MERGING FORMATION OF FRC AND ITS APPLICATION TO HIGH-BETA ST FORMATION

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Abstract

Merging formation of field-reversed configuration (FRC) explored not only a new scenario of highly-efficient FRC formation/amplification experiment but also a new boundary research between FRC, spheromak and spherical tokamak (ST). A new finding is that the produced FRC is transformed stably into an ultra-high-ß ST by applying external toroidal field $B_{t,ext}$. The toroidal field was observed to vanish around magnetic axis after the $B_{t,ext}$ application to the FRC, indicating formation of diamagnetic ST. The hollow current profile of FRC was maintained during the equilibrium transition, eliminating a need for the difficult hollow-current-formation process of start-up discharge of high-ß ST. The energy-conversion effect of merging transformed the force-free merging spheromaks with paramagnetic current into the FRC with diamagnetic current and the further application of $B_{t,ext}$ did the FRC into the ultra-high-ß (>60%)/diamagnetic ST, indicating the close relationship between FRC and ST in second stability.

1. INTRODUCTION

A novel merging formation of FRC has been developed in the TS-3 merging experiment at University of Tokyo[1-3]. As shown in Fig.1, two force-free (low-ß) spheromaks with opposing toroidal magnetic field B_t were axially collided and were transformed into an oblate FRC with $B_t \approx 0$ and $ß \approx 0.6$-1[1-3]. The toroidal magnetic energy of the low-ß spheromaks was successfully transformed into the ion thermal energy of the high-ß FRC by use of energy conversion effect of magnetic reconnection[2]. This unique method has various advantages over the conventional fast theta-pinch formation: (1) slow formation, (2) stable and highly-efficient formation, (3) large ion heating power of merging and (4) current drive by ohmic heating coil or by continuous merging. The produced FRCs have high-ß >0.6 (>>0-0.1: spheromaks), ion temperature $T_i \approx 100$-200eV much higher than electron temperature $T_e \approx 20$eV and low elongation factor ε: 0.8-1 (<<5-20: conventional FRCs). This equilibrium transition indicates importance of boundary research between the paramagnetism of spheromaks / low-ß STs and the diamagnetism of FRCs / high-ß STs. This paper addresses three important issues on this boundary research: (1) how different the high-ß FRC equilibrium is from that of low-ß spheromak equilibrium, (2) by what mechanism the FRC equilibrium is maintained stably without the Taylor relaxation to another spheromak and (3) whether the produced FRC can be transformed to a high-ß/diamagnetic ST in the second stability or not. The high-ß ST formation through FRC indicates the close relation between high-ß ST and FRC. This new method is useful to optimize the CT configuration for higher ß, better stability and longer confinement time.

2. EXPERIMENTAL SETUP

The TS-3 merging device was used to study the boundary between FRC, spheromak and ST. Its cylindrical vacuum vessel with length of 1m and diameter of 0.8m has two poloidal (PF) coils and two sets of eight electrode pairs to form two spheromaks with opposing B_t. Their polarities of B_t were determined by those of the electrode discharge currents. A center stack of torus and OH coils (diameter≈0.12m) was inserted along the geometric axis to produce external toroidal field for ST operation and volt-second for current sustainment of CTs. Each produced spheromak had major radius R≈0.18-0.22m, aspect ratio A≈1.5, $T_i \approx T_e \approx 10$eV, $n_e \approx 2$-50×10^{19}m^{-3} and B<2kG. Merging speed of the two spheromaks was controlled by magnetic pressure of the PF coil currents and separation coil currents on the midplane. A 2-D array of magnetic probe composed of 200 coils was inserted on r-z plane of the vessel to measure directly the 2-D magnetic field profile. The poloidal flux contours, current density etc., were calculated based on this measurement. A polichrometer with optical multichannel analyzer was used for Doppler broadening measurements of spectrum lines to obtain radial profile of T_i. An electrostatic probe was inserted to measure the T_e profile and the n_e profile which was calibrated by the CO_2 laser interferometer.

