

Experiments on Nonneutral Plasma Confinement in a Field Composed of a Magnetic Quadrupole and an Electric Octapole

A. Mohri¹, Y. Kiwamoto², T. Yuyama², T. Michishita²,
H. Tanaka³, T. Maekawa³

¹Institute of Physical and Chemical Research, Wako city 351-016, Japan

²Department of Fundamental Sciences, Faculty of IHS, Kyoto University,
Kyoto 606-8501, Japan

³Graduate School of Energy Science, Kyoto University,
Kyoto 606-8502, Japan

Cusped magnetic fields were investigated in 1960's as a representative Minimum-B configuration to confine neutral plasmas.^{1, 2, 3)} In this field, however, the magnetic field lines go out of the central region and the weak field region including a null-point acts as a scattering centre of particles where no adiabatic condition is satisfied. Methods to reduce large particle losses brought by the above mechanisms have been examined, e.g., the use of rf-ponderomotive forces, but the confinement was not remarkably improved. On the other hand, particle losses along magnetic field lines of a nonneutral plasma can be blocked by an electrostatic field as is done in Penning trap.⁴⁾ The electric field which blocks up all escaping particles from a cusped magnetic field (quadrupole) should have a component of octapole which provides a centripetal electric field near each magnetic cusp. In general, for nonneutral confinement in a magnetic field of pole number $2j$ ($j=1, 2, \dots$), the electric field to be combined should have the pole number of $4j$. This report describes experiments on nonneutral electron plasmas in two apparatus, each of which has a combined fields of a cusped magnetic field and an electric octapole. This field configuration is abbreviated to "CMEO" hereafter.

It is readily shown by drawing the Störmer region that a proper CMEO configuration forms a complete bottle for a single charged particle with charge q , mass m and momentum \mathbf{p} .⁵⁾ The vector potential of a cusped field in the cylindrical coordinates (r, θ, z) is expressed by

$$A(r, z) = \frac{1}{2} B_0 L \left(\frac{r}{L} - \frac{z}{L} \right)^2, \quad (1)$$

where $\rho = r/L$, $\eta = z/L$, B_0 is the magnetic field at $r=0$ and $z=L$, and L is the characteristic length. The octapole potential is

$$V(r, z) = V_0 \left(\rho^2 + \eta^2 \right)^2 P_4 \left[\frac{\rho - \eta}{\sqrt{\rho^2 + \eta^2}} \right], \quad (2)$$

where P_4 is the Legendre function and V_0 is the potential at $r=0$ and $z=L$. When the canonical angular momentum of the particle is P_θ and the Hamiltonian is $H = (\mathbf{p}_r^2 + \mathbf{p}_z^2)/2m + V(r, z)$ with

$$L = \frac{1}{2m} \left(P_\theta / r - qA \right)^2 + qV, \quad (3)$$

then the particle motion with momentum p_0 at the origin is constrained by the relation

$$(r, z) \quad p_0^2 / (2m) = \dots \quad (4)$$

This gives the Störmer region. Examples of the region are shown in Fig.1 where $P = 2P / (qL^2 B_0)$ and $\dots = q_0 / \dots$.

The Störmer regions for the pure cusped field ($\dots = 0$) are always open to the outside, while they are closed in the CMEO ($\dots = 6$). The CMEO is thus expected to form a trap for nonneutral plasma as long as their self-field is kept under an allowable limit. The confinement time in the CMEO will be much more prolonged compared with that in usual cusped fields. To examine such a possibility, experiments on electron plasma confinement in the CMEO have been performed using two small apparatus.

