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Ion Kinetic Relaxation of Two Merging Spheromaks to an FRC

KAWAMORI Eiichirou and ONO Yasushi

High Temperature Plasma Center, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

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The ion kinetic effect on the relaxation of merging spheromaks to a field-reversed configuration (FRC) was studied experimentally using varied S^* (the ratio of the minor radius to the ion skin depth) from 0.5 to 10. The merging spheromaks relax to an FRC ($\lambda_p \sim 0$) or to another spheromak ($\lambda_p \sim \lambda_{Taylor}$), depending on whether their initial poloidal eigen value λ_p was smaller or larger than the threshold value λ_0. The varied skin depths of several ion species in the up-scaled experiment revealed that the threshold value λ_0 for the relaxation to an FRC increased inversely with the S^* value. The decrease in S^* promoted the relaxation to an FRC, annihilating the magnetic helicity, in sharp contrast with the conventional Taylor relaxation.

Keywords:

Ion skin depth, field-reversed configuration, spheromak, relaxation

A number of field-reversed configuration (FRC) experiments have observed robust stability of FRC equilibria, even if they lack magnetohydrodynamic (MHD) stability. In particular, the slow formation of an oblate FRC has been developed in the TS-3 merging device using axially colliding two spheromaks with opposing helicities [1,2]. It was observed that the merging spheromaks relax either into an FRC or into another spheromak, depending on whether the initial magnetic helicity is smaller or larger than a threshold value as shown in Fig. 1(a). This observation suggests that FRCs are equipped with some global stability as robust as the Taylor state. The ion kinetic effect is considered to be one of the key factors to explain the robust relaxation to an FRC [2]. Interest has grown in studying the relaxa-tion to an FRC in large-scale varied S^* merging experiment, where S^* is the ratio of the minor radius to the ion skin depth (equal to the number of thermal ion Larmor radii under a high beta condition) which characterizes the ion kinetic effect on a plasma. Under the condition of a small S^* value, ions become demag-netized and the motion of ions and electrons decouple [3]. This paper reports the first experimental test of the FRC slow formation 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 0.5 to 10 during the bifurcated relaxations.

The TS-4 device has the two flux cores to produce the initial spheromaks by means of the inductive method. Each flux core has a set of poloidal (PF) and toroidal (TF) coils for poloidal and toroidal flux injection. They can produce the two spheromaks whose

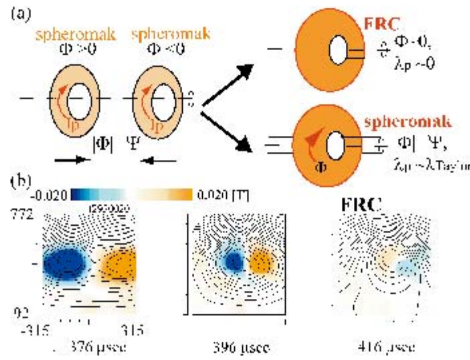

Fig. 1 (a) Schematic drawing of the relaxations of two merging spheromaks to an FRC and to another spheromak and (b) the example of the poloidal flux contour with B_t amplitude by red and blue colors in the FRC relaxation.

author's e-mail: kawamori@katsurai.t.u-tokyo.ac.jp

toroidal field B_t polarities are determined by those of the TF coil currents. The center conductor is located along the center axis in order to maintain the plasma stability against the n = 1 (tilt, shift) modes. A 2-D array of magnetic probe on the r-z plane was used to measure the 2-D magnetic field profile for calculation of the flux contour. In order to obtain the size parameter S^*, line-averaged density was measured using a CO_2 laser interferometer on the midplane.

