

Ion Kinetic Effect on Bifurcated Relaxation to a Field-Reversed Configuration in TS-4 CT experiment

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Abstract. Ion kinetic effect on the bifurcated relaxation of merging spheromaks to a field-reversed configuration (FRC) was studied experimentally using varied S_* which is the ratio of the minor radius to the ion skin depth from 1 to 7. The two merging spheromaks were observed to relax to an FRC or a new spheromak depending on whether the initial poloidal eigen value was smaller or larger than a threshold value. The threshold initial poloidal eigen value for the relaxation to an FRC increased with decreasing S_* value. Decrease in S_* promoted the relaxation to an FRC, annihilating the magnetic helicity, in sharp contrast with the conventional Taylor relaxation. Suppression of the low- n mode by the rotation shear of the toroidal modes is the most probable reason why the low- S_* condition promotes the relaxation into an FRC.

1. Introduction

A field-reversed configuration (FRC) is a very attractive concept because of its extreme high beta property although it is not new. The slow formation of an oblate FRC using axially colliding two spheromaks with opposing helicities has been developed in the TS-3 and 4 merging devices [1]. It was observed that the merging spheromaks relax either into an FRC or into a new spheromak, depending on whether the initial magnetic helicity was smaller or larger than a threshold value. This observation suggests that FRCs are equipped with some global equilibria as robust as the Taylor state. Robust equilibria and stability for MHD modes have been also observed in many FRC plasmas produced in linear theta pinch machines [2,3]. It is noted that most FRC experiments have been performed in kinetic regime. A question arises whether ion kinetic effect is a key factor to explain the robust relaxation to an FRC. Many numerical investigations especially the hybrid simulations (fluid electrons, kinetic ions) have shown that small size parameter S_* defined as the ratio between plasma characteristic length and ion skin depth stabilizes tilt instability [4]. On the other hand recent two-fluid theory has derived several preferred equilibria including force-free and non-force-free classes in helicity space [5]. In the overlapped region of these two classes, non-force-free class including FRC is energetically favorable. The size parameter S_* is important factor to measure both ion kinetic effect and two-fluid effect. Ions become unmagnetized and the motion of ions decouples with those of electrons under the small S_* regime, promoting ion kinetic effect and two-fluid effect [6]. Interest has grown in experimentally studying the relaxation to an FRC under varied S_* condition. This non-MHD stability effect closely relates with a high-beta/ high-flow equilibria useful for the future large-scale FRC and the high-beta ST experiments. This paper studies experimentally this bifurcated relaxation of two merging spheromaks in a wide range of S_* numbers. Several ion species were used in the up-scaled TS-4 device in order to vary S_* widely from 1 to 7.

2. Experimental Setup**2.1. TS-4 Merging Device**

The TS-4 Merging/ CT (Compact Torus) device is three times larger than TS-3, leading us to large- S_* experiments. The CT lifetimes in TS-4 are about 10 times longer than those of TS-3. As shown in Fig. 1, another important modification from TS-3 is to utilize flux cores for toroidal flux injection instead of electrodes. These modifications extend the lifetime of compact torus plasmas from that of TS-3. TS-4 has two flux cores as shown in Fig. 1. Each flux core has a set of poloidal (PF) and toroidal (TF) coils for poloidal and toroidal flux injection by inductive method. They can produce the two initial spheromaks whose toroidal field B_t polarities are determined by those of the TF coil currents. The center conductor is located along the center axis to maintain the plasma stability against the $n=1$ (tilt, shift)

