Paper

FRC Formation Process of Two Colliding Spheromaks with Counterhelicity

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A merging formation of field-reversed configuration (FRC) has been studied for the first time without central conductor, using two merging spheromaks with opposing toroidal magnetic field. Without the n=1 stabilization effect of the central conductor, the merging process was maintained stably probably due to (1) plasma flow shear generated by the counterhelicity reconnection and (2) line-tying effect of the magnetic field lines. This relaxation from the force-free (≈0.05-0.1) spheromaks to the high-beta (≈0.7-1) FRC is attributed to efficient (≈80%) conversion of the toroidal magnetic energy of the former to the ion thermal energy of the latter. This energy conversion was caused by a direct ion heating and acceleration effect of reconnection under the toroidally symmetric condition. This ion heating energy was found to increase inversely with the field amplitude parallel to the X-point line. Further plasma acceleration by high-field compression was observed to increase the reconnection speed, revealing the new fast reconnection mechanism called the current sheet ejection.

Keywords : magnetic reconnection, merging, FRC, spheromak, ion heating, energy conversion, outflow

1. Introduction

A spheromak and an FRC have both simply-connected topologies as compact toroids but their stability are maintained by different equilibrium principles. The spheromak with toroidal and poloidal magnetic fields B_t, B_p is often observed to be in the Taylor minimum-energy states, which are widely known to be stable force-free states without plasma thermal pressure. On the other hand, the FRC solely with poloidal magnetic field B_p has the high-beta equilibrium whose stability is interpreted possibly by some thermal and kinetic effects. Recently, an interest has grown in generating FRCs with the large-s (average number of ion gyroradii) number in slow time scale for future large-scale confinement experiments(1)(2), extending the FRC stability into non-kinetic MHD regime. However, the conventional theta-pinch formation was found to have some basic difficulty to produce large size FRCs stably and efficiently in slow time scale. New slow formation techniques have been developed by use of double coaxial coils in Washington University(2) and by use of two low-beta merging spheromaks in University of Tokyo(3). Since 1986, we have developed the slow formation of FRC, using two merging spheromaks with opposing toroidal field B_t (3)(4). In this experiment, the thick center conductor stabilized the n=1 tilt and shift modes. An important question arises as to how stably the high-beta FRCs are produced using the merging low-beta spheromaks, if the central conductor is removed. Especially, it is important to study whether their n=1 (tilt and shift) stability are maintained without central conductor. This paper addresses the fast reconnection process, the global stability and ion heating during counterhelicity merging of two spheromaks without central conductor. It reveals the novel mechanisms for the stable merging formation of FRC (5)-(7) and the related fast reconnection caused by anomalous resistivity and current sheet ejection. The stable formation of FRC without the center conductor indicates new n=1 stabilization of the counterhelicity spheromaks in sharp contrast with the n=1 disruption of the conventional prolate spheromaks.

2. Experimental Setup

As shown in Fig. 1, the TS-3 merging device has eight pairs of electrodes and a poloidal field coil on both sides of the cylindrical vessel to produce two spheromaks with opposing B_t(3)(4). Polarities of toroidal field B_t and magnetic helicity are determined independently by those of the Z-discharge currents between the electrodes. A 2-D magnetic probe array composed of 144 pick-up coils was placed on the R-Z plane of the vessel to measure 2-D profiles of B_p and B_t on each single discharge. These data were used to calculate the poloidal flux (Ψ) contour, and evolution of

