Experimental Study of the bifurcated relaxation of merging spheromaks into an FRC

E. Kawamori, M. Turuda, K. Sato, Y. Ono

University of Tokyo

1. Introduction

It is found that the merging spheromaks relax either into a high beta Field-Reversed Configuration (FRC) or into a spheromak in TS-3, depending on whether the initial magnetic helicity is smaller or larger than a threshold value [1]. Although the TS-3 experiment was operated under the low-s condition, the up-scaled TS-4 experiment has made it possible to investigate the high-*s* FRC relaxation. In order to study ion kinetic effect for the bifurcated relaxation, the counterhelicity merging experiment was carried out in the TS-4 device with various ion species such as hydrogen and helium, argon plasmas. We also show the preliminary result of the counterhelicity merging experiment with the reversed B_t polarities of merging spheromaks. Because it is expected that the polarity of generated flow shear by the magnetic reconnection depends on the B_t polarities of merging spheromaks, the effect of troidal ion flow shear on the equilibrium and the stability of an FRC may be studied.

2. Experimental Setup

The TS-4 device has the two flux cores that are used to produce the initial sphromaks by the inductive method. The major radius of CTs is typically about 50 cm. A 2-D array of magnetic probe on the r-z plane was used to measure 2-D magnetic field profile for calculation of flux contour. Another 8 magnetic probes were located toroidally around the separatrix on the midplane to measure toroidal mode activity of CTs. The detail of the device is described elsewhere [2].

3. Experimental Results

3.1. Ψ_{right}/Ψ_{left} Scan Experiment

Under varied flux ratio Ψ_{right}/Ψ_{left} of merging spheromaks, the poloidal eigen value $\lambda_p \equiv \mu_0 I/\psi$ was measured after relaxation. Here I is the poloidal current flux function. It is expected that a spheromak is produced in the case that Ψ_{right}/Ψ_{left} does not equal unity and an

FRC is produced in the case of $\Box_{right}/\Box_{left}$ ~1. The eigen value $\lambda_p \sim \lambda_{Taylor}$ and $\lambda_p \sim 0$ indicate a spheromak and an FRC, respectively. Effect of ion species on relaxation was studied.

Low *s* case(Ar discharge)

Figure 1 shows time evolution of the polroidal flux contour with B_t amplitude and λ_p in the Ar discharge. After the merging, λ_p decreased to zero, indicating that magnetic helicity vanished. Then equal but opposing toroidal field was generated. This result shows spontaneous deformation of reconnected field lines. Alfvén time was estimated to be about 10 μs in the condition of ion density n_i =5 $\times 10^{19}$ m^{-3} and magnetic field strength B= 0.03 T. The produced FRC was stably sustained.

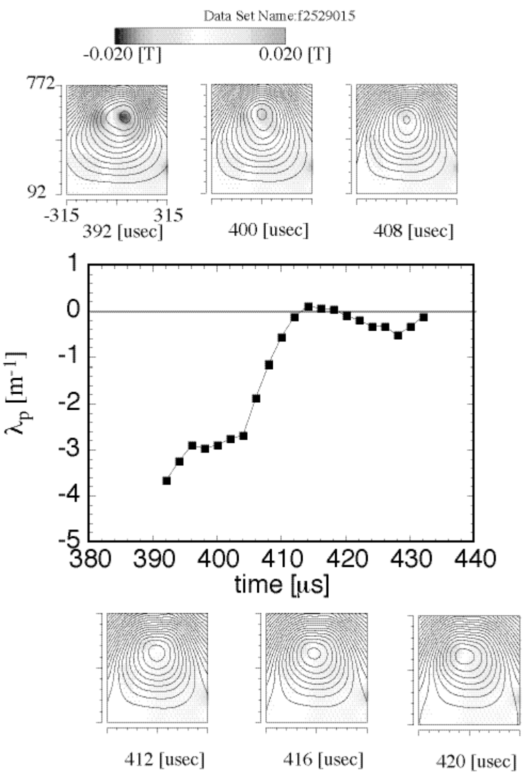

Fig. 1 Time evolution of the poloidal flux contour with B_t amplitude and λ_p .

Figure 2 is temporal evolution of the poloidal eigen value $\lambda_p/\lambda_{Taylor}$ normalized by the value in a cylindrical spheromak and toroidal mode amplitudes during the FRC formation. During the relaxation to λ_p ~0 state, all toroidal mode activities (n=1to 4) were suppressed. The process of spontaneous FRC formation was stable and toroidaly symmetric.

