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Spontaneous and Artificial Generation of Sheared Flow in Oblate FRCs in TS-3 and 4 FRC Experiments

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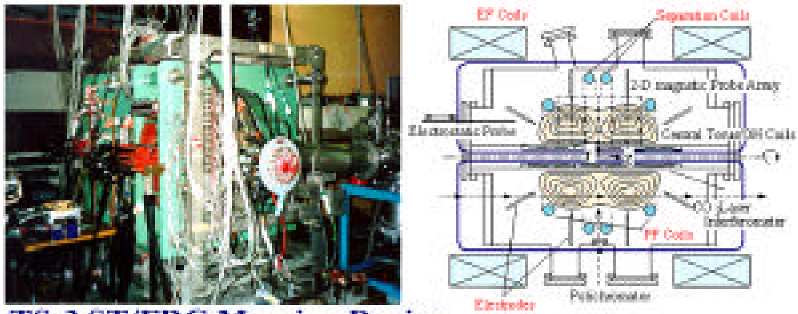
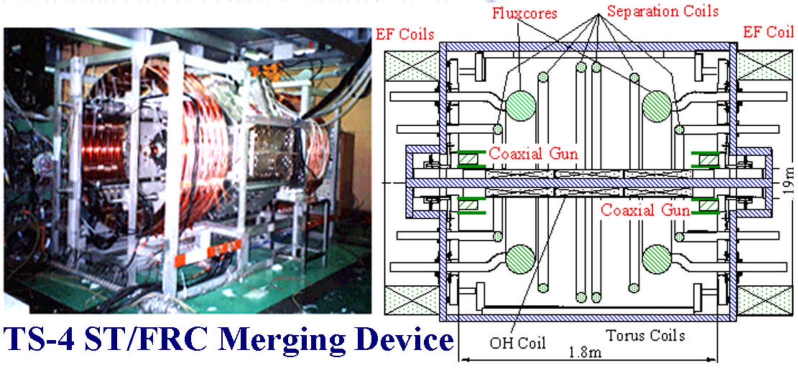
Abstract. Spontaneous formation of toroidal flow was measured for the first time in oblate FRCs produced in TS-3 and 4 experiments. The toroidal ion flow (V_i≈10km/sec) was found to peak around the magnetic axis, indicating formation of high flow shear inside the separatrix. The toroidal flow was observed to deform the magnetic field lines of the FRC, producing bipolar toroidal field profile. In high-s FRC (averaged number of ion gyro-radius “s”=4.5) with slow flow, its n=1 mode kept growing, causing collapse of the whole configuration. However, in low-s FRC (s=3) with fast flow, the rotating n=2 mode (saturated) became dominant after n=1 mode saturation. The spontaneous formation of flow shear possibly transformed the n=1 mode into the n=2 mode, suggesting a new sheared flow stabilization of n=1 mode. The flow shear was also generated artificially using the “sling shot” effect of the counterhelicity reconnection. The n=1 and 2 mode amplitudes were reduced down to 1/5-1/10 due to the generated flow shear. A new method for continuous sheared-flow generation was proposed for stabilization and heating of FRC by use of intermittent merging of spheromaks with opposing B_t.

1. Introduction

The highly efficient formation of field-reversed configuration (FRC) has been developed in TS-3 merging experiment[1] using two merging spheromaks with opposing toroidal field B_t[2]. This counterhelicity reconnection transformed two force-free (ß=5-10%) spheromaks (produced in slow time scale) into an oblate FRC with ß=70-100%, exploring unknown oblate FRC regime. These successful results lead us to the upscaled experiment TS-4 for further studies of its high-s (averaged number of ion gyro-radius) stability and electron confinement. Since the FRCs are unstable to several low-n magneto-hydrodynamic (MHD) modes, two-fluid or kinetic effect has been considered to explain the FRC lifetime markedly longer than the MHD time scale[3]. We have already reported the bifurcated relaxations of two merging spheromaks to an FRC and to another



