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A keV Collisionless Theta-Pinch Plasma Confined in the Caulked-Cusp Torus (CCT) Field†

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A keV Collisionless Theta-Pinch Plasma Confined in the Caulked-Cusp Torus (CCT) Field

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Abstract. At the Madison Conference it was reported [1] that a periodic caulked-cusp field is effective in the suppression of toroidal drift of a toroidal theta-pinch plasma as well as in its stabilization. Here, it is demonstrated that a theta-pinch plasma produced at low pressure regime is confined stably for a longer time of around 80 μs in the caulked-cusp torus (abbreviated to CCT) field, using the second machine CCT-II which is larger and fatter with a fewer rings than the first one CCT-I used at the time of the Madison Conference. Energy distribution of particles of the theta-pinch plasma is investigated by means of energy analysis of fast neutral particles emitted from the confined plasma. And it is found that the plasma confinement time is limited to be 80 μs by the decrease of the confining field strength due

to the decay of the crowbarring current and the induced ring-current, while the density decay time is estimated to be 120 μs. Those are confirmed also with the measurements of time variation of spectral lines $H_\beta (D_\beta)$ and the continuum due to bremsstrahlung.

1. INTRODUCTION

As is well known, a caulked-cusp field is formed in a homogeneous magnetic field by setting a current flowing ring so as to make the magnetic field of the ring-current reverse to the homogeneous field. Then, a closed null field line is produced inside the ring. The caulked-cusp torus field is built up by arranging such caulked-cusp fields along the minor axis of the torus at regular intervals (Fig.1). This configuration is easily produced by a toroidal theta= pinch machine equipped with many metal rings inside the discharge tube, where a current is induced in each metal ring due to the rise of theta-pinch field. In this case, the closed null field line is formed as the radius is to be about 3/4 of that of the ring and remains during the discharge due to the good conductivity of the ring.

Using CCT-I machine which major diameter is 50 cm and the minor one 10 cm for the glass tube, we found and reported at the previous conference that the equilibrium of the toroidal theta-pinch plasma is established when a minimum of the toroidal magnetic field exists at the midplane between two neighbouring rings (Fig.2a). This is necessary and sufficient condition to get the equilibrium state as far as our experiments showed. The CCT is named to a periodic caulked=cusp torus field having such field minima. The produced plasma is confined in the region determined by $|\int \frac{d\ell}{B}|_{max}$ outside the ring and so the rings are burried beneath the plasma surface.

Here, the behavior of the theta-pinch plasma confined in the CCT-II machine are reported in detail.

2. EXPERIMENTAL ARRANGEMENTS

In the case of CCT-I machine, the field minima were formed by using 24 rings of 5 cm in diameter. It is obvious that the field minima is realized with the fewer rings when the fatter toroidal machine is used. The CCT-II machine has been constructed as the major diameter is 50 cm and the minor one 20 cm for the glass tube equipped with 12 rings of 12 cm in diameter (Fig.3). The magnetic lines of force of the vacuum field are shown in Fig.1. The diameter of the confinement region is estimated to be around 12 cm by $|\int \frac{d\ell}{B}|$ calculation for the vacuum field.

The theta-pinch operation has been carried out mainly with a 30 kV and 100 kJ capacitor bank. The field on the axis rises to the maximum of 13 kG at 5.8 μs and it decays with the e-folding time of 170 μs after crowbarring. The maximum induced electric field at the instance of the firing of capacitor bank is 180 V/cm at the interior periphery of the glass tube. Helium, hydrogen and deuterium gases are used in the range of 1 mtorr to 20 mtorr.

3. PLASMA BEHAVIOR

In the case of CCT configuration, the obtained streak photographs show the suppression of toroidal drift and the stable plasma confined more than several tens μs (Fig.4). By this fact, it is verified again that the CCT principle which is characterized with the existance of the field minimum at the midplane is valid for the confinement of a theta-pinch plasma.

Details of the implosion phase of the theta-pinch are shown in Fig.5 in which the time variation of the azimuthally induced diamagnetic current in the plasma sheath at the midplane are plotted. The resistivity of the plasma sheath is estimated to be 0.01 Ωm which is deduced to be two order of magnitude higher than the classical value, which implies an anomalous resistivity. The hollow plasma sheath contracts first on the tube axis at 1 μs after the firing and the center of produced plasma column drifts to 2 cm outside the axis where the field is minimum (Fig.6). Subsequently to the radial oscillation, the pinched plasma column expands into the whole region of the CCT confining field with the characteristic time of around 15 μs, as is seen in the photograph. After the expansion, the plasma diameter holds ∿12 cm during several tens μs, while the position of the highest plasma density is still remained at 2 ∿ 4 cm outside the tube axis (Fig.10a). Such a behavior is similar as that observed in the CCT-I machine [2, 3].