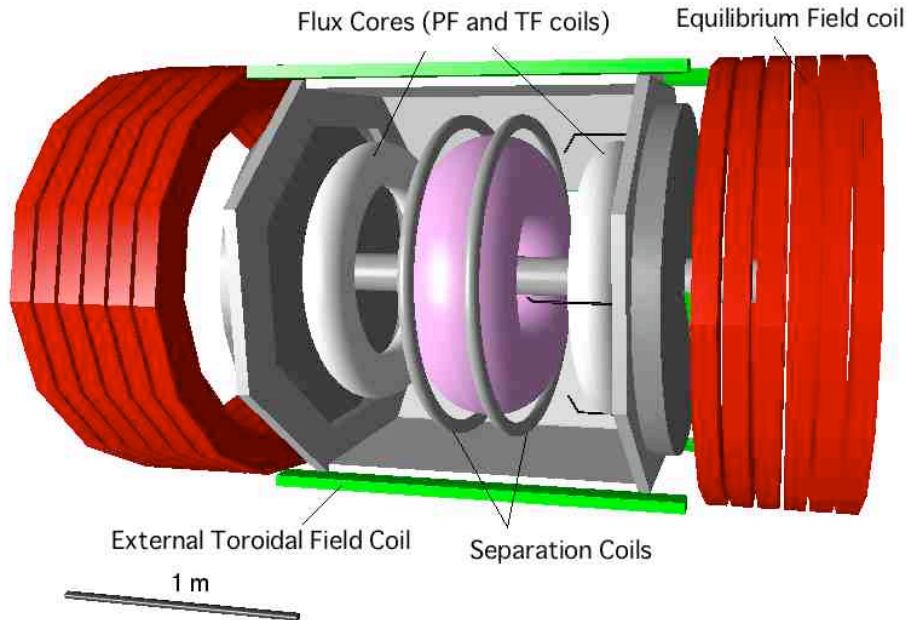


FIG. 1. Schematic of TS-4 CT/Merging Device.

modes. It is equipped with center solenoid and external toroidal field coils which were not used in this experiment. The major radius and separatrix elongation of compact toroids in this experiment were about 0.4~0.5 m and 0.5-0.7, respectively.

2.2. Diagnostics

A 2-D array, which consisted of B_z and B_t magnetic probes on the r - z plane, was used to directly measure 2-D magnetic field profile for calculation of flux contour. Another eight magnetic probes were installed toroidally on the midplane to measure toroidal mode activity of CTs. Its maximum resolutions of toroidal mode were four in amplitude and three in phase. Plasma density was measured by a CO_2 laser interferometer with a Michelson geometry using several chords on the midplane of TS-4. In this study, the line-averaged density at the chord of $r=18$ cm was used in order to obtain the size parameter S_* , where r was the length from the geometric axis of the center conductor.