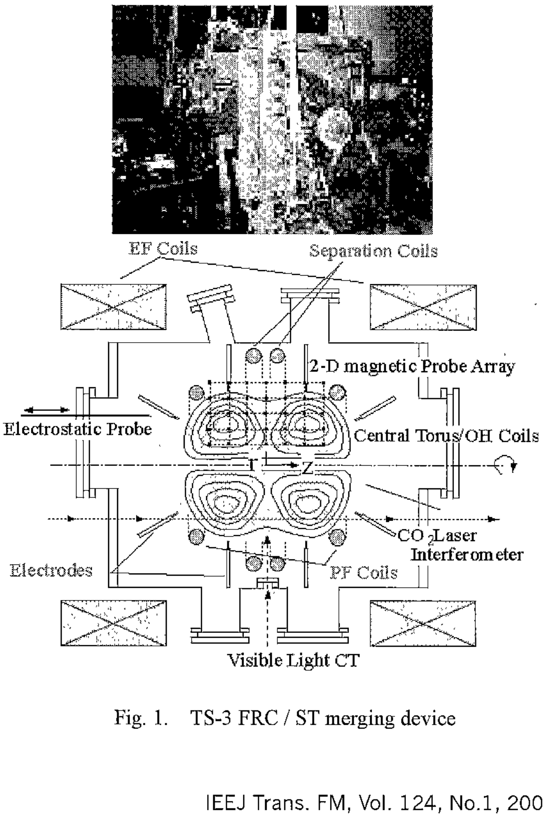

Fig. 1. TS-3 FRC / ST merging device

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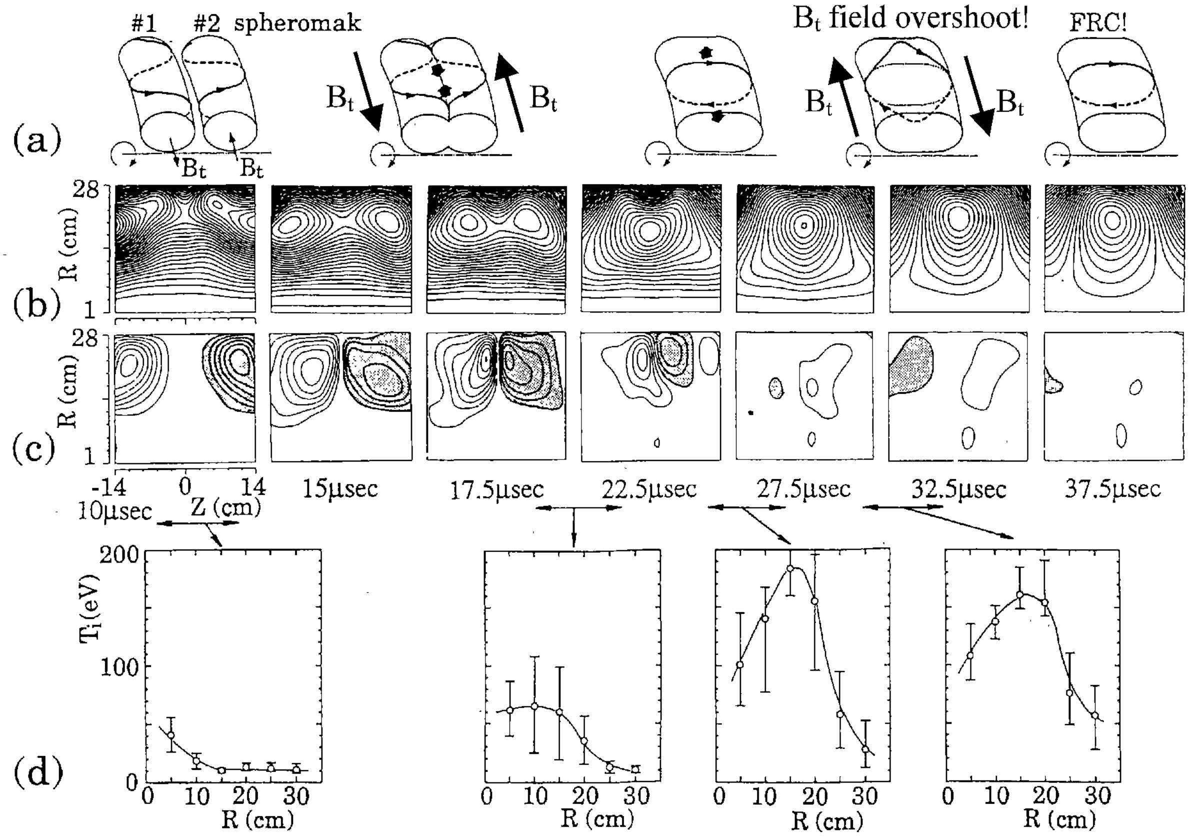