Energy analysis of fast neutral particles emitted radially at the midplane gives several meaningfull data in this experiment. At the instance of the maximum contraction, a strong signal which seems to be due to a crowd of energetic particles of 0.7 ∿ 1.3 keV is observed at the midplane with faint intensity signals of the other energy region (Fig.7). Mass analysis with magnetic momentum analyzer shows that most of the emitted neutral particles consist of hydrogen atoms, and that bursts of hydrogen molecules appear rarely a few μs after the maximum contraction. The energy level of the mono-energetic particles varies linearly with the applied capacitor voltage and also varies as a function of filled gas pressure (Fig.8). It is worthy to note that these results are consistent with the free particle model [4] and similar to the results obtained elswhere [5] that the ion temperature deduced from the neutron flux is propotional to the applied capacitor voltage and inversely propotional to the square root of the filling D_2 gas pressure. Here, the flux of neutral particles in all energy region decreases first with the time constant of 10 μs, but the flux at lower energy region less than 0.5 keV increases again and reach at the peak at 40 μs and decays. Also, the energy level of the most energetic particles decreases first, however, the plasma temperature itself still holds around 0.3 keV at 60 μs and after (Fig.9).

$H_\beta(D_\beta)$ line and the continuum radiation at 4978 Å are observed at the midplane and at the ring-plane where the ring lies. Time variations and spacial distributions of the continuum show that the plasma is contained fairly well in the CCT confining region even at the later stage of the confinement (Fig.10). Similarly, the $H_\beta(D_\beta)$ measurement suggests that the plasma density decreases with e-folding time of 120 μs and the plasma contacting on the inside of the ring seems to occur at the final stage of 70 ∿ 80 μs owing to the approach of the null field point (Fig.10b). At 100 μs, the field minimum at the midplane disappears as is seen in Fig.2b.

4. CONCLUSIVE REMARKS

From the obtained results mentioned above it is concluded that 1) the produced theta-pinch plasma consists of two components on the velocity distribution: a crowd of energetic particles and low temperature plasma of back ground, 2) at the instance of the maximum contraction of pinch, the CCT field configuration is so deformed due to the inward momentum of the plasma particles that radial oscillation and axial motion of plasma occur subsequently, and rapid decreases of the density and the temperature are caused by the restoring of the configuration, 3) at the expansion stage up to 15 μs into the CCT confining region, all parameters decrease due to the expansion, and 4) at the confinement stage after the expansion, the high temperature plasma are confined stably more than several tens μs.

Thus, the effectiveness of the CCT field on the suppression of toroidal drift of a keV collisionless theta-pinch plasma is demonstrated again and the stable confinement of plasma are exhibited for a longer time of 80 μs which is limited by the decrease of the ring current. Particle measurements show a linear relationship between the applied capacitor voltage and the energy level of most energetic neutral particles.

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FIGURE CAPTIONS

Fig.1. Magnetic lines of force in the CCT-II machine.

Fig.2. Radial distribution of the measured magnetic pressure without plasma at the midplane (a) at the instance of field maximum and (b) at 100 μs. The solid line is the computed value.

Fig.3. Cross-sectional view of the glass tube with metal rings of CCT-I and II.

Fig.4. Streak photograph of the confined plasma, taken at the midplane.

Fig.5. Time variations of diamagnetic current distributions of the theta-pinch plasma at the midplane.

Fig.6. Motion of the plasma axis.

Fig.7. Energy distributions of ions at the maximum contraction when the initial pressure is 5 mtorr. Capacitor voltage is (a) 30 kV, (b) 25 kV, (c) 20 kV and (d) 15 kV, respectively.

Fig.8. Voltage dependence on the energy level of the most energetic particles.

Fig.9. Energy distributions of ions inside the plasma estimated with fast neutral particles emitted at 1 μs, 20 μs and 60 μs.

Fig.10. Time variations of spatial distributions for the continuum (solid lines) and H_β (broken lines) (a) at the midplane and (b) at the ring-plane.

