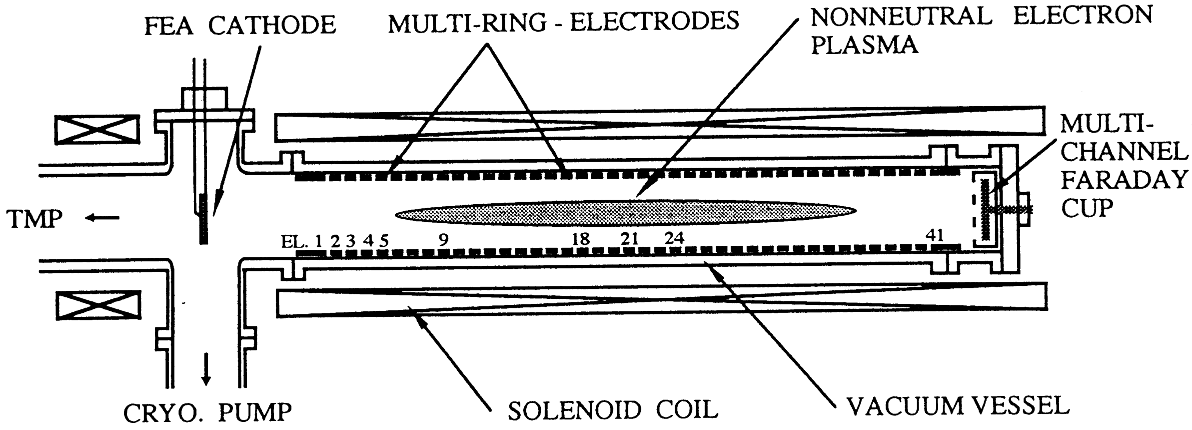

Figure 1. A schematic drawing of the experimental device.

3. Experimental Results

3.1. Injection and Trapping

Injection Firstly, electrons are emitted from FEA by applying DC negative bias V_E to the emitters and positive pulses V_{EG} between the emitters and the gates. Then the potential of 9 electrodes (EL1 - EL9) is raised from the well potential to V_1 $(> V_E)$ and the electrons are injected into the trap. After the duration τ_{inj}, the potential of the electrodes is set back to the well potential and the emission of electrons is terminated. This cycle is repeated N_{inj} times with a frequency f_{inj} and the electrons are accumulated gradually. When the conditions are set so that V_{well} = -80 V, V_E = -68 V, V_{EG} = 68 V, V_1 = -59 V, the injected current is about 10μA. Trapped electron number is 3 $\times 10^8$ for one pulse injection of $\tau_{inj} \simeq 70\mu s.$

3.2. Multi-pulse stacking

Temporal evolution of trapped number of electrons using multi-pulse stacking Repeating the injection and the trapping, multi-pulsed electron beams are stacked in the trap. The time evolutions of the trapped electron number are shown for various pulse frequencies (f_{inj} = 5 - 400 Hz) in Fig. 2(a). The evolution seems to be divided into three stages. During about 5 s from the begining of the injection, the total number of the trapped electrons increase rapidly (stage I). Then the rate of increase becomes smaller (stage II), and saturated in about 20 s (stage III). At the stage I, the rate of increase is larger for the higher frequency. The trapped electron number for the transition from state I to stage II is about 5 - 6 $\times 10^9$, and larger for the higher frequecy. At the stage II, the rate of increase is nearly the same for different frequency. At the stage III, saturation occurs when the trapped electron number becomes 8 $\times 10^9$ for all the frequencies. At frequencies above 200 Hz, small deterioration appears.

The evolutions of the trapped electron number are shown as a function of the injection pulse number in Fig. 2(b). The increasing rate for the pulse number is smaller for the higher frequency. This fact suggests that the trapped number per one pulse is smaller or some deterioration occurs for the higher frequency.

