HIGH-POWER INITIAL HEATING OF COMPACT TORUS BY MEANS OF MERGING EFFECT

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Abstract

Novel high-power heating experiment of compact torus (CT) has been developed in the TS devices by use of merging effects. This method enables us to inject whole magnetic and thermal energies of a colliding CT into a target CT within short reconnection time. The maximum heating power of 10MW was obtained in our initial low-field (0.3-0.8kG) and small-scale ($R<0.2$m) experiment. This heating energy is provided mostly by ion acceleration effect of magnetic reconnection. The q-value of the target CT was varied continuously from low-q reversed-field pinch (RFP) region ($q\approx 0.2$) to high-q spherical tokamak (ST) region ($q\approx 30$). The ion heating energy as well as the merging speed increases with decreasing the q-value (B_t component) of two toroids and with increasing their external compressing force of current sheet. The most probable interpretation for these phenomena is that unmagnetized ion motion causes the anomalous dissipation of the current sheet when it is compressed shorter than its ion gyroradius. The merging process causes the β-values of CTs to increase by factor 2-3 and the β increment increases with increasing the q-value of CT.

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 CT is one of the major applications of reconnection effects to fusion plasmas[1-4]. As shown in Fig. 1, the produced CT is collided with the target CT in the axial direction. Their reconnection is expected to heat plasma through its particle acceleration effect[4]. This heating method is unique, because whole magnetic/thermal energy of the colliding CT can be used for heating of the target CT 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 CTs. Our TS-3/4 devices can produce and merge together various CTs with wide range of q-value. This paper addresses two important issues on the high-power heating characteristics: (1) how its heating and reconnection characteristics depend on the q-value of the merging CTs, (2) how this heating changes the CT equilibria, especially in terms of their beta (β) values. The fast merging of low-q CT realized the maximum heating power of 10MW in our initial experiment and increased β of the target CT by factor-2-3, revealing the high-β properties of CT equilibria.

2. EXPERIMENTAL SETUP

Our TS-3/4 merging devices enable us to axially collide and to merge two CTs with wide range of q-value from 0.2 to 30. As shown in Fig. 2, the TS-3 merging device has two poloidal field (PF) coils and two sets of eight electrode pairs for two CT formations in a cylindrical vacuum vessel with length of 1m and diameter of 0.8m. These coils were used to inject arbitrary amount of toroidal and poloidal fluxes into the CTs. Right after their formation, the CTs have major and minor radii of 0.2m and 0.14m. Reversed currents I_{acc} of the two PF coils were used to increase the plasma colliding force as well as the reconnection speed. The arbitrary toroidal field $B_{t,ext}$ was applied to the CTs, varying toroidal field B_t ($=B_{t,ext}+B_{t,in}$) of the CT continuously from

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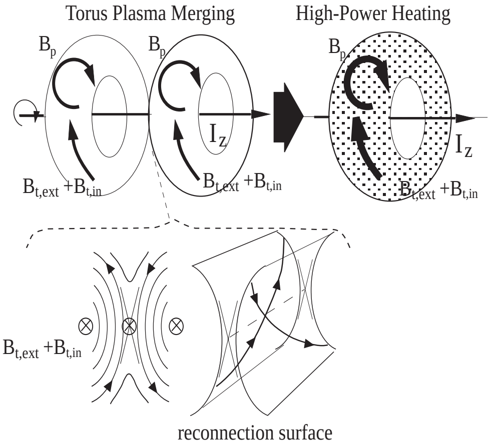

FIG. 1 Plasma heating scheme of compact toroids by use of merging (magnetic reconnection) effect.

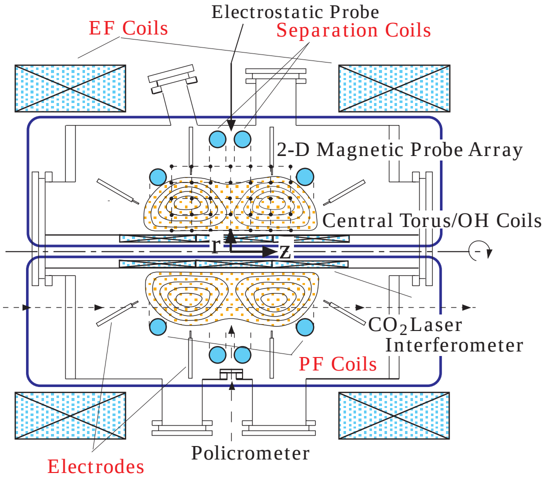

FIG. 2 The TS-3 merging device.