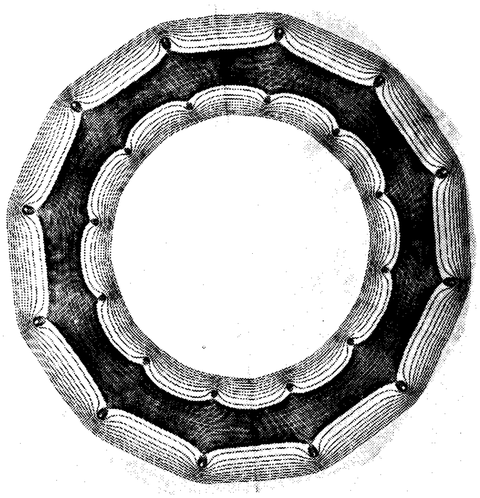


Fig. 1

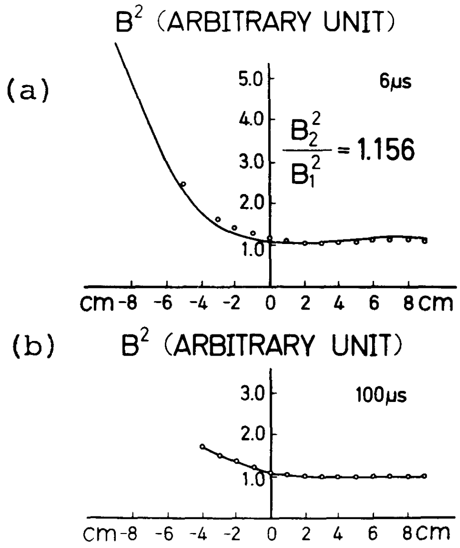


Fig. 2

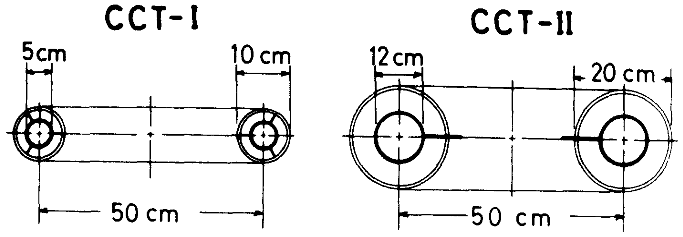


Fig. 3

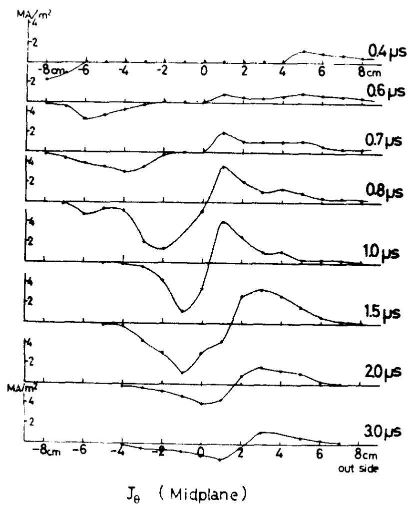


Fig. 5

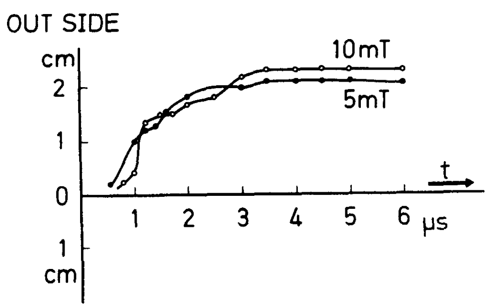


Fig. 6