TS-3 ST/FRC Merging Device



TS-4 ST/FRC Merging Device

FIG. 1. TS-3 and TS-4 CT merging devices

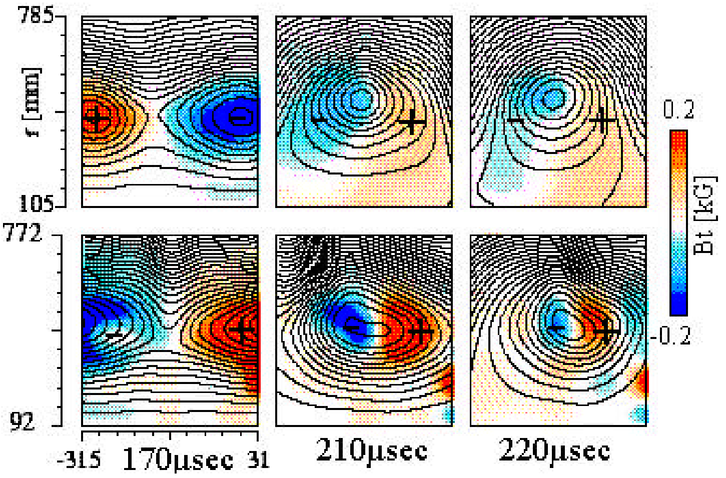
spheromak, suggesting the kinetic effect of the FRC[4]. A question is what type of non-MHD effect is crucial for equilibrium and stability of FRCs. This paper addresses three important issues of this kinetic effect: (1) direct measurement of ion velocity profile formed spontaneously in the oblate FRCs, (2) the ion flow / rotational effect on n=1 stability of the FRCs and (3) proposal of continuous sheared flow generation using intermittent counterhelicity merging.

2. Experimental Setups

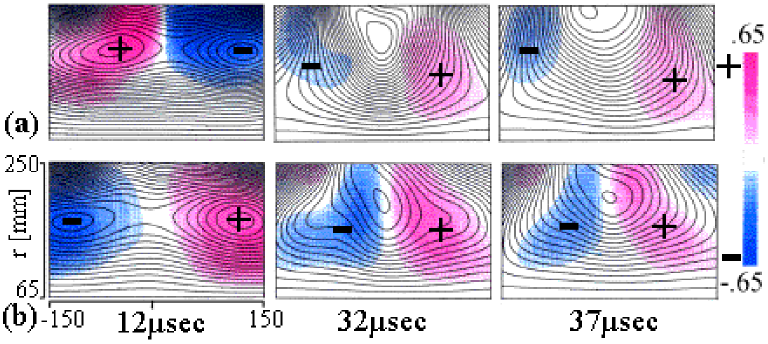
Figures 1 show the experimental setups of the TS-3 and TS-4 devices for the oblate FRC experiments. The TS-3 device utilizes two poloidal coils and two sets of eight electrode pairs and the TS-4 device does a fluxcore with poloidal and toroidal coils for poloidal and toroidal flux injection into initial spheromaks. In TS-3 and 4, the two spheromaks with R(major radius)≈0.2m and 0.5m were produced around the two PF coils/ two fluxcores, respectively. They were merged together to form an FRC through counterhelicity reconnection and heating process. In both devices, five internal and two external probe arrays were inserted on r-z plane to measure 2-D magnetic field profiles, flux contours and q profiles. Each probe array was covered with thin (5mm) glass tubes. Another eight magnetic probes were located toroidally around the separatrix on the midplane to measure toroidal mode activity of the FRCs. A polichrometer with an optical multi-channel analyzer was located on the midplane to measure radial profiles of ion temperature T_i and velocity V_i by means of the Doppler width and shift of carbon and hydrogen lines. An electrostatic probe was used to measure radial profiles of electron temperature and density.