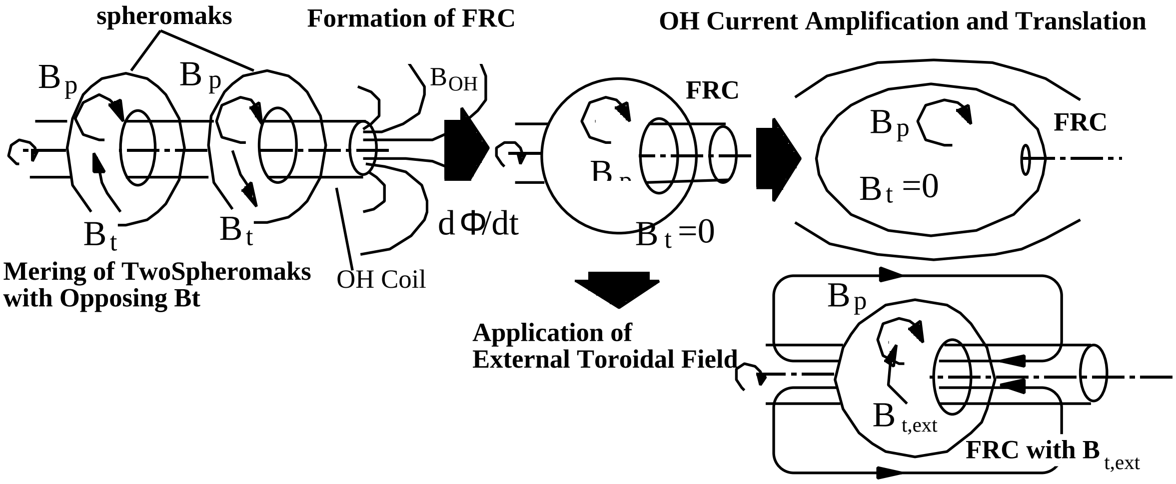


FIG. 1 FRC merging formation / OH current-amplification and application of external toroidal field (formation of high-ß ST/FRC)

3. EXPERIMENTAL RESULTS

3.1 EQUILIBRIUM TRANSITION DURING MERGING FORMATION OF FRC

Figures 2 show the poloidal flux/B_t contours, the radial profiles of B_t and the toroidal current densities j_t of the initial merging spheromak (a) and the produced FRC (b), which were obtained from the 2-D magnetic field measurement. The opposing B_t of two spheromaks were observed to vanish in agreement with the formation of an FRC without B_t. As already reported in Ref.[2], the particle acceleration effect of magnetic reconnection converted this toroidal magnetic energy into the ion thermal energy of the FRC. It is noted that the merging process transformed the peaked j_t profile of the spheromak to the hollow one of the FRC. This hollow j_t profile agrees with the theoretical prediction[4] and is needed to sustain the high thermal pressure of FRC. Its thermal pressures calculated both from $p=\mathbf{j}\times\mathbf{B}$ and T_i, T_e and n_e measurements were about five times larger than that of the spheromak.

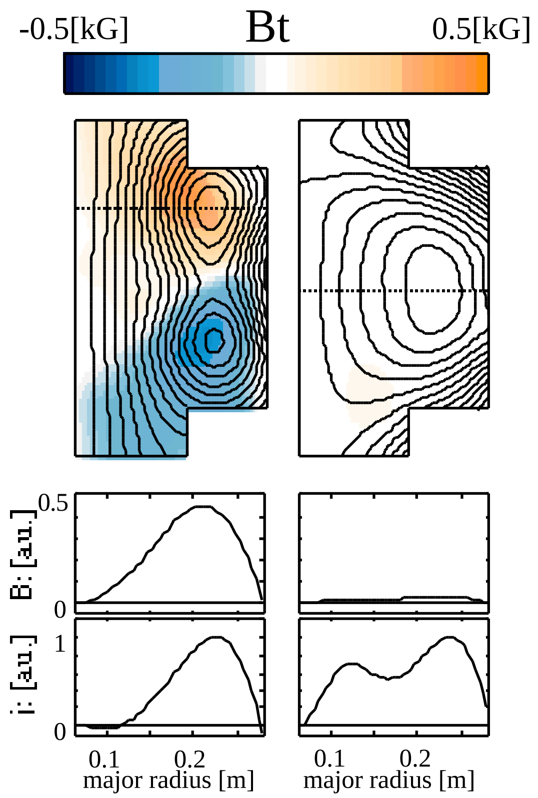
Figure 2(c) shows $h=(j_t/r)_{r=R}/\langle j_t/r\rangle$ factor calculated from the j_t profile, as a function of X_S (=radius ratio of separatrix to conductive shell). The *h* values of our oblate FRCs is located along the line of the conventional FRC scaling deduced from n_e measurement[4]. This fact indicates that our oblate FRC is similar to the conventional prolate FRCs in the high-X_s regime. However, j_t of our FRC was found to vanish sharply around the separatrix, unlike the theoretical models of FRC whose j_t were often assumed to be finite at the separatrix.