3. Experimental result

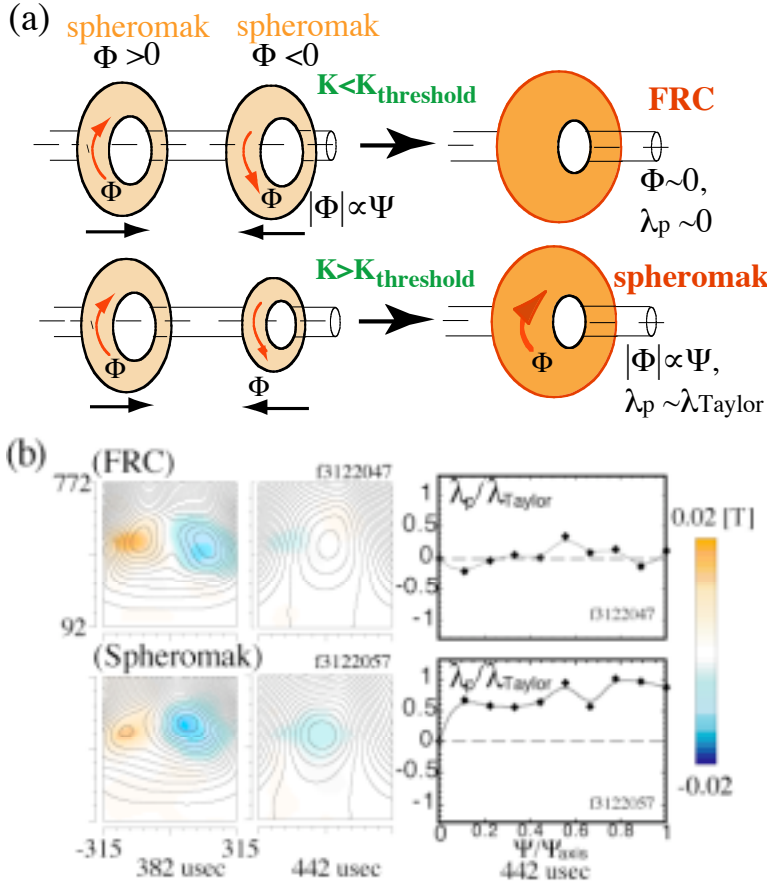


FIG. 2. a) Relaxations of two merging spheromaks to an FRC and to another spheromak and (b) the poloidal flux contours and the $\lambda_p / \lambda_{Taylor}$ profiles.

Figure 2 (a) shows the schematic drawing of the counterhelicity merging of two spheromaks with opposing helicity and its relaxed configurations. If their total magnetic helicity is larger than a threshold value, the two merging spheromaks relax to another spheromak. On the other hand, the merging spheromaks relax to an FRC if the magnetic helicity is smaller than a threshold value. Since the magnetic helicity $K \equiv K_{right} + K_{left}$ of two spheromaks is roughly proportional to $\Phi_{right} \Psi_{right} + \Phi_{left} \Psi_{left}$, the initial K was varied by changing the poloidal flux ratio $\Psi_{right} / \Psi_{left}$ using the relation $\Phi \propto \Psi$ in a Taylor-state spheromak configuration, where Φ and Ψ are the toroidal and poloidal flux and

the suffix represents each spheromak. We used the poloidal eigen value $\lambda_p \equiv \frac{\mu_0 I}{\Psi} = \mu_0 \left\langle \frac{\delta I}{\delta \Psi} \right\rangle_{\Psi > 0}$ as a key parameter to measure the relaxation followed by completion of merging, where I and Ψ are the poloidal current function and the poloidal flux, respectively. The bracket denotes the average inside the separatrix. The final state at $\lambda_p \sim 0$ represents the relaxation to an FRC with $B_t \approx 0$ and that with $\lambda_p \sim \lambda_{Taylor}$ (: the eigen value of the CT for the Taylor state) indicates the conventional Taylor-type relaxation to another spheromak. Effect of ion mass on the relaxation was investigated using various ion species such as H, He, Ne and Ar. Figure 2 (b) shows the poloidal flux contours with B_t field amplitude and the $\lambda_p / \lambda_{Taylor}$ profiles when the two initial Argon spheromaks relaxed to (a) an FRC and (b) a spheromak. The spatial profiles of $\lambda_p / \lambda_{Taylor}$ were observed to be flat in the both cases.

Figures 3 (a)-(d) show the time evolutions of $\lambda_p / \lambda_{Taylor}$ of the 15-17 merging spheromaks for the different initial $\lambda_p / \lambda_{Taylor}$ in the H, He, Ne and Ar discharges. The solid red lines in Fig. 3 (a)-(d) represent the $\lambda_p / \lambda_{Taylor}$ curves whose $\lambda_p / \lambda_{Taylor}$ relaxed into the FRC range of $|\lambda_p / \lambda_{Taylor}| \leq 0.3$ over one Alfvén time. The dotted black lines represent all other cases whose