Fig. 2. Time evolutions of presumable magnetic configuration (a), poloidal flux contour (b), toroidal field contour (c) and radial ion temperature (T_i) profile on the midplane (d) during the FRC merging formation

the toroidal current density j_t, using the following formulae:

$$\Psi = 2\pi \int_{r_c}^{r} r' B_z dr'$$

$$j_t = \partial B_r / \partial z - \partial B_z / \partial r \, .$$

Another replaceable 2-D array of magnetic probe were placed on R-θ plane to measure the toroidal mode (n) amplitudes from n=1 to n=3. The electron temperature T_e and the electron density n_e were measured by an electrostatic probe inserted radially and also by a CO_2 laser interferometer. Doppler shifts and widths of CII and H_β spectrum lines were measured by a polychromator to obtain radial profiles of ion temperature T_i on the midplane.

3. Experimental Results

3.1 Energy Conversion during Merging Formation of FRC A significant increase in ion temperature was documented during this merging formation of FRC, revealing a new equilibrium transition mechanism from the low-beta (0.1-0.2) spheromaks to the high-beta (0.7-1.0) FRC(3)(4). Figures 2(b) and (c) show the 2-D contours of poloidal flux surface and toroidal field amplitude, measured by 2-D magnetic probes array. The white and black colors represent the positive and negative toroidal field. Two spheromaks with opposing B_t were observed to merge together from t=0μsec to 20μsec. The reconnected field lines offered an overshoot / oscillation: initially, the polarity of B_t is positive on the left-hand side and negative on the right-hand side and then after t=27.5μsec, it becomes negative on the left-hand side and positive on the right-hand side. Since the poloidal flux contours represents the r-z contours of field-lines, we can easily concluded that the overshoot of toroidal field was caused by oscillation of reconnected field lines (shown in Fig. 2(a)) right after magnetic reconnection. Figure 2(d) show the radial profiles of ion temperature T_i measured on the midplane (Z=0). From t=12.5μsec to 22.5μsec, the reconnected field lines had bipolar toroidal fields: positive for Z<0cm and negative for Z>0cm. This fact indicates that the reconnected field lines were stretched in the toroidal direction (Fig. 2(a) t=15-17.5μsec), bearing large $\boldsymbol{j \times B}$ force. Then, the inner-halves and the outer-halves of the reconnected field-lines were accelerated oppositely in the toroidal (partly radial) direction together with plasma ions and electrons, as illustrated in Fig. 2(a) t=17.5-32.5μsec. Using the measured 2-D magnetic field profile, the maximum velocity of reconnected field lines was estimated to be as large as 1 to 1/3 of the local Alfven speed: 50-15km/sec. The Sweet-Parker model(8) predicted that the outflow speed of reconnected field lines / plasmas should be as large as the Alfven speed. The macroscopic velocity of reconnected field-lines almost agrees with ion velocity measured by the Doppler shift of CII line. The ion acceleration was observed together with the large increase in ion temperature T_i. As shown in Fig. 2(d), we observed the selective ion heating from 10eV to 200eV within the short reconnection time of 10μsec, while the electron temperature T_e increased slightly from 10 to 20eV. The total increase in the ion thermal energy $W_{i,th}$ was estimated to be 200J, which was as large as 80% of the dissipated magnetic energy $W_m \approx 250$J. Since the neutral current sheet dissipation was as small as 20J, W_m was considered to be converted to $W_{i,th}$