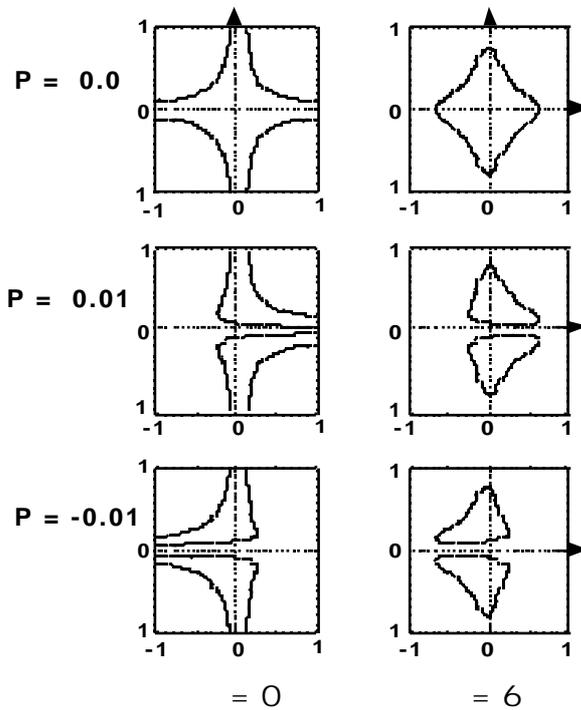


Fig.1 Störmer regions in the cusped magnetic field and the CMEO for $Lp_0/m = 20$.

Experiment I ⁵⁾

The Penning-like trap named MRE-4 was used to make a configuration of the CMEO. This trap has 45 ring-electrodes with inner radius $R=3.5$ cm, and they are axially aligned with pitch $p=1.6$ cm. The octapole field is generated by applying appropriate potentials on the rings near central region as shown in Fig.2(a). The cusped magnetic field was generated by setting the

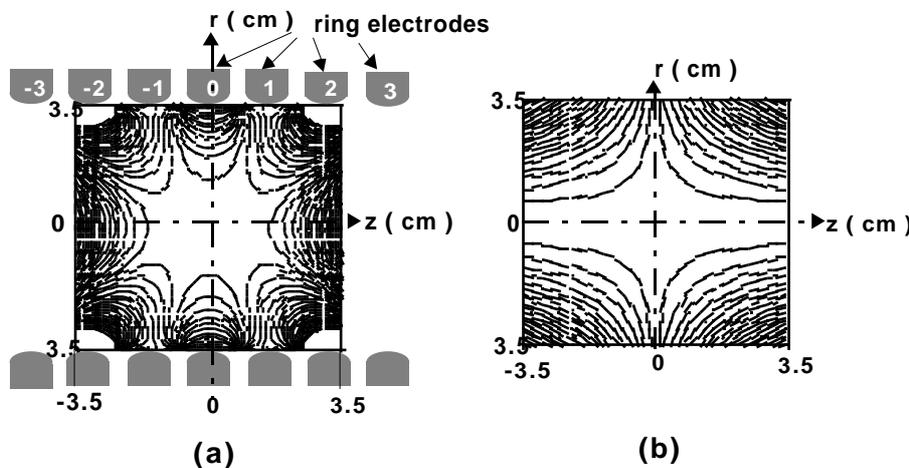


Fig.2 (a) Equipotential surfaces of the produced octapole. (b) Field lines of the cusped magnetic field.

polarities of twelve magnetic coils to be mirror-symmetric to the midplane. The field strength at the surface of the central electrode, i.e., at $r=R$ and $z=0$ is $B_{RW}=50$ G at maximum.

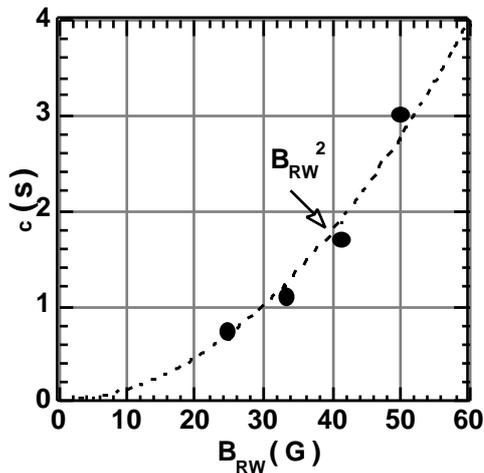


Fig.3 Dependence of τ_c on B_{RW} .