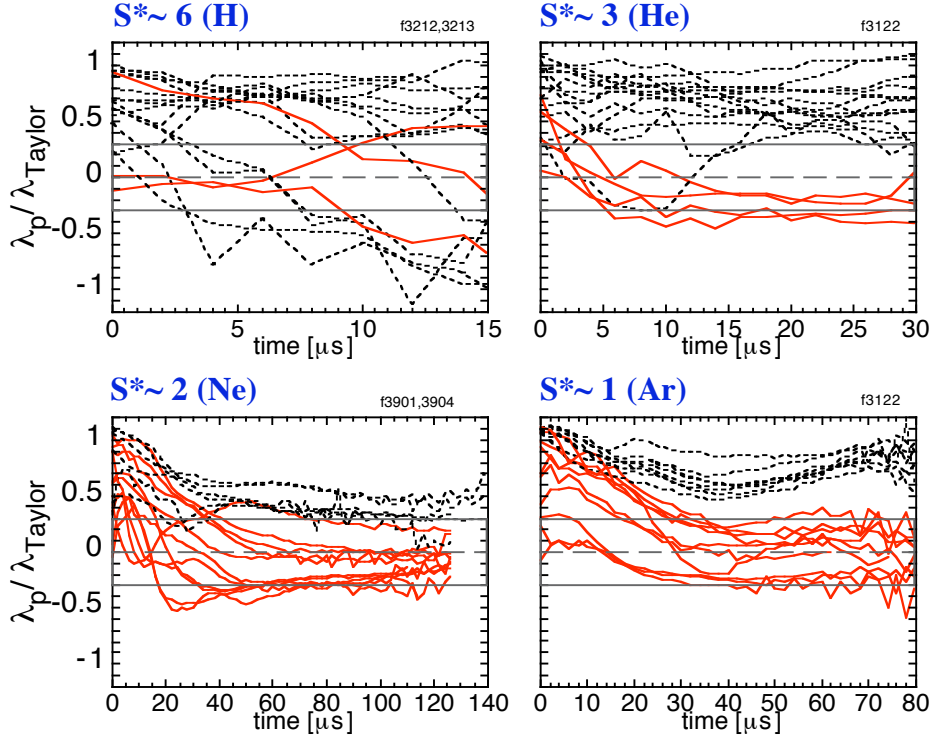


FIG. 3. Time evolutions of $\lambda_p / \lambda_{Taylor}$ obtained in the H, He, Ne and Ar discharges. The time $t=0$ is that of the merging completion of two spheromaks. The red lines and black dotted lines represent the cases of the relaxation to an FRC and a spheromak.

$\lambda_p / \lambda_{Taylor}$ relaxed into the spheromak range. In the case of $S^* \sim 1$ (Ar), $\lambda_p / \lambda_{Taylor}$ curves were observed to bifurcate into the FRC regime and to the spheromak regime. In the case of the initial $\lambda_p / \lambda_{Taylor} > 0.9$, they relaxed to $\lambda_p / \lambda_{Taylor} \sim 0.7-1$, while they spontaneously approached nearly $|\lambda_p / \lambda_{Taylor}| \leq 0.3$ in the case of $\lambda_p / \lambda_{Taylor} < 0.9$. The bifurcated relaxations to an FRC ($\lambda_p / \lambda_{Taylor} \sim 0$) and to a spheromak ($\lambda_p / \lambda_{Taylor} \sim 1$) were clearly identified in the case of $S^* \sim 1$ and 3. It is noted that the FRC-like relaxed states often have a finite values of $\lambda_p / \lambda_{Taylor}$ from -0.3 to 0.3 as shown in Figs. 3 (a), (b) and (c). This fact suggests that the FRC-like equilibria are permitted to have small but finite magnetic helicity K . In the case of Fig. 2(c), the merging spheromaks with $\lambda_p / \lambda_{Taylor} < 0.2$ pass through $\lambda_p / \lambda_{Taylor} = 0$ and finally relax to another compact toroid at $|\lambda_p / \lambda_{Taylor}| \geq 0.3$. The small $\lambda_0 / \lambda_{Taylor}$ states in $S^* \sim 6$ were found to be unstable in contrast with those in the small S^* cases. In a similar way to the $S^* \sim 1$, the threshold poloidal eigen values $\lambda_0 / \lambda_{Taylor}$ were estimated to be about 0.6 in the $S^* \sim 3$ case and 0.2 in the $S^* \sim 6$ case, respectively. The threshold poloidal eigen value $\lambda_0 / \lambda_{Taylor}$ for the relaxation to an FRC is plotted as a function of the S^* value as shown in Fig. 4. The threshold $\lambda_0 / \lambda_{Taylor}$ was observed to decrease inversely with the S^* value. These results indicate that the merging spheromaks with higher helicity relax into an FRC without helicity with decreasing their S^* value. The ion kinetic effect or the two-fluid effect is the most probable reason why low- S^* helps the merging spheromaks to relax into an FRC.