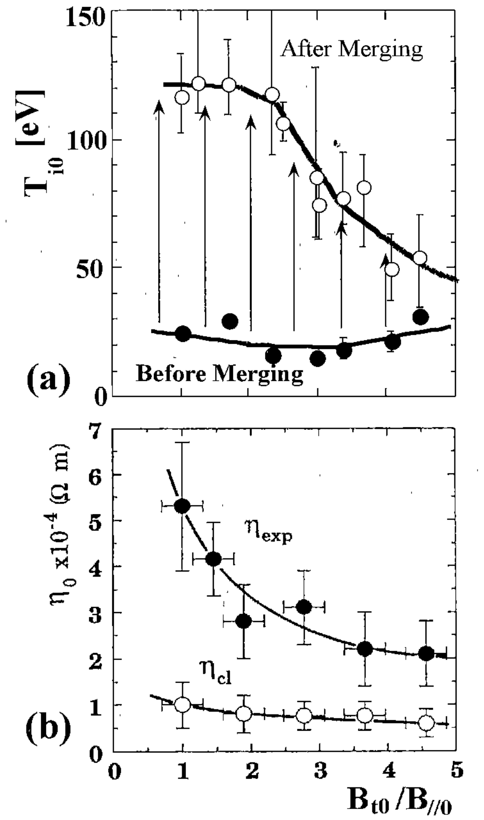

Fig. 3. The center ion temperature T_{i0} (a), and the effective resistivity η_0 of neutral current-sheet (b) as a function of the field component B_{t0} parallel to the X-line (normalized by the reconnecting field component $B_{//0}$)

through the reconnection outflow. This direct energy-conversion is probably due to the ion viscosity heating in the forming process of velocity shear, not due to the finally formed global ion flow itself whose energy is as small as 20J. During and after the counterhelicity reconnection, the ion viscosity force against the field-line overshoot motion was considered to increase significantly because number of unmagnetized ions increased significantly around the X- and O-points due to the toroidal field annihilation. During the FRC formation, more than half of the total magnetic energy (whole toroidal magnetic energy and a part of poloidal magnetic energy) was converted into ion thermal energy, indicating the large increase in unmagnetized ions and ion viscosity. Based on the classical ion viscosity, the ion heating power is estimated to be as large as 30MW in rough agreement with our observation. This efficient energy conversion of magnetic reconnection is the most probable mechanism for this high-beta equilibrium transition and is useful for the initial heating of FRCs, leading us to the scenario of FRC slow-formation, heating and flux (current)-amplification proposed in Ref.(3). During the whole reconnection / merging process, the merging plasmas were maintained stably without the central conductor, even if the shape of reconnected flux surfaces are prolate during the merging time $\approx$10μsec. The measured n=1 mode amplitude was smaller than 10% of the equilibrium field during the counterhelicity reconnection. It is noted that the counterhelicity reconnection produced significant sheared flow as shown in Fig. 2(a). Recently the new shear flow stabilization of MHD instabilities are being considered in tokamaks and FRCs(9)(10). The large sheared flow produced by the reconnected field lines is the most probable cause for the stable formation process of FRCs(7).