3. Experimental Results

Recently, these oblate FRC equilibria were found to have finite deformation of magnetic field lines probably caused by the toroidal flow[5]. Figures 2 show the poloidal flux contours with B_t amplitude of the initial merging spheromaks and the produced FRCs in TS-4 (I) and TS-3 (II) experiments. In both cases, the merging spheromaks had toroidal currents I_t with the same polarity but different combinations of opposing B_t. However, all of the produced FRCs had positive B_t on the



(I) B_t field overshoots in TS-4



(II) B_t field overshoots in TS-3

FIGS. 2. (I) FRC formation in TS-4 and (II) that in TS-3 by counterhelicity mergings of two spheromaks with (a) normal and (b) reversed polarities of opposing B_t*.*

right side and negative B_t on the left side. Note that these B_t polarities did not depend on initial B_t polarities of merging spheromaks but on the direction of I_t. The observed FRC formations by two types of counterhelicity merging spheromaks and field deformation after the FRC production are illustrated in Fig.3. The deformation of reconnected field lines was observed especially in the low-s (averaged number of gyro-radius≈3) FRC, suggesting existence of plasma flow, possibly the ion flow with which the FRCs are equipped.

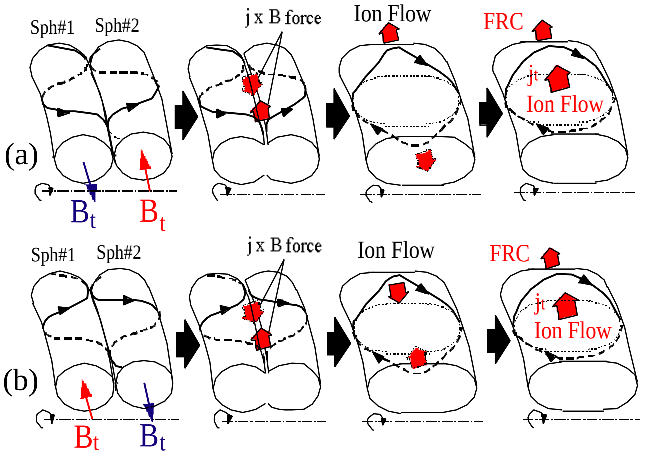


FIG. 3. Two "slingshot" motions of reconnected field-lines and their deformations after the FRC formations, when two merging spheromaks had (a) normal and (b) reversed polarities of opposing B_t.

The radial profiles of toroidal ion velocity were measured directly by the Doppler shift measurement of CII lines[5]. As shown in Fig. 4, the large toroidal flow shears were produced by the reconnection outflow ("slingshot" effect[2]) or reconnected field lines stretched toroidally around 22μsec during the merging/ reconnection. Their flow polarities depend on the B_t polarities of the merging spheromaks. This fact explains the positive flow shear for the normal B_t case (a) and the negative one for the reversed B_t case (b) observed at 22μsec. However, it is noted that the flow directions after the FRC formations were always positive (at 38μsec). This polarity agrees with their I_t (plasma current) polarities. These facts suggest that the FRC equilibrium tends to have large ion flow parallel to I_t. In agreement with the recent two-fluid theory[3] and the hybrid-simulations[6,7], the FRCs probably have a large amount of ion current generated spontaneously around the zero-field area (magnetic axis).

The next question is how the observed ion flow influences the FRC stability. In TS-3, the oblate FRC tends to be unstable to n=1 tilt mode when its elongation and s-number (averaged number of ion gyroradius) exceed respective critical values. The n=1 toroidal mode of the produced FRC was observed to rotate together with ion flow. Its speed increased inversely