Figure 5 shows the time evolutions of $\lambda_p / \lambda_{Taylor}$, the phase angles θ and the amplitudes \tilde{B}/B_0 of toroidal modes from $n=1$ to 4 for the cases of a) $S^* \sim 6$ and b) $S^* \sim 1$. The polarity of rotation $-\theta$ corresponds to the negative I_p direction, where I_p is the plasma

current. While $\lambda_p/\lambda_{Taylor}$ once became about zero in the case of $S^* \sim 6$, the increment in $\lambda_p/\lambda_{Taylor}$ was followed by the slight growth of the $n=4$ mode at $t=382 \mu\text{s}$. After $394 \mu\text{s}$, normal cascade of mode numbers from $n=4$ to $n=2$ was also observed and $\lambda_p/\lambda_{Taylor}$ approached unity with the growth of $n=2$. No clear rotation of the toroidal modes was seen during the relaxation. This result indicates that the merged spheromaks relaxed to another spheromak due to MHD activity with no rotation in the high S^* regime. On the other hand in the case that the low

S^* merging spheromaks initially had a finite $\lambda_p/\lambda_{Taylor}$, the decrease in $\lambda_p/\lambda_{Taylor}$ was accompanied by the suppression of the $n=1, 3$ and 4 modes from $t=380$ to $410 \mu\text{s}$. Simultaneously, the clear rotations of $n=1$ and 3 modes were observed. However, the amplitude of $n=2$ saturated after its slight increase. In this case, the merging spheromaks with

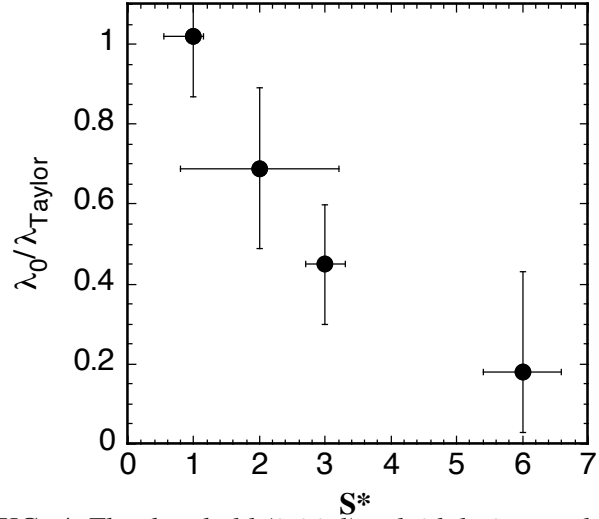


FIG. 4. The threshold (initial) poloidal eigen value $\lambda_0/\lambda_{Taylor}$ as a function of S^* .