3.2 Ion Heating Effect of Co and Counterhelicity Merging An important question is how the fast reconnection, anomalous resistivity of current sheet and ion heating are related with each other. At first, a mechanism for the anomalous resistivity and the selective ion heating was verified by magnetizing plasma ions of the cohelicity merging toroids. The cohelicity merging of two spheromaks has toroidal field B_{t0} at X-point to magnetize ions while its poloidal field component – the reconnecting field component $B_{//0}$ is equal to that of counterhelicity merging. While the counterhelicity merging without toroidal field B_{t0} at X-point heats ions up to 200eV, the maximum ion temperature T_{i0} was observed to decrease to 120eV in the cohelicity spheromak merging with finite $B_{t0}\approx B_{//0}$ at X-point and further down to 50eV in the cohelicity tokamak merging with large $B_{t0}>>B_{//0}$. This sharp contrast was studied to make clear the general relationship between toroidal field B_{t0} at X-point and T_{i0} before and after magnetic reconnection of two spheromaks (and tokamaks). Figure 3(a) shows the center ion temperature T_{i0} before and after the reconnection (at t=10μsec and at t=22.5μsec, respectively) under ten different B_{t0} conditions. Only for this experiment, the thin center toroidal coil whose outer radius was as small as 0.5cm was inserted along the geometric axis to vary the toroidal field component B_{t0} parallel to the "X-point" line. We kept equal the initial poloidal flux - the reconnecting field component $B_{//0}$ of each merging toroid for this scan, realizing a constant (within 10%) initial $B_{//0}$ condition. It was clearly shown that T_{i0} increased significantly as B_{t0} was decreased toward zero. This large increase in T_{i0} was connected with large anomalous resistivity at the X-point and the resulting fast reconnection. Figure 3(b) shows the neutral current-sheet resistivity η_0 averaged over the reconnection time as a function of the normalized toroidal field $B_{t0}/B_{//0}$. Assuming that the global velocity $v\approx0$ at the X-point, the effective resistivity η_0 was calculated using the following equation:

$$\eta_0 = \{E_t + (\boldsymbol{v}\times\boldsymbol{B})_t\} / j_t = E_t / j_t = \frac{d\Psi_{com}/dt}{2\pi r_x} / j_t ,$$

where E_t, j_t, r_X, B_p and Ψ_{com} were the toroidal electric field, the current density and the radius of the X-point, the poloidal (reconnecting) magnetic field and the reconnected poloidal flux, respectively(4). The effective resistivity $\eta_0=E_t/j_t$ was observed to increase significantly, as B_{t0} was decreased. The η_0 value of the merging spheromaks with $B_{t0}\approx B_{//0}$ was about 2.5 times larger than that of the merging tokamaks with $B_{t0}\approx 5B_{//0}$. The Spitzer resistivity η_{cl} was also calculated from the measured electron temperature T_{e0}, under the assumption of $Z\approx3$. The η_0 value was observed to approach the classical resistivity η_{cl} as B_{t0} was increased toward $5B_{//0}$. The lower hybrid drift instability and some drift-kink instability are being considered as a cause and mechanism for this large anomalous resistivity in low B_{t0} regime(11). Both of our experiment and the macro-particle simulation agreed that the large increase in η_x occurred when the current sheet thickness was compressed shorter than the ion gyroradius around the X-point. Since the ion gyroradius increases inversely with B_{t0}, η_0 is considered to increase inversely with B_{t0}. The annihilation of B_{t0} at the neutral current sheet caused the anomalous magnetic diffusion of current sheet, increasing the reconnection speed significantly. It is widely known that the

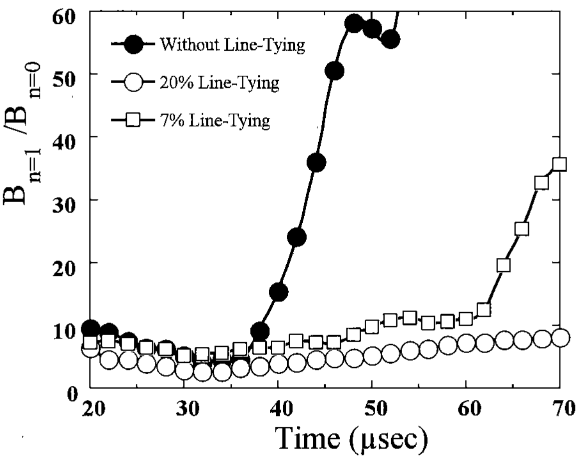

Fig. 4. The n=1 mode amplitudes of the produced FRCs with different ratios of line-tying fluxes with the separation coils: 0%, 7% and 20% at t=25μsec

reconnection speed u (inflow speed of field lines/ plasma) is described as $u = \eta_0 j_t / B_{//0}$, where j_t is the toroidal current density of current sheet and $B_{//0}$ is the reconnecting field component mentioned above[8]. Then, the fast reconnection is considered to produce the fast ion outflow out of the current sheet, causing the selective ion heating of reconnection.