Figures. 3 (a) - (c) show the time variation of the total number of trapped electrons, the line-integrated electron density on the axis and the plasma radius for the condition that V_{well} = -80 V, V_E = -68 V, V_1 = -59 V and $f_{inj} = 40$ Hz. The central density increases as the injection starts, becomes maximum value at t $\simeq$ 1 s and decreases as the plasma radius increases. After t $\simeq$ 8 s, the central density do not change, while the total trapped electron number gradually increases as the plasma radius becomes large. After t $\simeq$ 16 s, the plasma radius increases up to 3 cm and then keeps constant. Coincided with this, the total trapped electron number saturates.

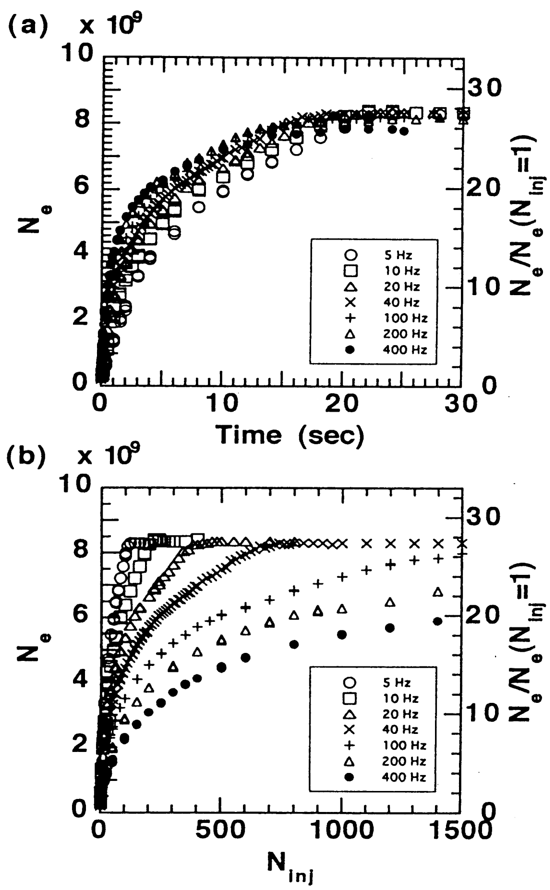

Figure 2. Variation of the trapped electron number as functions of (a) time and (b) injected pulse number, for various pulse frequencies.

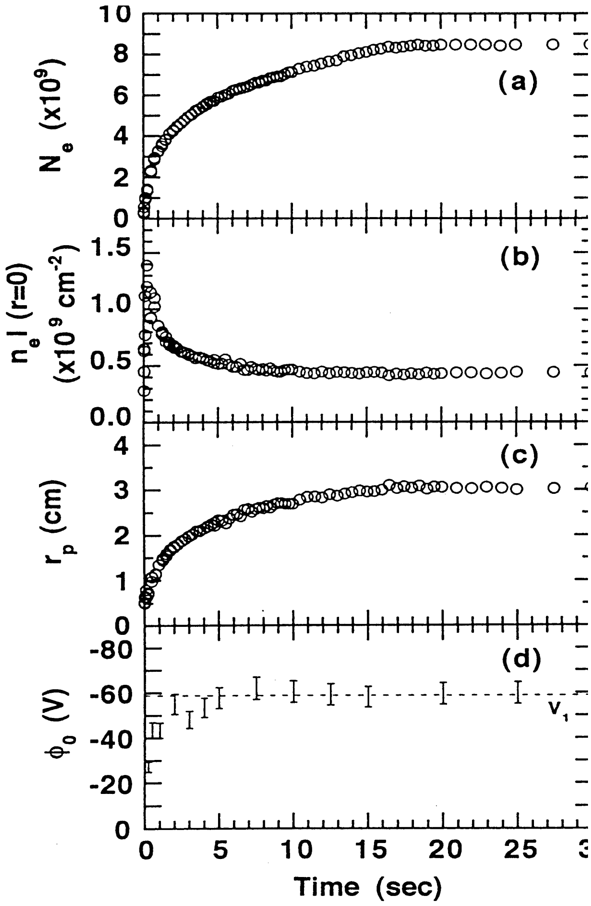

Figure 3. Temporal evolution of (a) the total trapped electron number, (b) the line-integrated density on the axis, (c) the plasma radius and (d) the calculated potential on the axis.

