

## Experiment on Nonneutral Electron Plasma Confinement in a Field Composed of a Magnetic Quadrupole and an Electric Octapole

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Cusped magnetic fields have been investigated from the earlier stage of fusion research considering their excellent characteristic of Minimum-B configuration [1-3]. However, all of the magnetic field lines diverge from the inside through the cusps, and the central region becomes a scattering centre of particles because the field around there is too weak to keep adiabatic motions of them. The confined particles are thus lost rapidly. To reduce the losses, many trials have been done so far. One of them was the use of rf-poderomotive force to push back the escaping particles [4]. Combination of electrostatic fields with cusped magnetic fields also have been studied as alternative configurations [5].

In the case of nonneutral plasma, electrostatic fields can plug particles escaping along magnetic field lines, as demonstrated in traps of Penning type [6] or cylindrical traps [7]. This plugging method will be applied to cusped magnetic fields[8,9]. Superposition of a cusped magnetic field and an electrostatic octapole (abbreviated to CMEO) forms a field configuration which perfectly trap a single particle [9]. Preliminary experiments showed that fairly good confinement of electron plasmas is realized in CMEO [9,10]. This report presents recent experimental results on electron plasma confinement in the second device of CMEO configuration: CMEO-2.

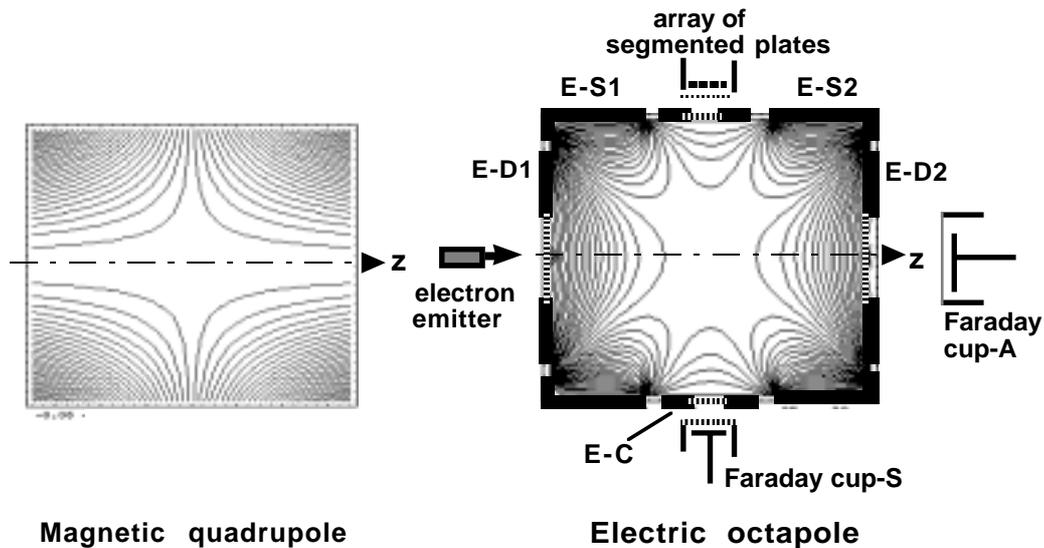


Fig. 1 Magnetic quadrupole and electric octapole of CMEO-2.

## Experimental Arrangement

Figure 1 shows the fields inside the CMEO-2. The octapole is generated by five electrodes surrounding the confinement region. The allotment of applied voltages on the electrodes is determined so as to make a pure octapole in the main region. The inner radius of the cylindrical electrodes: E-S1 and E-S2 is  $R=7$  cm and the axial distance between the disk electrodes: E-D1 and E-D2 is 16.4 cm. The electrostatic well depth  $\phi_w$  is the potential difference between the centre ( $r=0, z=0$ ) and the inner radius of the wall at  $r=R$ . This well depth is changeable up to  $\phi_w=18.3$  V. The magnetic quadrupole generated with external coils is superimposed on the electric octapole to form a CMEO configuration. As a measure of the magnetic field strength, its radial component at ( $r=R, z=0$ ),  $B_R$ , is used hereafter. Then,  $B_R < 360$  G in this experiment. The disk electrodes E-D1 and E-D2 have large holes covered with tungsten meshes. Pulsed electron beams are injected through the mesh of E-D1 into the confinement region. The beam energy is adjusted to be higher than the potential depth at the centre and the voltage of E-D1 is raised synchronously to each beam pulse so as to allow the beam entering. Stacked number of electrons,  $N$ , is measured by dumping them either into a Faraday cup-A on the axis or into a Faraday cup-S installed on the outside of E-C. To have information of the spatial extent of the confined plasma, a array of segmented plates with 1 mm pitch are also attached on the outside of E-C. These segments are aligned perpendicular to the axis, i.e., parallel to the midplane of the circular cusp.