3.3 Stability of Merging Plasmas and the Produced FRC

The removal of central conductor permitted all toroidal modes to grow during and after the merging / reconnection, depending on global stability of the produced plasma. An important question is whether the prolate merging spheromaks and the produced FRC are maintained stably or not. Figure 4 shows the time evolutions of n=1 toroidal mode amplitudes of the merging spheromaks and the produced FRC with three different line-tying fluxes on the midplane during and after the reconnection. The line-tying flux is the common magnetic flux between the produced FRC and the separation coil shown in Fig. 1. We varied the amount of line-tying flux with the separation coil by changing their coil currents. Figure 4 indicates that all counterhelicity merging processes were maintained stably at least during the merging / reconnection. In all cases, the initial n=1 mode amplitude was found to decrease down to 1/2 during the counterhelicity reconnection. The large toroidal flow-shear produced by the counterhelicity reconnection is the most probable cause for the n=1 mode stabilization. As shown in Fig. 2(a), the toroidal flow has positive sign for $r<R$ and negative sign for $r>R$, where R is the major radius. The large flow shear produced by this bipolar flow is considered to convert the unstable n=1 mode into the higher modes, stabilizing the n=1 mode consequently. In the case of the FRC with zero line-tying flux, the n=1 mode started growing after t=35μsec when toroidal flow mostly decayed[12].

Another important finding was that the n=1 mode can be stabilized easily by increasing the line-tying flux of the FRC. We varied the line-tying flux by increasing the separation coil currents, in order to study the effect of linked flux on the n=1 stability of FRC. The flux that linked FRC and the separation coils is considered to suppress the n=1 motion of the produced FRCs. When the line-tying flux was about 7% of the total poloidal flux (at t=25μsec), the produced FRC was stabilized until t=60μsec and the n=1 mode started growing after t=60μsec due to decrease in the line-tying flux. When the line-tying flux was as large as 20% at t=25μsec, the FRC was maintained stably during the whole discharge. These facts indicate that the line-tying flux with external coil stabilizes the n=1 mode of oblate FRCs.

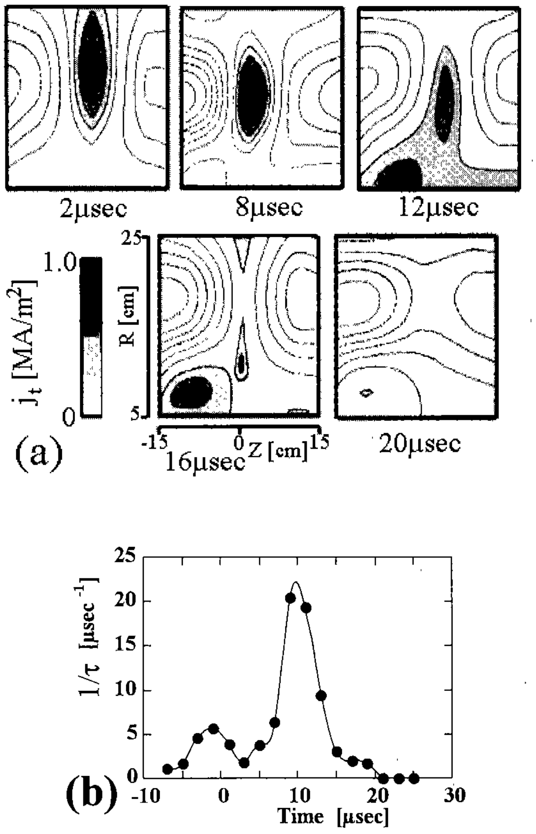

Fig. 5. R-Z contours of toroidal current density j_t (upper) and the ratio of reconnected flux to total flux (lower) during the counterhelicity merging overdriven by the strong compression force

