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High-Power Heating of CTs and STs in TS-3/4 Merging Experiments

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Abstract

Novel high-power heating of compact torus (CT) has been demonstrated at TS-3/4 experiments, using its axial merging. Its advantage is that whole magnetic and thermal energies of a colliding CT can be injected into a target CT within short reconnection time. The maximum heating power of 10MW was obtained in our initial low-field (0.03–0.08T) and small-scale ($R < 0.2$m) experiment. This heating energy is provided mostly by ion acceleration effect of magnetic reconnection. The ion heating energy increases with decreasing the q-value (B_t component) of two toroids. The merging process causes the β-values of CTs to increase by factor 2–3 and the poloidal β increment increases with increasing the q-value of CT. Now larger device TS-4 ($R \sim 0.5$m) with less impurity is under construction to inspect a scaling of heating effect of merging, confinement and stability properties of high-β CTs/STs.

Keywords:

compact torus, spherical tokamak, plasma merging, high-power heating, high-beta

1. Introduction

The TS (Tokyo Univ. Spherical Torus) experimental group has been investigating various merging phenomena of CTs (STs, spheromaks and RFPs) and their applications, using the TS-3 merging device. Its main objects are (1) 3-D investigation of magnetic reconnection and its application, (2) comparison of various CTs in a single device and (3) merging formation of FRC and its application to ultra-high-β ST formation. The high-power heating of ST/CT is one of the major applications of reconnection effects to ST plasmas for fusion confinement. When a ST is collided with a target ST in the axial direction, their reconnection is expected to heat plasma through its particle acceleration effect [1]. This heating method is attractive for the initial heating of ST, because whole magnetic/thermal energy of the colliding ST can be used for heating of the target ST within short merging/reconnection time. Unlike the other heating methods, it will realize GW-order heating power easily in the present large tokamak experiments and is expected to be a future attractive high-power heating method of STs. This paper addresses two important issues on the high-power heating characteristics: (1) how its heating characteristics depend on the q-value of the merging ST/CTs, (2) how this heating changes the ST/CT equilibria, especially in terms of their beta (β) values. And finally, recent progress of the TS-4, a large scale merging experiment device, will be described, which enables us to demonstrate higher heating power (> 100MW) of merging using ST with longer life time (> msec).

2. Experimental Setup

Our TS-3/4 merging devices enable us to axially collide and to merge two ST/CTs with wide range of q-value from 0.2 to 30. The vertical cross-section of the TS-3 merging device is shown in Fig. 1. Its cylindrical

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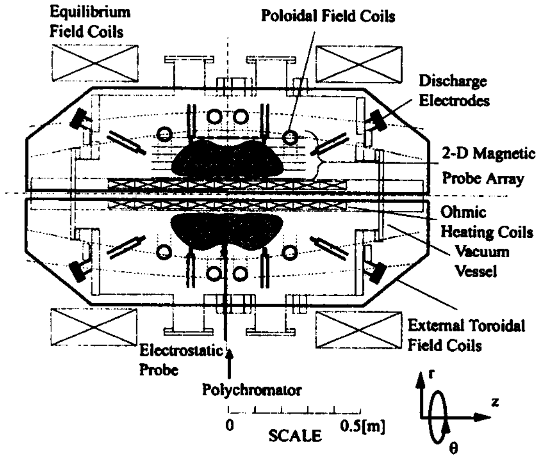
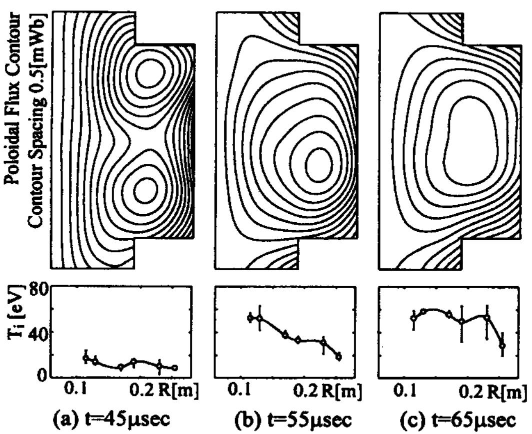


Fig. 1 A cross section of the TS-3 device. Two PF coils and two sets of eight electrodes set on both sides of the $z = 0$ plane generate two CTs separately. TF coil current I_{tfc} varies q-value of CT.