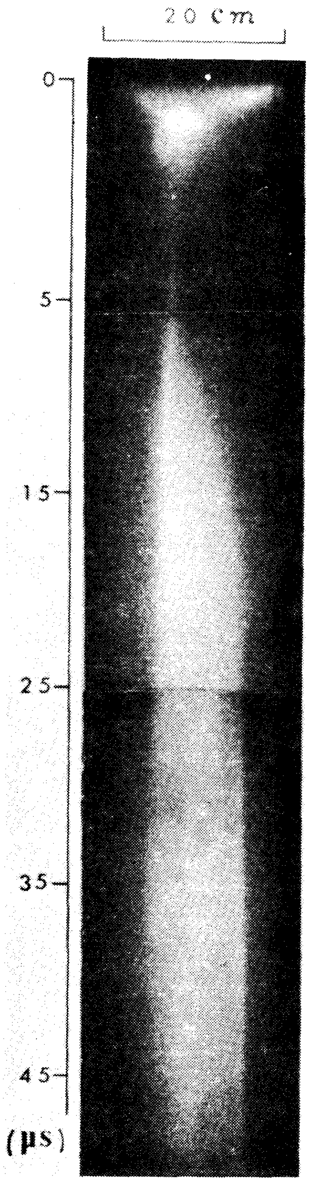


Fig. 4

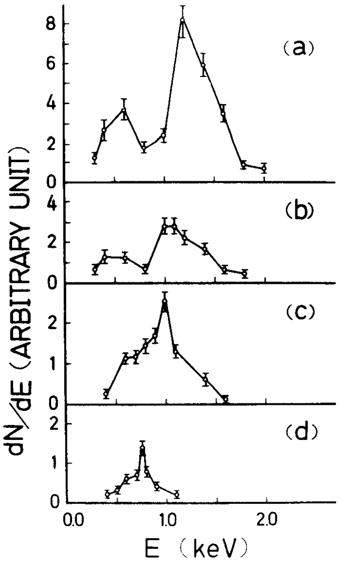


Fig. 7

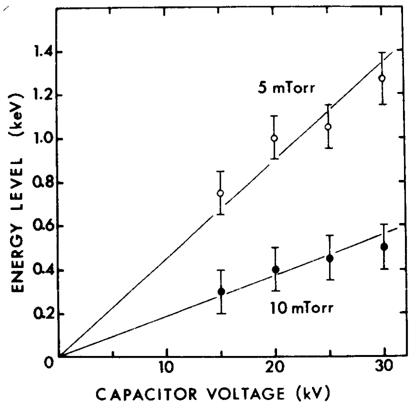


Fig. 8

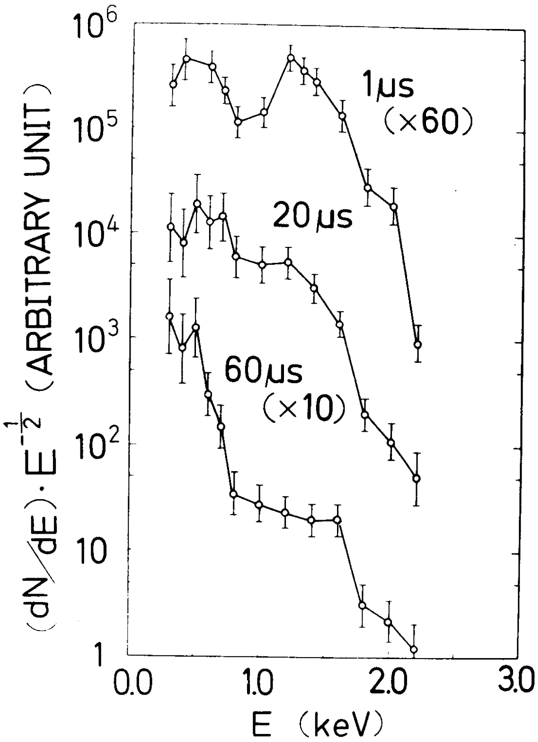
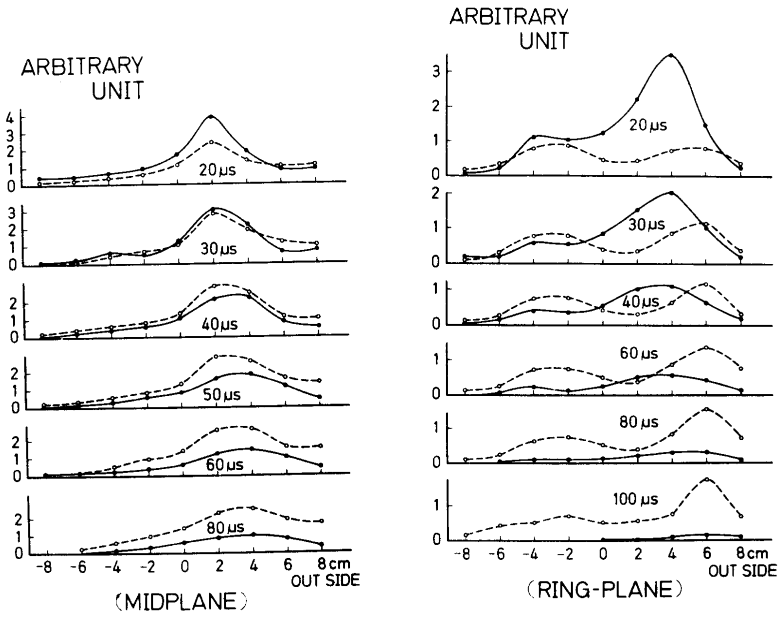


Fig. 9



(a) (b)

Fig. 10