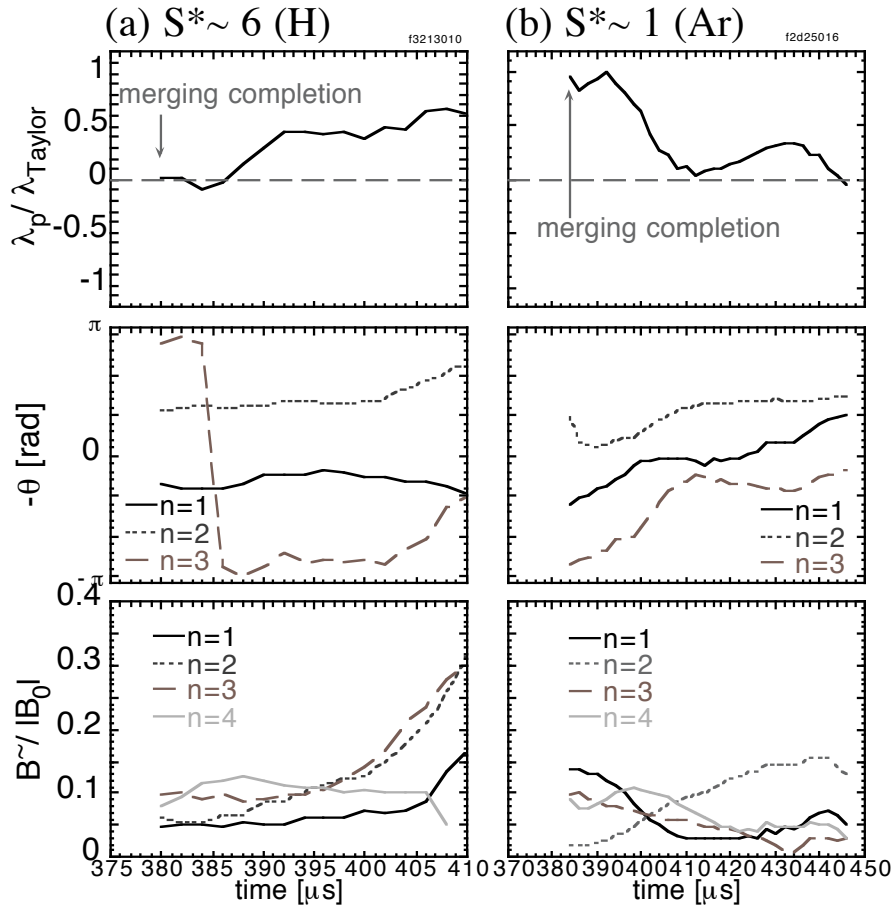


FIG. 5. Time evolutions of $\lambda_p/\lambda_{Taylor}$, phase angle $-\theta$ and amplitude $\tilde{B}/|B_0|$ of each toroidal mode for the cases of a) $S^* \sim 6$ (H) and b) $S^* \sim 1$ (Ar).

a finite initial $\lambda_p / \lambda_{Taylor}$ finally relaxed to the FRC with $\lambda_p / \lambda_{Taylor} \sim 0$.

4. Discussion

Figure 6 shows two motions of reconnected field lines and the time evolutions the phase angle $-\theta$ of the toroidal modes when two merging spheromaks had a) normal and b) reversed polarities of opposing B_t . One of the differences between the normal and the reversed B_t polarities is the polarity of the $\mathbf{j} \times \mathbf{B}$ force generated by outflow of magnetic reconnection (“slingshot” effect [7]) as shown in Fig. 6 (left). Directions of the $\mathbf{j} \times \mathbf{B}$ forces at the outer halves ($r > r_o$: major radius) and the inner halves ($r < r_o$) are opposite with each other in both cases. This means that the $\mathbf{j} \times \mathbf{B}$ force causes a sheared rotation in radial direction. The direction of the rotation at the radial location ($r < r_o$) of the toroidal mode probes depends on the B_t polarities of the merging spheromaks, in agreement with the negative θ direction for the normal B_t case (a) and the positive θ one for the reversed B_t case (b). It was observed that the $n=1 \sim 3$ modes rotated in the negative θ under the condition of normal B_t case (a) and vice versa (right of Fig. 6). These facts suggest that the $\mathbf{j} \times \mathbf{B}$ force driven by magnetic reconnection generated sheared rotation of the low- n modes.