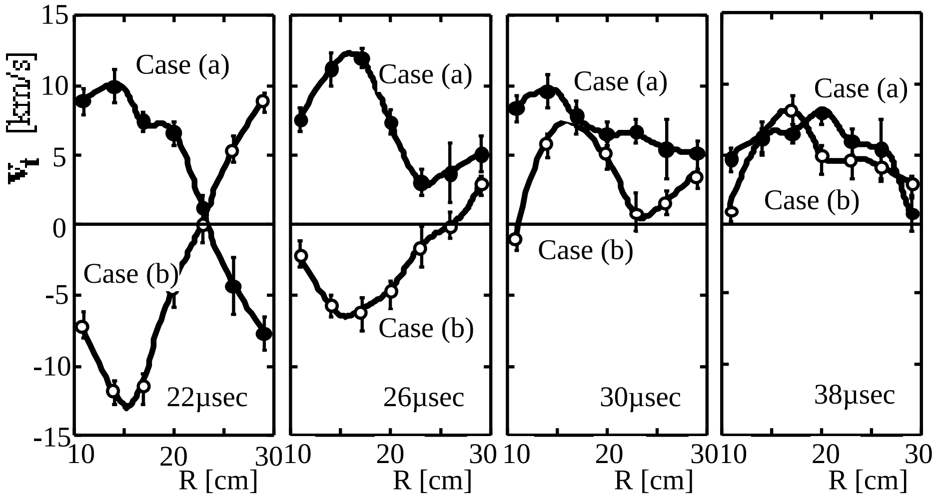


FIG. 4. Radial profiles of toroidal ion velocities during and after the FRC formations when two merging spheromaks had (a) normal and (b) reversed polarities of opposing B_t (TS-3).

with s-number. Figures 5 show toroidal rotation angles of the n=1 modes and n=1 and 2 mode amplitudes for (a) high-s and (b) low-s FRCs, respectively. The elongation factors of those FRC were set tilt-unstable. The high-s FRC (s=4.5) had slow toroidal rotation and its n=1 mode kept growing, causing collapse of the whole configuration. On the other hand, the low-s FRC (s=3) had fast flow/ rotation close to the Alfven speed. Note that the n=2 mode became dominant after the n=1 mode saturation and the saturated n=2 mode kept rotating. The spontaneous formation of sheared flow inside the FRC possibly transformed the n=1 mode into the n=2 rotational mode, suggesting a new flow-shear stabilization mechanism of n=1 tilt mode. This non-linear saturation of n=1 mode and transformation from n=1 to n=2 mode[5] agree qualitatively with the recent hybrid simulation made by Belova[6].

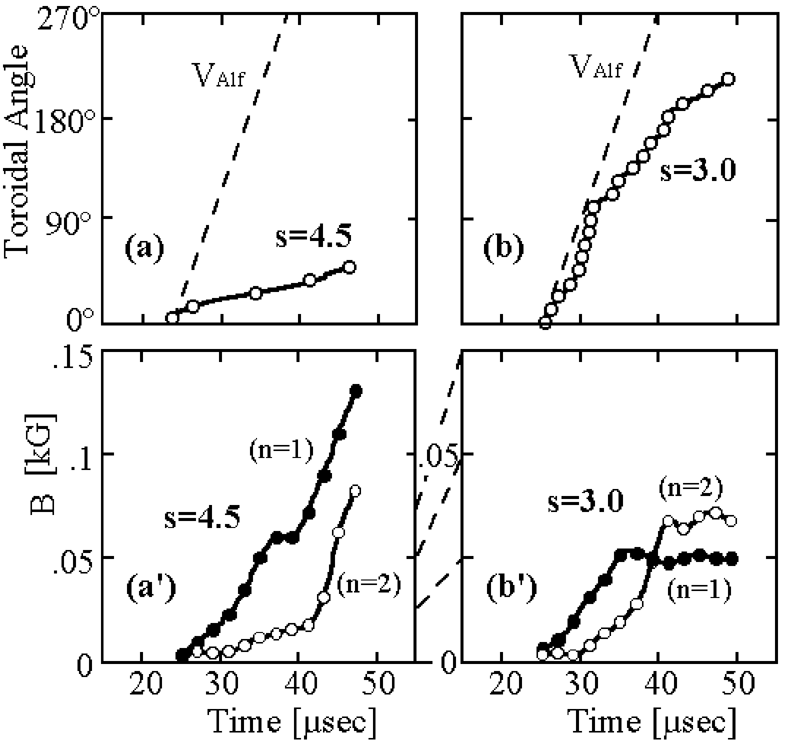


FIG.5. (a) Toroidal rotation angle of n=1 mode and (a') n=1 and 2 mode amplitudes of the FRC with s=4.5 and (b) (b') those of the FRC with s=3.0 (TS-3).