3.2 BOUNDARY BETWEEN FRC AND SPHEROMAK

It is worth studying the boundary between FRC and spheromak to interpret the merging formation FRC. An important question is why the merging spheromaks do not relax to another spheromak but to an FRC. The Taylor relaxation predicts that the merging toroids relax to another spheromak, minimizing their initial magnetic energy W under conservation of their initial magnetic helicity K. We have been investigating these bifurcated relaxations: the Taylor relaxation and the new relaxation to FRC when the sum of their initial K is not zero. By adjusting the initial W within 10% , K was varied from zero to the value for the Taylor state by adjusting the flux ratio of two spheromaks from 1 to 0. The values of K and W were obtained from the measured 2-D magnetic field profiles, using the following formulae:

$$W = \int_V B^2 dv = 2\pi\int_S (B_z^2+B_r^2+B_t^2) r dr dz, \qquad K = \int_V \mathbf{A}\bullet\mathbf{B} dv = 2\int_V (I\Psi/2\pi r^2) dv = 4\pi\int_S (B_t\Psi/\mu_0) dr dz,$$

where **A** is the vector potential, $I= 2\pi r B_t/\mu_0$ is the poloidal plasma current, and V and S are the plasma volume and the (r-z) cross-section inside the separatrix. The toroidal symmetry of magnetic field was maintained within 5%. Figure 3(a) shows the eigenvalue $\lambda=I_p$ (poloidal current)/ Ψ(poloidal flux) of the finally relaxed plasmas after merging as a function of K_{norm}: the initial K normalized by the value for the Taylor state. The merging toroids were observed to relax either to FRCs with $\lambda\approx0$ ($B_t\approx0$) or to spheromaks with $\lambda\approx1.2\times10^7$[A/Wb] (the value for the Taylor state), depending on whether the initial K_{norm} was smaller or larger than the threshold value $K_{norm}\approx0.3$, respectively.



(a) initial spheromaks (b) produced FRC

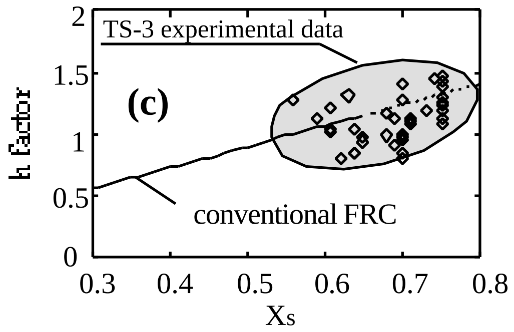


FIG. 2 Poloidal flux contours and radial profiles of Bt, jt of the initial spheromaks (a) and the produced FRC (b), and the FRCs in h-Xs space (c).