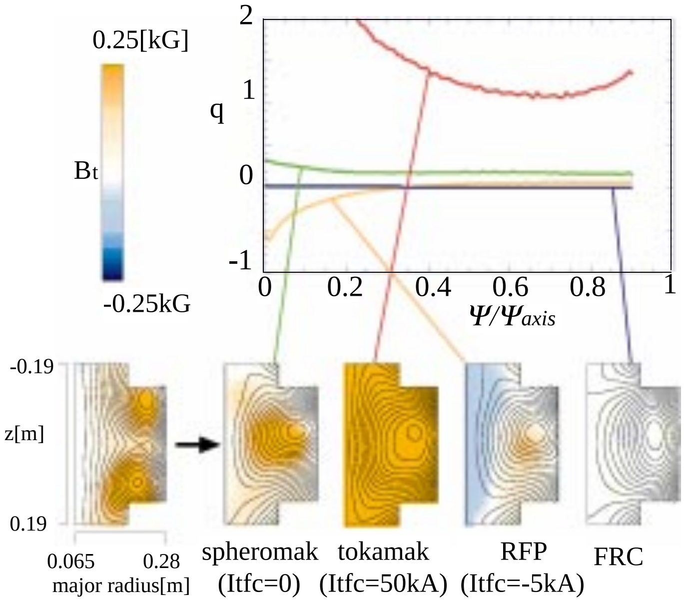

FIG. 3 Poloidal flux contours with Bt field strength and q profiles of ST, spheromak, RFP and FRC.

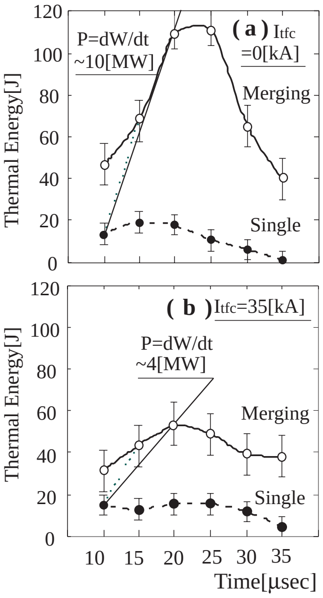

FIG. 4 Time evolutions of thermal energies of merging CTs (solid lines) and single CTs (dotted lines). The CTs are spheromaks (a) and STs (Itfc=35kA) (b).

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 and C_{II} lines. An electrostatic probe was inserted at z=0cm 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 3 show poloidal flux with B_t contours and q profile of the CT plasmas with various center toroidal coil current I_{tfc} right after merging. For simplicity, the injected CT had the same flux as the target CT to maximize the heating effect. These data were obtained from the 2-D magnetic probe measurements on r-z plane. As I_{tfc} was increased from -5kA to 50kA, the q-value was observed to increase from the RFP regions ($q_0 \approx 0.1$), through the spheromak region to the tokamak region ($q_0 > 1$). In the present operation, the initial merging plasmas had the poloidal magnetic field $B_p \approx 0.5$kG, ion and electron temperatures $T_i \approx T_e \approx 15$eV and density $n_e \approx 5 \times 10^{19}$m^{-3}. Figures 4 show time evolutions of thermal energies of the merging CTs and a single CT, which were calculated from measurements of T_i, T_e and n_e. In all cases, the thermal energies of the merging CTs were observed to increase significantly as soon as they started merging. The maximum heating power of 10MW was obtained in the case of spheromak ($I_{tfc}=0$). The thermal energies of the merged CTs were much larger than those of the single CTs in all cases. It is also noted that the heating energy increases with decreasing the q-value of the merging CTs. Figure 5(a) shows the center ion temperatures T_{i0} before and after the reconnection (at t=10μsec and at t=22.5μsec), as a function of I_{tfc}[4]. In the case of $I_{tfc}=0$, T_{i0} increases significantly from 15eV to 120eV, while T_e stays around 15eV. This fact indicates that the heating of the target CT is mostly caused by its ion heating effect. It is noted that T_{i0} increases with decreasing I_{tfc}, in agreement with Fig. 4. The T_i increment at $I_{tfc}=0$ is as high as 110eV, while that at I_{tfc}=20kA is as low as 40eV.

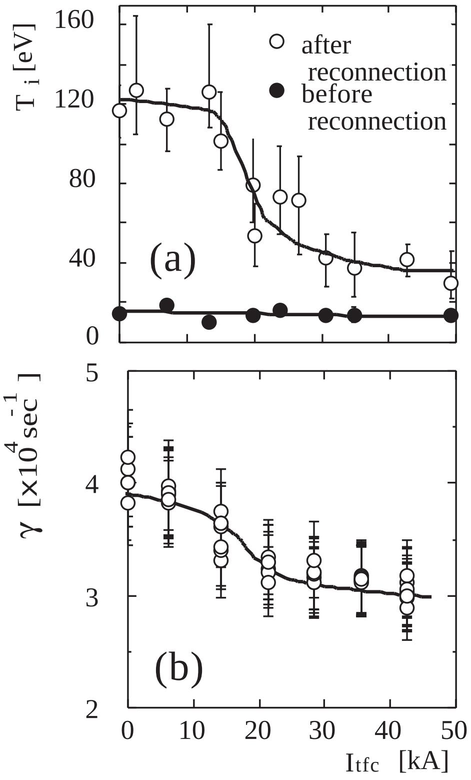

FIG. 5 Dependences of ion temperature T_i before and after merging (a) and reconnection rate γ on I_{tfc} (b).