## Experimental Results

The equilibrium in CMEO is determined by the balance of the self electric field of the plasma with the externally applied octapole. Therefore, the total particle number  $N$  must be upper limited by the externally formed potential well depth  $\phi_w$ . Figure 2 shows that obtainable maximum  $N_{\max}$  becomes larger with  $\phi_w$  in the case at  $B_R=360$  G. The relation between  $N_{\max}$  and  $\phi_w$  is almost linear. In weaker magnetic field,  $N_{\max}$  decreases, suggesting that the magnetic field also has an effect on the obtainable number of confined particles.

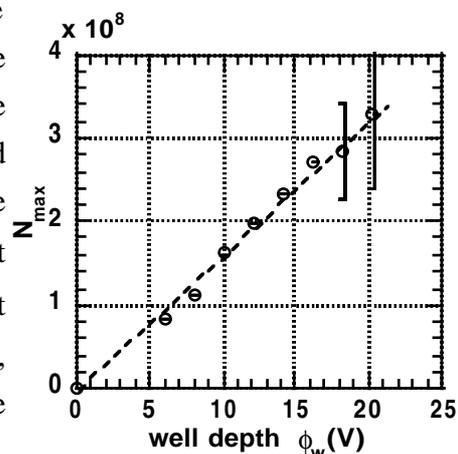
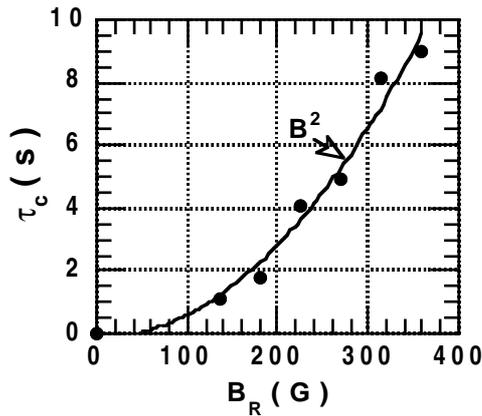
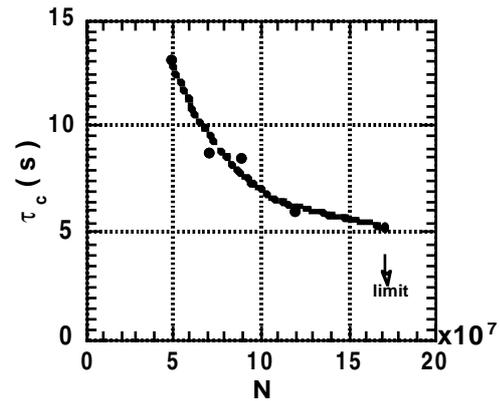


Fig.2  $N_{\max}$  for different  $\phi_w$ .

The confinement time  $\tau_c$  depends on many parameters. Figure 3 shows dependence of  $\tau_c$  on  $B_R$  where  $\phi_w=10$  V and  $N$  is kept constant as  $N \sim 4.7 \times 10^7$ . In the figure,  $\tau_c$  is nearly proportional to  $B_R^2$ . This data was taken at the vacuum pressure of  $p_v \sim 6 \times 10^{-8}$  mb. However, the confinement time is very sensitive to the vacuum pressure. When  $p_v$  goes up twice,  $\tau_c$  becomes shorter more than four times. In addition, it should be noted that positional miss alignment between the magnetic field and the octapole much deteriorates the confinement.


 Fig. 3 Dependence of  $\tau_c$  on  $B_R$ .

 Fig. 4 Dependence of  $\tau_c$  on  $N$ .

In order to see the effect of the plasma space charge on the confinement, the dependence of  $\tau_c$  on  $N$  is surveyed by keeping  $\phi_w$  constant. The result is shown in Fig.4, where  $\phi_w=10$  V and  $B_R=360$  G. The confinement time becomes shorter as  $N$  increases. These facts implies there is a mechanism which makes the particle transport larger as the self space charge goes up. Contrarily, the confinement time becomes longer at lower  $N$ . The longest time attained up to now is 17.5 s for the case of  $N=4 \times 10^7$ .

When confined electrons are dumped through the circular cusp, the array of segmented plates detect the axial distribution of the emerging electrons. The signal of charge on each plate corresponds to the line density along the magnetic field lines which penetrate the plate. Figure 5 shows time variations of the line density profiles for two different well depths. Here, the vacuum pressure is  $p_v \sim 2 \times 10^{-7}$  mb so that collisional diffusion becomes easily observable. When the well depth is as shallow as  $\phi_w=10$  V ( Fig.5(a) ), the profile rapidly evolves to make