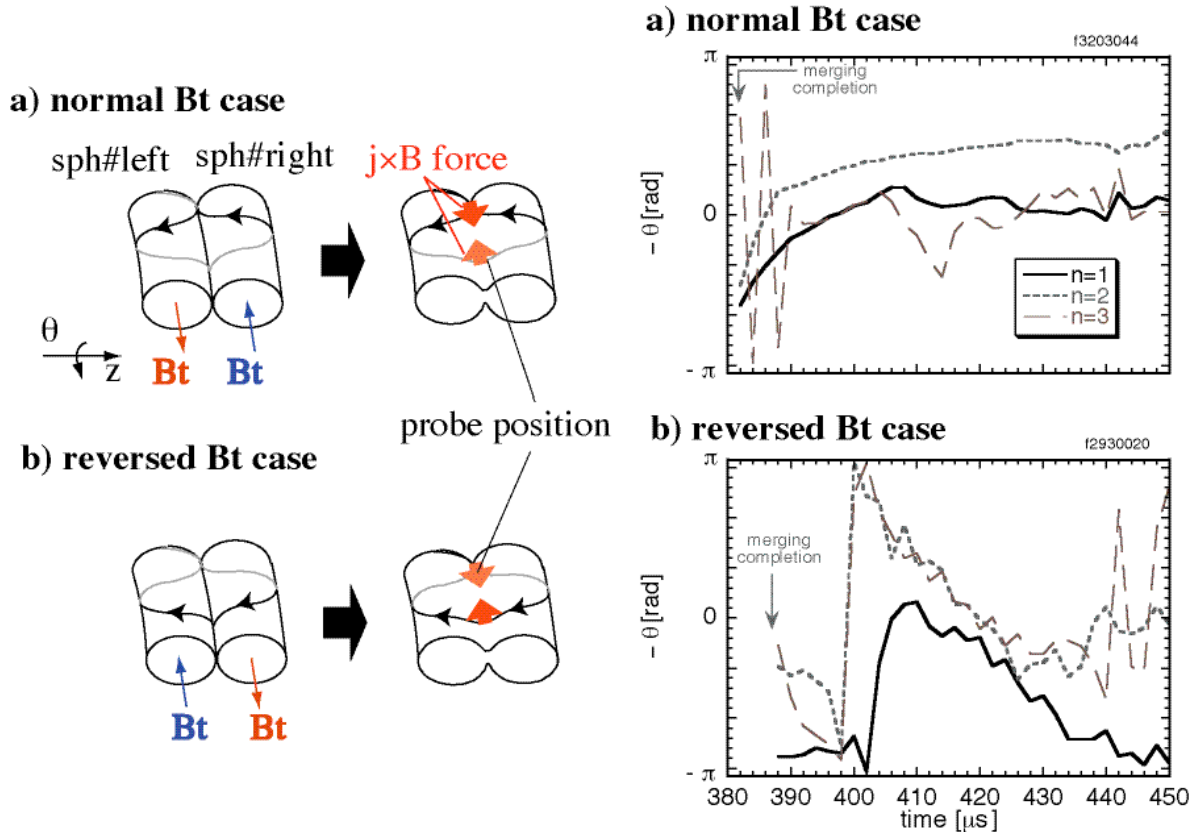


FIG. 6 Two motions of reconnected field lines (left) and time evolutions of phase angle $-\theta$ of toroidal modes (right) when two merging spheromaks had a) normal and b) reversed polarities of opposing B_t .