(a) t=45μsec (before merging) (b) t=55μsec (in progress of merging) (c) t=65μsec (after merging)

Fig. 2 Time evolutions of ploidal flux contours and ion temperature profile of CTs which are (a) before merging, (b) in progress of merging and (c) after merging.

vacuum vessel with length of 1m and diameter of 0.8 m is equipped with two poloidal field (PF) coils and two sets of eight electrode pairs. These coils were used to inject arbitrary amount of toroidal and poloidal fluxes into two ST/CTs. Their major and minor radii are 0.2 m and 0.14 m respectively ($A \sim 1.4$). The arbitrary toroidal field $B_{t,ext}$ was applied to the ST/CTs, varying toroidal field $B_t = B_{t,ext} + B_{t,in}$) of the ST/CT continuously from low-q RFP region to high-q tokamak region. The 2-D array of magnetic probe was located on the r-z plane of the vessel to measure the poloidal and toroidal magnetic field profiles of the merging plasmas. Radial profile of ion temperature T_i was measured on the midplane by use of a Doppler broadening of H_β lines. An electrostatic probe was inserted at $z = 0$ to measure radial profiles of electron temperature T_e and density n_e.

3. Experimental Results

3.1 High Power Heating Effect of Merging

Figures 2 show time evolutions of poloidal flux contours and ion temperature T_i profiles of STs which are before merging, in progress and after merging. The injected ST had the same flux as the target ST to maximize the heating effect. The reversed current of the two PF coils accelerated the merging process, completing their merging within 10μsec. The ion temperature T_i was observed to increase significantly from 5 to 60eV. Figures 3 show time evolutions of thermal energies of the merging STs and a single ST, which are calcurated based on those measurements. In all cases, the thermal energies of the merging STs were observed to increase significantly as soon as they begin to merge. It is noted that the heating energy increases with decreasing the q-value of the merging STs. The heating energy was mainly caused by an increment of ion temperature while electron temperature and density mainteined almost the same values. The maximum heating power of 10MW was obtained in the case of spheromak ($I_{tfc} = 0$). The thermal energies of the merged STs were much larger than those of the single STs in all cases.

3.2 High Beta Equlibrium Transition of STs

A question is how much of the injected heating energies are confined in those STs with different q-values. As shown in Fig. 3, the thermal-energy of the high-q ST decays much slower than that of the spheromak with the lowest q. Figures 4 show the poloidal beta β_p, the central beta β_0 and the averaged beta β_N (normalized by the Troyon scaling value) of the CTs after merging and the single CTs, as a function of I_{tfc}. It was clearly observed that the merging process increases β_p and β_0 by factor 2–3. It is noted that the β_p increment increases with increasing I_{tfc} (q-value). These results indicate that the ST with higher q-value has better confinement to sustain the large heating energy of merging. It is interesting to check whether this tendency agrees with the Troyon scaling or not. Figure 4(c) indicates that the present averaged β is always about four times larger than the Troyon limit. It is concluded

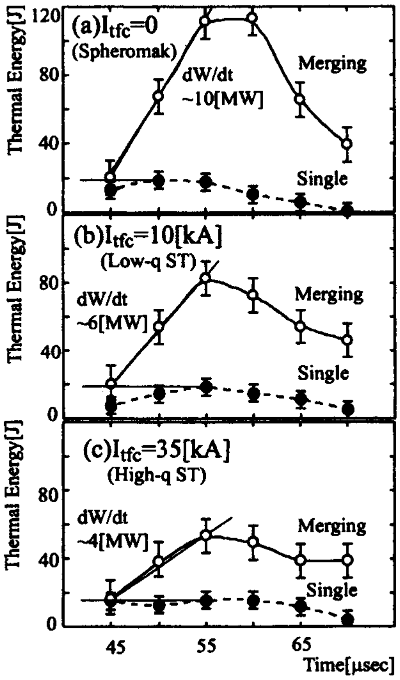


Fig. 3 Time evolutions of thermal energies of CTs with (a) I_{tfc} = 0 (spheromak), (b) I_{tfc} = 10 [kA] (low-q ST), and (c) I_{tfc} = 35 [kA] (high-q ST). Solid lines indicate merging CTs and dashed lines indicate single CTs.