Electrons to be confined were accumulated by axially injecting pulsed electron beam through a spindle cusp. The total number of accumulated electrons N was measured by dumping confined electrons to a Faraday cup installed outside the other spindle cusp. The number N increased with the number of the beam pulses. In the case that the electrostatic well depth was 1.7 V and $B_{RW}=50$ G, the stacked number saturated to $N \sim 3 \times 10^7$. The confined time τ_c was measured by changing the time of dump. The observed dependence of τ_c on B_{RW} for the case $N \sim 1.5 \times 10^7$ is shown in Fig.3. The confinement time was increased as

$$\tau_c \propto (B_{RW})^2 \text{ and the longest one was 3 s.}$$

When the octapole was not applied, no stacking was observed because of rapid escape of injected electrons.

Experiment II

A new experimental device was made so as to increase the field strengths and the volume of the CMEO trap. The octapole is generated by five electrodes surrounding the confinement region, as shown in Fig.4. The inner radius of the cylindrical electrodes is $R=7$ cm and also the axial length inside is 8.2 cm. The electric well depth becomes 20 V when the potential difference between the central cylinder and the side cylinder: $(V_c - V_2)$ is 100 V. The cusped magnetic field at the inner surface on the midplane can be increased up to $B_{RW}=360$ G. The side disks have large holes covered with tungsten meshes, through which pulsed electron beams are injected. Trapped electrons are dumped through two holes made on the central cylinder for N measurement.

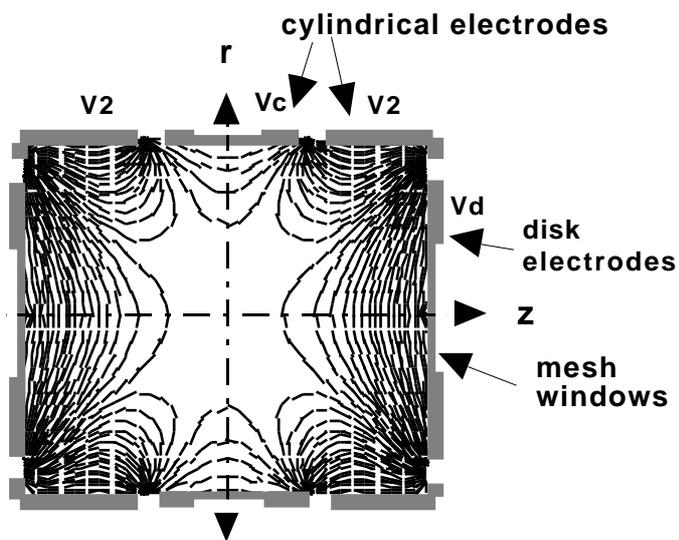


Fig.4 Equipotential surfaces inside the trap region.

For the case that $B_{RW} = 360$ G and the well depth was 10 V, the trapped particle number became $N = 2.6 \times 10^8$ which was ten times larger than the obtained one in the Experiment I. However, the confinement time was not improved so much as $\tau_c = 0.7$ s. Dependence of τ_c on the magnetic field strength was not so large as observed in the previous Experiment I, and τ_c became longer than 1 s for lower N. In this case the vacuum pressure was about 6×10^{-8} mbar or higher and misalignment between the axes of magnetic field and the octapole may be present, since a little adjustment of the axes improved the confinement. Electric fluctuations inferred from their induced signals on electrodes were at a small level in amplitude. Therefore, such a poor confinement may be attributable to the field error and the low vacuum environment. Better confinement in this system would be expected by getting a higher vacuum and by compensating error fields.

Conclusive Remarks

It was experimentally demonstrated that the electromagnetic configuration composed of a cusped magnetic field and an electric octapole can confine nonneutral plasma. The observed confinement time was much longer than that in the pure cusped magnetic field. It was found very easy to realise a confinement time longer than a second in small scale apparatus as used in the experiments described here. However, the field accuracy of the trap is required to be sufficiently high; otherwise particle losses would be increased. Detailed understanding of the equilibrium state in this configuration is necessary either to estimate the spatial density distribution or to consider its application to practical cases.

References

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