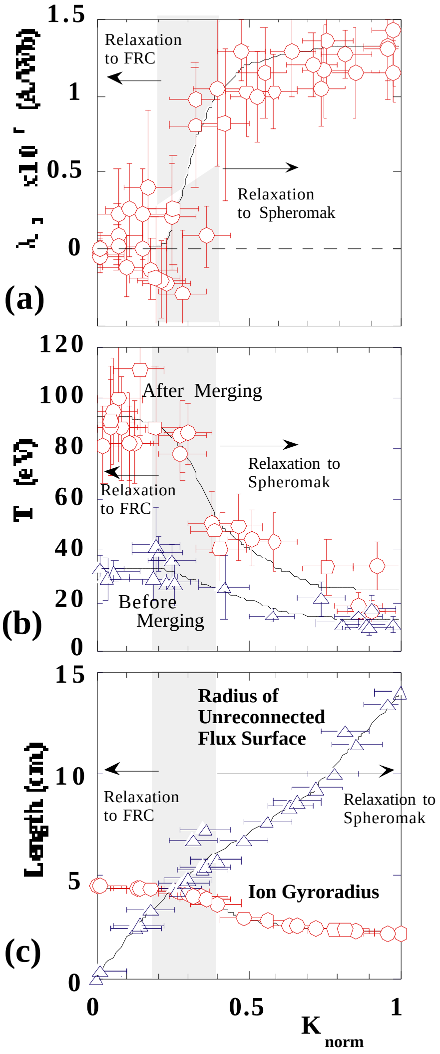


FIG. 3 Dependence of poloidal eugenvalue (a), ion temperature (b), ion gyroradius and radius of unreconnected flux surface (c) as a function of initial helicity Knorm normalized by the value for the Taylor state.

This λ value agrees well with the theoretical value calculated from the Taylor state spheromak with cylindrical boundary. This magnetic field measurement agrees well with the T_i measurement shown in Fig. 3(b). When the merging spheromaks relaxed to an FRC, T_i increased significantly from 10eV up to 90-100eV, while T_i increased as small as 10-40eV when they relaxed to a spheromak. The high thermal pressure of FRC was due to the high T_i which was caused by ion acceleration effect of magnetic reconnection[2]. However, the high T_i was quickly lost when the merging toroids relaxed to the low-ß spheromak probably through the field-line relaxation process. Figure 3(b) shows the radius r_{Bt} of unreconnected flux surface and its spatially-averaged ion gyroradius ρ_i, as a function of K_{norm}. Since the flux surfaces reconnect from peripheral to center, the center unreconnected flux has finite B_t, while the peripheral reconnected flux has almost no B_t. As K_{norm} is decreased to zero, r_{Bt} decreases and ρ_i increases. Note that r_{Bt} becomes equal to ρ_i around the mentioned threshold value K_{norm}≈0.3. If ρ_i becomes larger than r_{Bt} after the low-K_{norm} merging, the ion gyromotion is considered to affect the poloidal current I_p inside r_{Bt}. It leads to its anomalous dissipation and ion heating (T_i>>T_e) caused by some microinstability such as lower-hybrid modes, in agreement with the recent macroparticle simulation[5].

3.2 BOUNDARY BETWEEN FRC AND HIGH-ß ST (ULTRA-HIGH-ß ST FORMATION BY USE OF FRC)

Recently, we found that the oblate FRC can be transformed into a new high-ß equilibrium of ST. Our basic idea is shown in Fig. 4(a): typical q_Ψ-p_Ψ (s-α) diagram of ST for ballooning instability (q_Ψ: shear parameter, p_Ψ: pressure gradient). Because of strong toroidal effect, it has the narrow window between the first and second stability regimes, unlike those of the conventional tokamaks[6]. It has been studied how low-ß STs in the first stability regime can be transformed into high-ß STs in the second stability regime through this narrow window. However, it is easier to transform the oblate FRC to the high-ß ST in the second stability regime, because the FRC with ß≈1 is located near this regime. We demonstrated this new type of high-ß ST formation by applying the external toroidal field $B_{t,ext}$ to the FRC, as shown in Fig. 1.

Figures 4(b) show the 2-D contours of poloidal flux and toroidal field amplitude and radial profiles of j_t and thermal pressure p calculated from $p=\mathbf{j}\times\mathbf{B}$, after $B_{t,ext}$ was applied to the FRC right after its merging formation. The OH current drive was also used to maintain the flat top