3.4 Current Sheet Ejection during Fast Magnetic Reconnection

Strong compression force for the plasma merging also increases the reconnection speed as well as the ion temperature. As long as reconnection speed increases, the fast outflow increases the ion heating power of reconnection. Hence the anomalous resistivity of the current sheet is not only one mechanism to cause the fast reconnection and ion heating. Dynamical change in current sheet structure revealed another possible mechanism for fast reconnection under high-compression force and high B_{t0} condition. Figure 5(a) shows the R-Z contours of toroidal current density when the two spheromaks were over-compressed by the two PF coil currents. From t=0μsec to 8μsec, the neutral current sheet was observed to peak around the X-point, forming a round current sheet like a plasmoid. Then, from t=8μsec to 16μsec, it was ejected from the squeezed X-point area. Note that the reconnection speed was slow during the formation of round current sheet and that it was drastically fast during the sheet ejection. Figure 5(b) shows the time evolution of the reconnection rate: the growth rate 1/τ of the reconnected flux normalized by the total flux (reconnection ratio). The reconnection rate 1/τ is defined as

$$1/\tau = d(\Psi_{com}/\Psi_{total})/dt,$$

where Ψ_{com} and Ψ_{total} are the reconnected poloidal flux and the total poloidal flux, respectively. It was observed that the reconnection rate during the sheet ejection ($\approx 20\times10^6\mathrm{sec}^{-1}$) was about seven times higher than that ($\approx 3\times10^6\mathrm{sec}^{-1}$) before the ejection. The sheet ejection is considered to promote the sheet dissipation mechanically, increasing the reconnection electric field at the X-point. The sheet ejection is a possible mechanism to increase the reconnection speed in addition to the anomalous dissipation of the current sheet in agreement with the recent macro particle simulations(11).

4. Summary

The two merging spheromaks with counterhelicity revealed the stable ion heating process of magnetic reconnection for the oblate FRC formation, when the central conductor was removed. Contraction of reconnected field-lines accelerated and heated plasma ions directly and selectively probably through the large ion viscosity around the wide field-null area. The efficient (~80%) ion heating of counterhelicity reconnection realized the stable equilibrium transition from the low-beta merging spheromaks to the high-beta FRC. The FRC merging formation without the center conductor was caused by the ion heating and the fast reconnection just like that with the conductor. However, it is because the prolate merging spheromaks were not destabilized by the n=1 modes in sharp contrast with the conventional MHD prediction. The counterhelicity merging process suppressed the n=1 mode amplitude smaller than 10% of the equilibrium field, probably due to the large toroidal flow shear produced by the counterhelicity reconnection. After decay of the flow shear, the n=1 mode was observed to grow, when the FRC is fully pinched off from the coils. However, the n=1 mode was suppressed when the line-tying flux with external coils was over 10~20%. The ion heating effect was suppressed by increasing the field component parallel the X-point line. Another new finding is that the fast reconnection and ion heating were caused not only by the anomalous resistivity of current sheet but also by the sheet-current ejection. When the two merging spheromaks were overcompressed together, the round current sheet was ejected like a plasmoid, causing the fastest reconnection. The sheet ejection and anomalous resistivity of current sheet are the most probable causes for the fast reconnection under the high external compression force. The sheet ejection was not related with the removal of center conductor. However the lower compression force caused the sheet ejection when the conductor was removed. It is possibly because the removal of the conductor decreases the magnetic pressure around the geometric axis.

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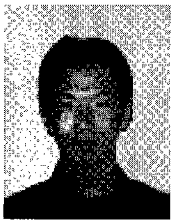

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