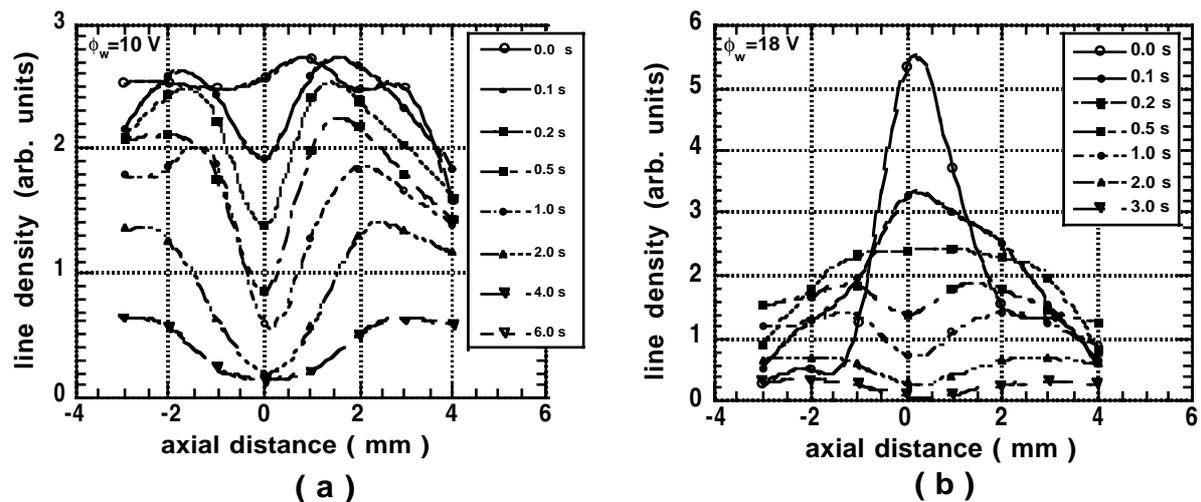


Fig. 5 Evolutions of axial profiles of line density emerging through the circular cusp.

(a) case of shallow well depth:  $\phi_w=10$  V,  $N(t=0.5 \text{ s})=2.0 \times 10^8$ ,

(b) case of deep well depth:  $\phi_w=18.3$  V,  $N(t=0.5 \text{ s})=1.6 \times 10^8$ .

a hollow, immediately after the end of stacking. This reflects there takes place a quick expansion of the electron cloud in the trap. The central region is nearly free of field except the self field, so that the initially injected electrons around the centre expand quickly. Besides, they easily diffuse out across weak magnetic field present in the outer region. This expansion is slowed down by increasing the octapole field as is noticed in Fig.5(b), where the potential well is 1.8 times as deep as in the case of Fig.5(a). In the above case,  $N \sim 1.6\text{--}2.0 \times 10^8$  and  $B_R = 360$  G. When  $N$  is decreased to  $4.7 \times 10^7$  at the same  $B_R$ , the expansion becomes slow as shown in Fig.6. On the other hand, the plasma expands faster at lower  $B_R$ .

### Conclusive Remarks

It has been experimentally shown that global confinement characteristics of nonneutral plasma in CMEO are tightly related to the internal dynamics of the plasma. The plasma can be held for long time when the well is deep enough to reduce the expansion. In this experiment, the vacuum is not so high as to make the collisional diffusion negligible. More long confinement is expected in an extremely high vacuum.

This configuration would be useful in many research fields such as atomic physics, nuclear physics and engineering.

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### References

- 1) J. Berkovits, H. Grad and H. Rubin: Proc. 2nd U. N. Int. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958) Vol.31, p.177.
- 2) G. Schmidt: Phys. Fluids **5** (1962) 994.
- 3) G. Gibson, W. C. Jordan and E. Lauer: Phys. Fluids **6** (1963) 116.
- 4) T. Watari, S. Hiroe, T. Sato and S. Ichimaru: Phys. Fluids **17** (1974) 2107.
- 5) T. J. Dolan: Plasma Phys. Control. Fusion **36** (1994) 1539.
- 6) F. M. Penning: Physica **3** (1936) 873.
- 7) J. H. Malmberg and J. S. deGrassie: Phys. Rev. Lett. **35** (1975) 577.
- 8) T. N. Tiouririne, Leaf Turner and A. W. C. Lau: Phys. Rev. Lett. **72** (1994) 1204.
- 9) A. Mohri, T. Yuyama, Y. Kiwamoto, Y. Yamazawa and T. Michishita: Jpn J. Appl. Phys. **37** (1998) L1553.
- 10) A. Mohri, Y. Kiwamoto, T. Yuyama, T. Michishita, H. Tanaka and T. Maekawa: 6th EPS ECA **23J** (1999) 465.

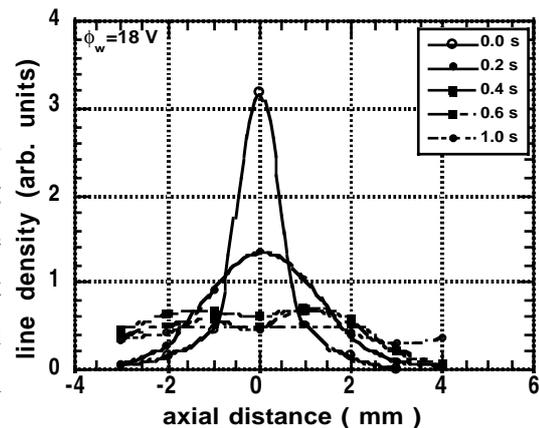


Fig. 6 Evolution of line density profile for  $\phi_w = 18.3$  V and  $N = 4.7 \times 10^7$ .