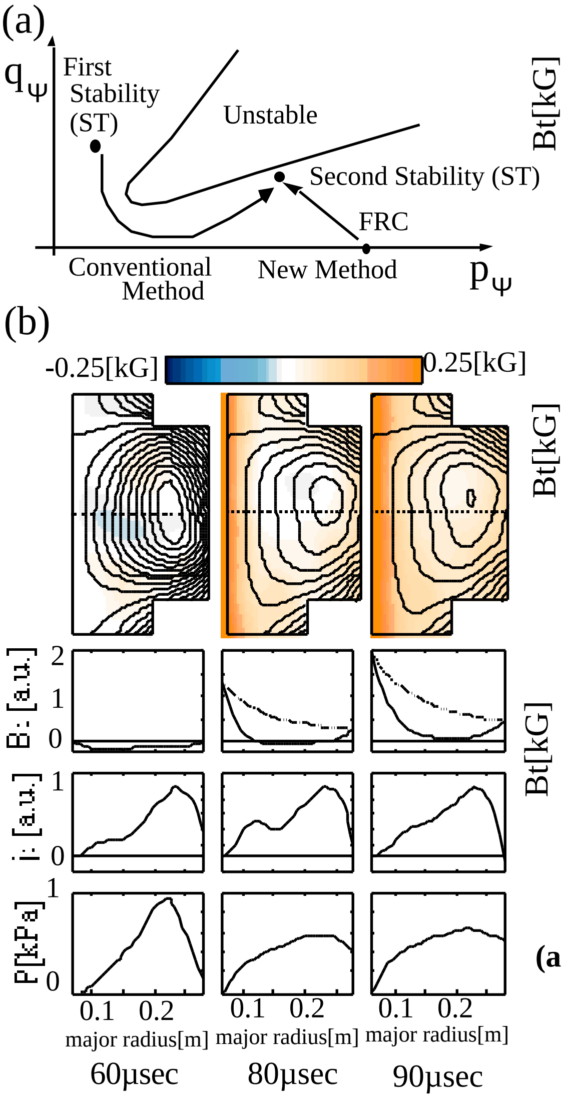


FIG. 4 Basic idea of forming high-ß ST in s-α diagram (a), r-z contours of poloidal flux and toroidal field strength and radial profiles of B_t, j_t and thermal pressure p of the FRC and the produced high-ß ST (b).

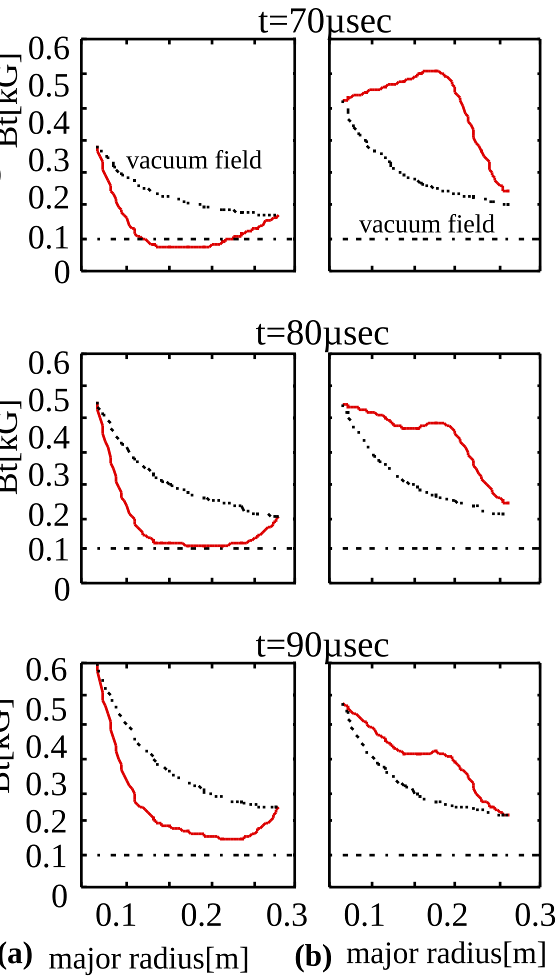


FIG. 5 Radial Bt profiles of high-ß ST (a) and conventional ST (b).