Figure 4 indicates that the largest velocity shear ($<V_i>\approx$ 10km/sec) was obtained from the "sling shot" motion of reconnected field lines. Figure 6(a) shows time evolutions of n=1 and 2 mode amplitudes during the FRC formation when its elongation and s-value were set tilt-unstable. Before the counterhelicity merging, the n=1 and 2 mode amplitudes already exceeded 15% of the n=0 mode amplitude B_0 due to the tilt

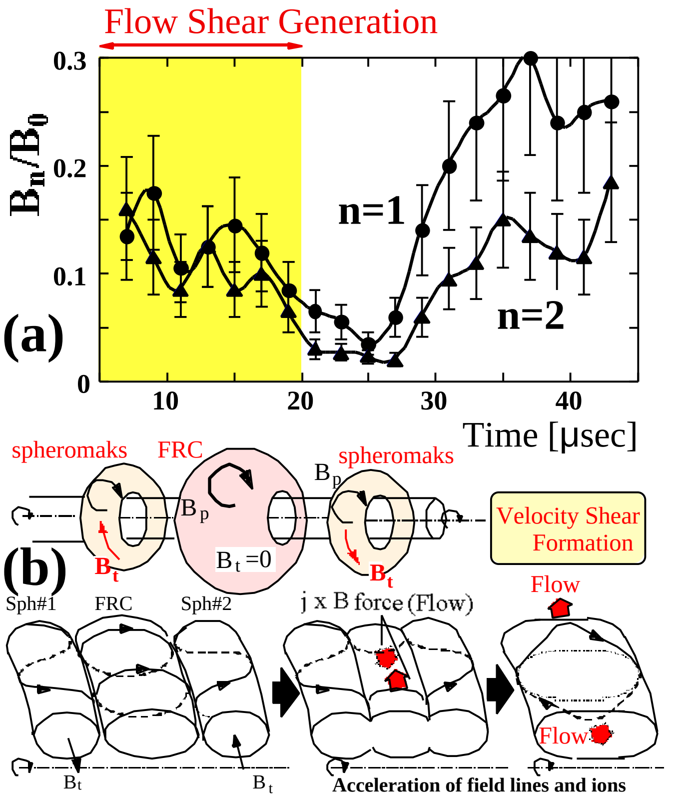


FIG. 6. (a) Toroidal mode amplitudes n=1 and 2 during and after shear-flow generation of counterhelicity merging/ reconnection and (b) the proposed continuous generation of shear-flow by multiple counterhelicity merging.

motion. However, the n=1 and 2 mode amplitudes were reduced by factor 5-10 during the sheared flow generation phase of reconnection. As the sheared flow decayed after the FRC formation, both modes started growing again and the whole plasma collapsed. This result indicates that the artificial generation of flow shear by counterhelicity reconnection also stabilized the n=1 mode.

New steady generation of sheared flow is being proposed to stabilize and heat the produced FRC continuously. As shown in Fig. 6(b), another two small spheromaks with opposing B_t are collided intermittently with the produced FRC. The reconnected field lines are stretched toroidally to generate toroidal sheared flow as shown in Fig. 6(b). This multiple merging method is considered to be useful for the stabilization and heating of FRC.

4. Summary

In summary, spontaneous formation of sheared flow was observed in TS-3 and 4 FRC experiments. The direct measurement of toroidal flow indicates that the FRC spontaneously generates toroidal ion flow whose profile is peaked in the core. The toroidal mode rotation was also observed together with the toroidal flow. Both speeds were observed to increase inversely with the plasma s-value. When the high-s FRC was located in the tilt-unstable (highly elongated) regime, the slowly rotating n=1 mode kept growing and caused the whole configuration to collapse. However, when the low-s FRC had similar elongation, the n=1 mode was transformed into n=2 mode and both mode saturated during high-speed rotation. Finally, both saturated modes were observed to keep rotating stably. These facts suggest the new sheared flow stabilization effect of FRCs for the first time, in agreement with the recent hybrid simulation. The flow shear was also generated artificially in TS-3 by the “sling shot” effect of the counterhelicity merging/ reconnection. The generated flow shear was found to reduce the n=1 tilt mode significantly. Based on this results, a new continuous generation of sheared flow was proposed for stabilization and heating of FRC, using multiple (more than two) merging of spheromaks with opposing B_t.

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