Since the magnetic helicity $K \equiv K_{\mathrm{right}} + K_{\mathrm{left}}$ of two spheromaks is proportional to $\Phi_{\mathrm{right}}\Psi_{\mathrm{right}} + \Phi_{\mathrm{left}}\Psi_{\mathrm{leftt}}$, the initial K was varied by changing the poloidal flux ratio $\Psi_{\mathrm{right}}/\Psi_{\mathrm{left}}$ because of the relation $\Phi \propto \Psi$, where Φ and Ψ are the toroidal and poloidal flux and the suffix represents each spheromak. We used the poloidal eigen value $\lambda_p \equiv \mu_0 I/\Psi$ as a key parameter to measure the following relaxation, where I and Ψ are the poloidal current function and the poloidal flux, respectively. The final state at $\lambda_p \sim 0$ represents the relaxation to an FRC with $B_t \approx 0$ and that with $\lambda_p \sim \lambda_{\mathrm{Taylor}}$ indicates the relaxation to another spheromak. Figure 1 (b) shows the poloidal flux contours with B_t field amplitude when the two initial spheromaks have almost equal but opposing toroidal flux. The merging spheromaks were observed to relax to an FRC, annihilating the small initial K. Figures 2 (a)-(c) show the time evolutions of $\lambda_p/\lambda_{\mathrm{Taylor}}$ during the counterhelicity mergings of H, He, and Ar discharges. The solid lines in Fig. 2 (a)-(c) represent the curves whose $\lambda_p/\lambda_{\mathrm{Taylor}}$ relaxed into the FRC range of $|\lambda_p/\lambda_{\mathrm{Taylor}}| \leq 0.3$ over the Alfvén time. The dotted lines represent all other cases whose $\lambda_p/\lambda_{\mathrm{Taylor}}$ relaxed into the spheromak range. In the case of $S^* \sim 1$ (Ar), $\lambda_p/\lambda_{\mathrm{Taylor}}$ curves were observed to bifurcate into FRCs or to spheromaks. In the case of the initial $\lambda_p/\lambda_{\mathrm{Taylor}} > 0.9$, they relaxed to $\lambda_p/\lambda_{\mathrm{Taylor}} \sim 0.7 - 1$, while they spontaneously approached nearly $|\lambda_p/\lambda_{\mathrm{Taylor}}| \leq 0.3$ in the case of $\lambda_p/\lambda_{\mathrm{Taylor}} < 0.9$. The bifurcated relaxations to an FRC ($\lambda_p/\lambda_{\mathrm{Taylor}} \sim 0$) and to a spheromak ($\lambda_p/\lambda_{\mathrm{Taylor}} \sim 1$) were clearly identified in the case of $S^* \sim 1$ and 3 discharges. It is noted that the FRC-like relaxed states often have a finite values of $\lambda_p/\lambda_{\mathrm{Taylor}}$ from –0.3 to 0.3 as shown in Figs. 2(a) and (b). This fact suggests that the FRC-like equilibria is permitted to have small finite K. In the case of Fig. 2(c), the merging spheromaks with $\lambda_p/\lambda_{\mathrm{Taylor}} < 0.2$ pass through $\lambda_p/\lambda_{\mathrm{Taylor}} = 0$ and finally relax to another compact toroid at $|\lambda_p/\lambda_{\mathrm{Taylor}}| \geq 0.3$. The small $\lambda_p/\lambda_{\mathrm{Taylor}}$ 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 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 $\lambda_p/\lambda_{\mathrm{Taylor}}$ for the relaxation to an FRC ($\lambda_p/\lambda_{\mathrm{Taylor}} \sim 0$) was found to decrease inversely with the S^* value. The series of experiments indicates that the merging spheromaks with higher helicity relax into an FRC whose helicity is annihilated by 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. Actually, our toroidal flow peaked outside of the magnetic axis, agreeing quantitatively with that deduced from the two-fluid theory [3].

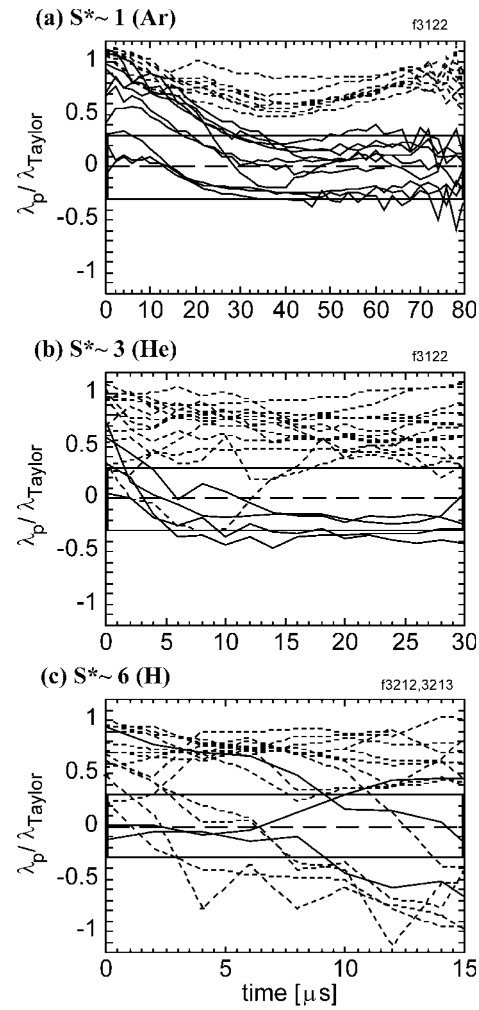

Fig. 2 Time evolutions of $\lambda_p/\lambda_{\mathrm{Taylor}}$ in H, He, and Ar discharges of the counterhelicity merging. The time t = 0 represents the time of merging completion.

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