of plasma current. The poloidal flux and B_t contours indicate that the FRC without B_t was transformed stably into a new ST with finite B_t. Its life time≈100μsec was longer than that of the produced FRC. More than 80% of the thermal pressure of FRC was maintained after the B_t application, indicating that no serious instability occurs during this equilibrium transition. The hollow j_t profile also lasted to sustain the high thermal pressure of the high-ß ST, as shown in Fig. 4(b). The sustained ß≈0.6 is much higher than the conventional ß of ST. Figures 5(a) and (b) show the radial B_t profiles of the high-ß ST transformed from FRC and the conventional ST. Note that the B_t profile (solid line) of the former ST is located in the diamagnetic side of the vacuum B_t profile (dotted line) in sharp contrast with the peaked B_t profile of the latter ST. The poloidal beta of the former is estimated as high as 1-1.2. Our new formation method was found to fully suppress the strong paramagnetism of ST probably by virtue of the new path to the high-ß ST shown in Fig. 4(a). These results indicate that this high-ß ST is much closer to the FRC than to the paramagnetic ST.

4. CONCLUSIONS

Our merging formation of FRC lead us to the new generation of oblate FRC experiment with high energy efficiency and current amplification. It also explored the new possibility of ultra-high-ß ST formation by use of FRC. All these results indicate the importance of studying the relationship between various CTs, especially FRC, high-ß ST, spheromak and low-ß ST. Figure 6(a) shows these CTs in A(aspect ratio)-q(safety factor)-ß(beta) space. Our FRC/ST experiments have been made to optimize the stability/confinement properties of CTs, because the FRC has high ß characteristics and ST has better stability and confinement. This motivation lead us to the construction of a new upgraded confinement device TS-4 for the boundary research of CT confinements and their merging. As shown in Fig. 6(b), it has two flux cores for two CT production in its cylindrical vacuum vessel with length of 2.5m and length of 1.9m. Two CTs with major radius≈0.5m, A≈1.2-1.5 and B_t≈3-5kG will be merged together for high-ß FRC/ST formation and heating. Our merging formation of FRC has been recently adopted by several US experiments: MRX, SSX, Swift-FRC and SPIRIT as a promising slow formation method of FRCs.

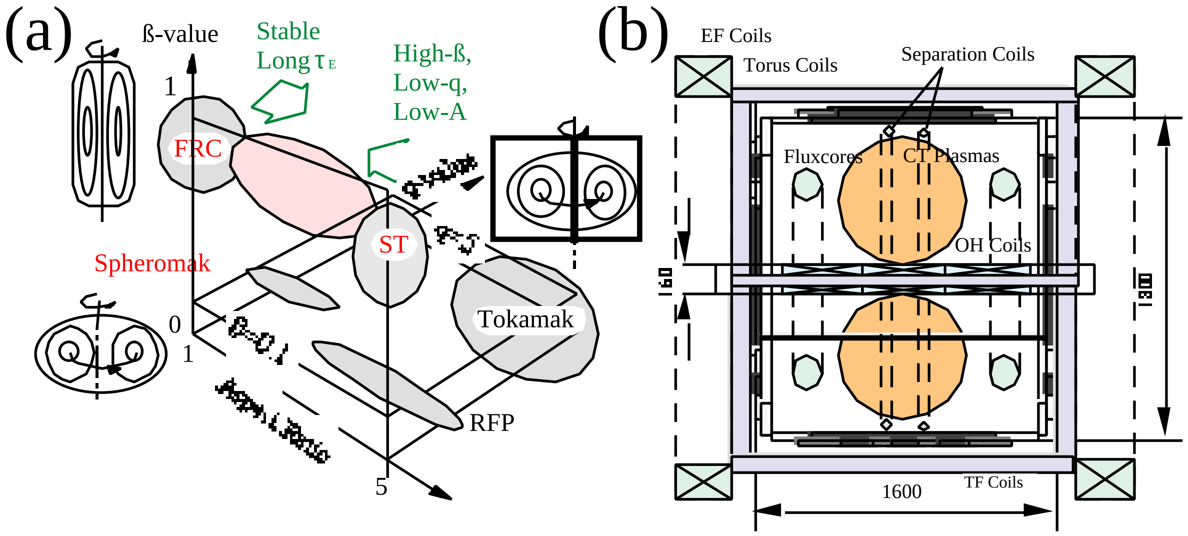


FIG. 6 Various CTs in A(aspect ratio)-q(safty factor)-ß(beta) space (a), and crosssection of TS-4 device for CT merging/confinement experiment (b).

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