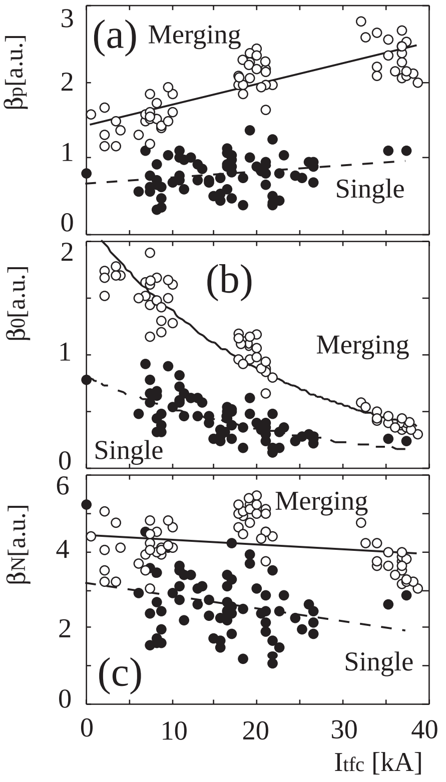

FIG. 6 (a) Poloidal beta β_p, (b) central beta β_0 and (c) averaged beta β_N (normalized by the Troyon scaling) of merged or single CTs as a function of toroidal field coil current I_{tfc}.

3.2 HIGH BETA PROPERTIES OF CTS

A question is how much of the injected heating energies are confined in those CTs with different q-values. As shown in Fig. 4, the thermal-energy of the high-q ST decays much slower than that of the spheromak with the lowest q. Figures 6 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}. Right after the heating, these betas tend to decrease sharply to the constant values which are shown in Fig. 6. 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. Though most of the B_t profiles were located still on paramagnetic side of vacuum B_t profile, the high-power heating effect of merging was observed to reduce the paramagnetism of CTs. It is interesting to check whether this tendency agrees with the Troyon scaling or not. Figure 6(c) indicates that the present averaged β is always about four times larger than the Troyon limit. It is concluded 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.

3.3 MECHANISM FOR ANOMALOUS DISSIPATION AND HEATING EFFECTS OF MERGING

Figure 5(b) also shows the reconnection rate $\gamma=(d\alpha/dt)/\alpha$, as a function of initial I_{tfc}, where α is the ratio of the reconnected poloidal flux to the total poloidal flux. It was observed that both of ion heating and reconnection rate increase with decreasing the q-value of CTs. The ion heating effect is considered to be related closely with the anomalous dissipation of current sheet. An important question is why the ion heating energy and the reconnection speed depend on I_{tfc} (q-value). Our finding is that the measured resistivity $\eta(=E_t/j_t)$ of current sheet is strongly correlated with ratio of the sheet width to the ion gyroradius. Figure 7 shows η evolutions with five different I_{tfc}, as a function of δ/ρ_i. All curves agree that the measured η stays almost constant($\approx$0.3mΩm) as long as δ is longer than ρ_i. This value is the order of the Spitzer resistivity calculated from the electron temperature. Note that η increases significantly, once δ is compressed shorter than ρ_i[5]. The maximum $\eta\approx$3mΩm is roughly fifty times larger than the Spitzer resistivity, leading to the observed fast reconnection in small I_{tfc} regime. These results agree well with the recent macroparticle simulation results by Horiuchi et al.[6].

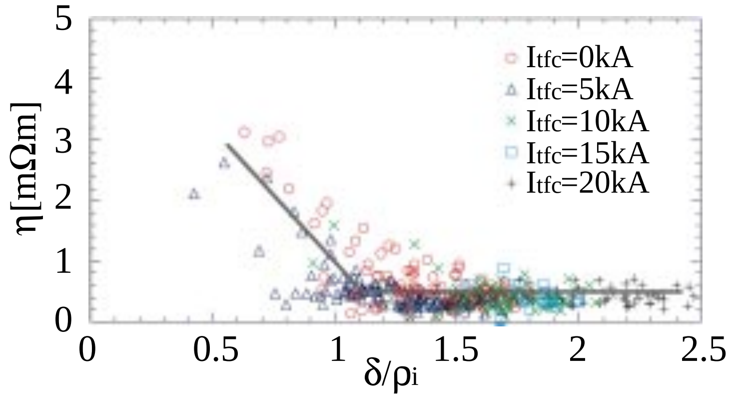

FIG. 7 Evolutions of effective resistivity η as a function of δ/ρ_i for five different I_{tfc} case.

4. CONCLUSIONS

In summary, our TS-3/4 CT merging experiments demonstrated the high-power heating characteristics of merging STs, spheromaks and RFPs for the first time. The maximum heating power of 10MW was obtained in the initial low-field and small-scale experiment. The heating effect of merging is explained well by the anomalous ion heating effect of magnetic reconnection. The ion heating energy and merging speed increase with decreasing their q-value. However, the CT with higher q-value was observed to confine the injected thermal energy longer. The ß increment of CTs are about four times larger than the Troyon scaling values. The most probable interpretation for this ion heating effect is the anomalous dissipation of the current sheet caused by the unmagnetized ion motion which occurs when δ is compressed shorter than ρ_i.

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