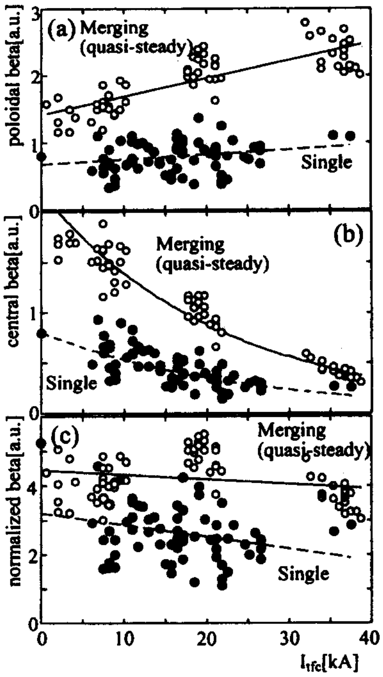


Fig. 4 I_{tfc} dependencies of (a) poloidal beta β_p, (b) central beta β_0 and (c) averaged beta β_N (normalized by the Troyon scaling value).

that the high-β confinement of CT improves with increasing its q-value, while the ion heating energy of merging increases with decreasing the q-value.

4. Discussions about Heating Power and Present State of the TS-4 Construction

4.1 Scaling of Heating Power

In this section, heating power generated by plasma merging estimated using a simple model. It is assumed that a major heating source is poloidal magnetic energy dissipated during magnetic reconnection event. Because poloidal flux is conserved during coaxial merging, poloidal magnetic energy of the colliding CT is converted into thermal energy of the merged CT:

$$W_p \sim \frac{B_p^2}{2\mu_0}L^3, \tag{1}$$

where L denotes a characteristic length of the plasma Merging time is estimated to be an order of Alfven time scale,

$$\tau_A \sim \frac{L}{v_A} = \frac{L\sqrt{\mu_0 n m_i}}{B_p}, \tag{2}$$

where m_i denotes a mass of an ion. Hence, heating power of merging is calculated to be

$$P = \frac{W_p}{\tau_A} \sim \frac{B_p^3 L^2}{2\mu_0\sqrt{\mu_0 n m_i}} \propto B_p^3 L^2. \tag{3}$$

This estimated scaling equation predicts that the heating power increased with increasing the plasma size and the magnetic field.

In the TS-3 (R ~ 0.2m, B_p ~ 0.05T), a few MW heating power was obtained. When the scaling described in Eq. (3) is applied to the TS-4 merging STs (R ~ 0.5m, B_p ~ 0.1T), heating power is estimated to be 100–500MW, which is more than fifty times as much as that obtained in the TS-3. If the plasma sized is further increased by factor 10 (R ~ 2m, B_p ~ 0.5T), GW/TW of heating power will be possibly obtained due to the effect of $B_p^3L^2$.

4.2 Present State of the TS-4 Construction

The TS-4, large scale merging experiment device is under construction. Figure 5 shows a cross section of the TS-4. Major changes from the TS-3 are large scale of 2–3 times, plasma formation method by use of flux cores, and module type large view ports. Large plasma with long life time (> μsec) makes it easy to determine a confinement capability and MHD stability of merging heated high-β CT. Plasma formated without electrode

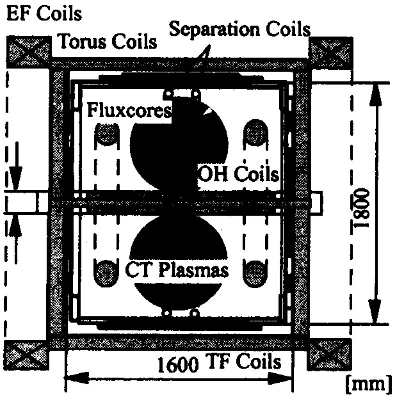


Fig. 5 A cross section of the TS-4 device. TF/OH coils and EF coils are under construction.

discharge containes less impurities which act as loss channels of thermal energy, so heating power have a probability to be much higher than the value predicted by the scaling. In the TS-4, many types of diagnostics can be applied with breaf reconstruction of module windows. Vacuum vessel and main flux cores of the TS-4 have already been constructed. TF/OH coils and EF coils will be ready soon.

5. Conclusions

In summary, our TS-3/4 ST merging experiments demonstrated the initial high-power heating characteristics of merging STs. The maximum heating power of 10MW was obtained in the initial low-field and small-scale experiment. The ion heating energy was found to increase with decreasing their q-value. It is because the ion heating of magnetic reconnection tends to be emphasized with decreasing the q-value. However, the larger amount of the injected thermal energy is confined in the ST with increasing its q-value. In the present experimental condition, the β increment of STs are about four times larger than the Troyon scaling values. The large-scale merging device: TS-4 is now being constructed to further investigate the initial heating effect of ST merging under the better confinement condition. In the TS-4 experiment, the confinement time of ST with major radius $R \sim 0.5$m is expected to be longer than the heating time of merging almost equal to the merging / reconnection time. Its results will provied a more concrete prospect to initial heating of fusion plasmas.

References

[1] Y. Ono *et al.*, Phys. Plasmas **4**, 1953 (1997).