Saturation caused by the potential limit The potential on the axis ϕ_0 calculated from the density distribution assuming that the plasma is spheroid, is shown in Fig. 3(d). The potential ϕ_0 becomes as same as the barrier potential V_1 for the injection at about 4 s, that is the boundary of the stage I and II. At stage I, the potential ϕ_0 is lower than the barrier potential V_1 and the injected electrons can be trapped into the potential well. When the trapped electron number increases and ϕ_0 becomes the same as V_1, the injected electrons can not be trapped until the plasma spread and the central density decrease. At stage II, the trapped electron number increases as the plasma spread by diffusion and the potential ϕ_0 decreases. When the plasma reached to the electrode surface, electrons can not be trapped any more and the total trapped electron number saturates. This is at the stage III.

3.3. Long time confinement by applying a rotating electric field

The rotating electric field is applied to the central section EL21 from 15 s after finishing the injection of electrons. Figure 4(a) and (b) show the time variation of the total electron number confined in the trap and the line-integrated electron density on the axis, respectively, for the cases with and without the $m = 2$ rotating electric field in the same direction of the plasma rotation at $f_{rot} = 3.5$ MHz and $V_0 = 30$ mVpp. Total electron number decrease gradually, but the central density is kept constant during the application of the rotating electric field. The confinement time become one order of magnitude longer than that without the rotating electric field. Radial profile measurements show that the central density increases and the peripheral density decreases, that is, the plasma radius becomes smaller. Similar results are obtained for the $m = 1$ mode. These phenomena occur only when the frequency f_{rot} is close to that of the electrostatic modes of the spheroidal nonneutral plasmas [5]. These facts suggest that the rotating electric field couples with the electrostatic mode and give the angular momentum, resulting in the suppresion of the radial diffusion.

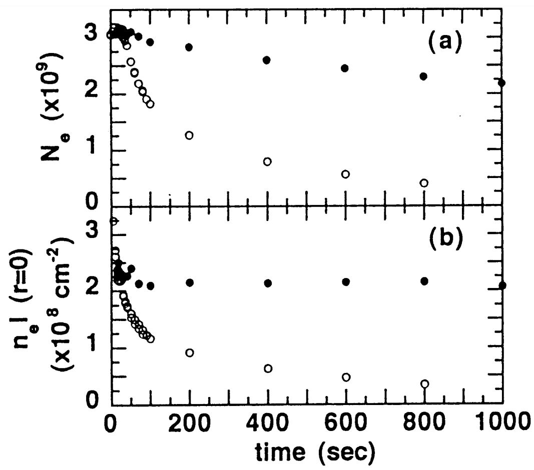

Figure 4. Time evolution of (a) total electron number and (b) line-integrated density on axis for the cases with and without application of the $m = 2$ rotating electric field.

4. Summary

Using the multi-pulse stacking method, electrons emitted from the equipotential surface of the FEA cathode are trapped and form the stable nonneutral plasma in the multi-ring electrodes trap. The saturation level of the total trapped electron number is determined by the condition that the self-charge potential on the axis reachs the barrier potential for the injection.

When the $m = 1$ or 2 rotating electric field is applied at frequency range of the electrostatic mode and in the same direction of the plasma rotation, the central density is kept constant and the confinement time becomes one order of magnitude longer. The plasma shrinks and the radial diffusion is suppressed.

Acknowledgements

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References

[1] J. H. Malmberg and J. S. deGrassie, Phys. Rev. Lett., **35**, 577 (1975).

[2] A. Mohri, H. Tanaka, T. Yuyama, T. Michishita et al., Material Science Forum, **175 - 178**, 967 (1995).

[3] A. Mohri, H. Higaki, H. Tanaka, Y. Yamazawa, M. Aoyagi, T. Yuyama and T. Michishita, Jpn. J. Appl. Phys., **37**, 664 (1998).

[4] X. -P. Huang, F. Anderegg, E. M. Hollmann, C. F. Driscoll and T. M. O'Neil, Phys. Rev. Lett., **78**, 875 (1997).

[5] D. H. E. Dubin, Phys. Rev. Lett., **66**, 2076 (1997).