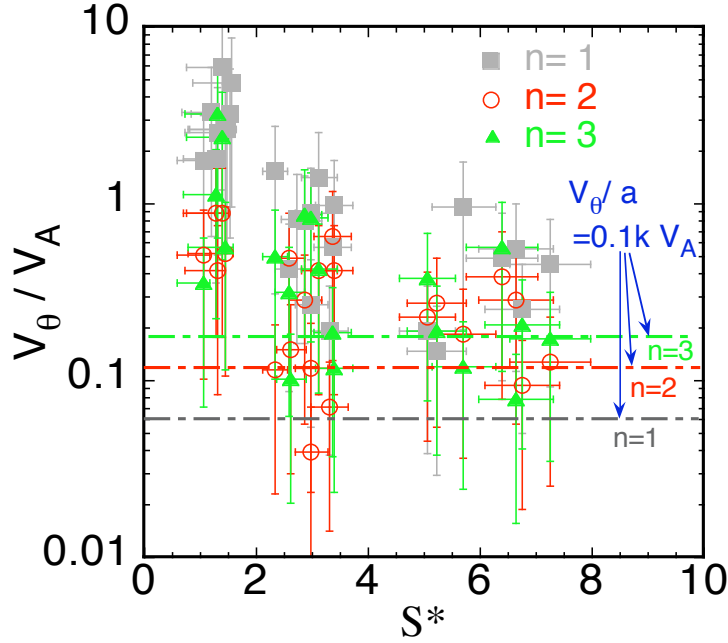


FIG. 7. The S^* value dependence of the toroidal velocities v_θ/v_A of $n=1, 2$ and 3 modes. The dotted lines represent the theoretical stability boundary $v_\theta/a=0.1kv_A$ for $n=1\sim 3$ modes.

increased inversely with S^* for $n=1\sim 3$. In the case of $S^* \sim 1$, v_θ was comparable to v_A in sharp contrast with the slow rotation under the high S^* condition. The theoretical study using linear stability analysis in Z-pinch plasma elucidated that the sheared axial flow with a linear shear of $v_z/a > 0.1kv_A$ is required for stability of $m=1$ mode where k and m are the axial wave number and the poloidal mode number [8]. The threshold values of flow shear $v_\theta/a = 0.1kv_A$ for $n=1\sim 3$ were also plotted in Fig. 7. Here, we assume the rotation velocities of the modes were zero on the magnetic axis and have a spatially uniform shear where a and k are defined as the distance from the magnetic axis to the probe position and n/R (R : the major radius). All discharge with $S^* \sim 1$ have v_θ/v_A faster than the threshold while the others with $S^* > 2$ have v_θ/v_A slower than (or comparable to) the threshold values. We observed growth and suppression of low- n modes under high- and low- S^* conditions, respectively. The fast sheared rotation was observed to stabilize the growth of low- n modes in agreement with the theory, suggesting that the Taylor relaxation was suppressed in low- S^* regime.

5. Summary and Conclusions

The effect of ion skin depth on the bifurcated relaxation of the merging spheromaks into a field reversed configuration (FRC) and a Taylor state spheromak was experimentally studied. The varied skin depths of several ion species in the large-scale experiment revealed that the initial threshold poloidal eigen value λ_0 for the relaxation to an FRC increased with decrease in the S^* value. An important finding is that the decrease in S^* is essential for the relaxation to an FRC, annihilating the magnetic helicity, in sharp contrast with the conventional Taylor relaxation. The ion kinetic effect or the two-fluid effect is the most probable reason why low-

The S^* dependence of the maximum toroidal mode rotation velocity v_θ normalized by the Alfvén speed v_A is shown in Fig. 7, where v_A was determined by the maximum value of the magnetic field strength inside the separatrix and the line-averaged density at the time of merging completion. Horizontal error bar was caused by fluctuating oscillation of the interferometry signal and uncertainty of charge number of the ions. Vertical one was determined from that of the toroidal mode probe signals. It was observed that v_θ

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S^* helps the merging spheromaks to relax into an FRC. The merged spheromaks with small λ_p relaxed to a spheromak due to MHD activity in high S^* regime. On the other hand in the case of $S^* \sim 1$, the decreases in the amplitudes of the low- n modes were accompanied by those fast rotations during the relaxation to the $\lambda_p \sim 0$ (FRC) state. The toroidal sheared rotation generated by the counterhelicity reconnection was considered to suppress the low- n modes essential to the Taylor relaxation, in agreement with the theory under the low- S^* condition.

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