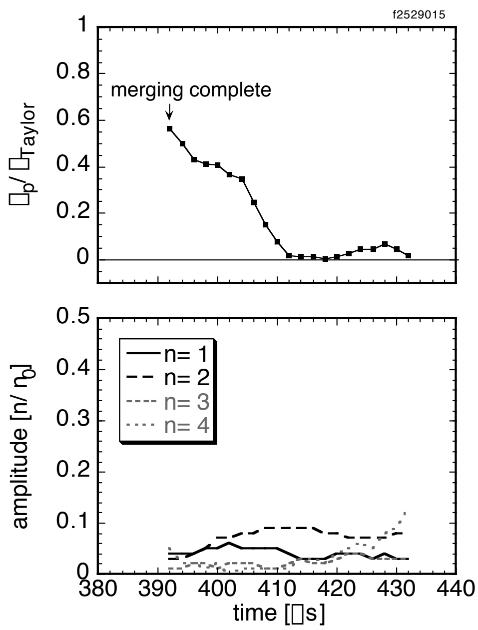

Fig. 2 Temporal evolution of □p/ □Taylor and toroidal mode amplitudes during the FRC formation.

The bifurcated relaxation of $□_p$ ~$□_{Taylor}$ and $□_p$ ~0 was clearly identified as shown in Fig. 3. *t*= 0 denotes the time just after the merging. When initial $□_p$/ $□_{Taylor}$> 0.7, that was maintained around constant value (triangle). When initial $□_p$/ $□_{Taylor}$< 0.6, on the other hand, $□_p$/$□_{Taylor}$ approached zero (square).

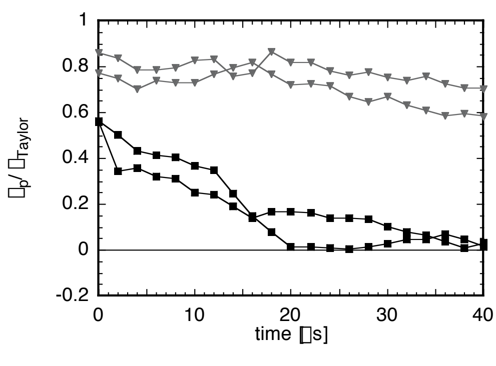

Fig. 3 Time evolution of the normalized poloidal eigen value □p/ □Taylor .

$□_p$ is plotted as a function of $□_{right}$/ $□_{left}$ as shown in Fig. 4. Open square denotes the value just after merging and closed circle is the value 20 □ seconds after the merging. When $□_{right}$/ $□_{left}$ >1.3, $□_p$ approached $□_{Taylor}$(hatched), indicating relaxation to a spheromak. Around$□_{right}$/ $□_{left}$ ~1, $□_p$ approached zero, indicating relaxation to an FRC. $□_p$ spontaneously approached nearly zero after the merging.

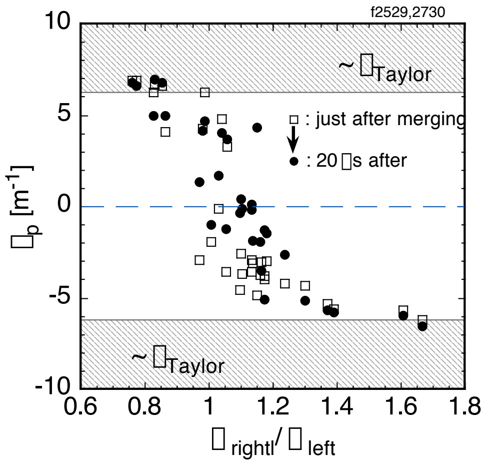

Fig. 4 □$_p$ is plotted as a function of □^{right}/ □^{left} in the low s discharge.

High *s* case(H, He)

Bifurcated relaxations in light ion discharge(H and He) cases are shown. □$_p$ just after the merging is plotted as a function of □$_{right}$/ □$_{left}$ as shown in Fig. 5. Closed and open squares denote hydrogen discharge and helium discharge case, respectively. In both cases, the □$_p$ ~0 state was obtained just after the merging.

Typical time evolution of □$_p$/ □$_{Taylor}$ and toroidal mode amplitudes in the case of □$_{right}$/ □$_{left}$ ~1 are shown in Fig. 6. Although □$_p$/ □$_{Taylor}$ became zero just after the merging, □$_p$/ □$_{Taylor}$ immediately increased. The increase in □$_p$/ □$_{Taylor}$ was accompanied by growth of troidal modes. The □$_p$ ~0 state (FRC) is more unstable in the present H and He discharge than the Ar discharge. The □$_p$ ~0 state was maintained for relatively short time in light ion discharge.

We roughly estimated *s* number in each discharge case under the condition of magnetic field strength B~ 0.03 T and ion temperature T_i= 100 eV. Because the ion temperature of the TS-4 plasmas was not obtained in the present experiment, this ion temperature is based on the results in TS-3. In Hydrogen case, ion larmor radius $r_L = m_i v / eB$ is estimated to be about 3 cm. Then the *s* number □ R/ r_L is about 20, where R is the major radius. In the helium case, the *s* number is about 10. On the assumption that Ar^+ ion density was dominant in the Ar case, the *s* number is about 3.

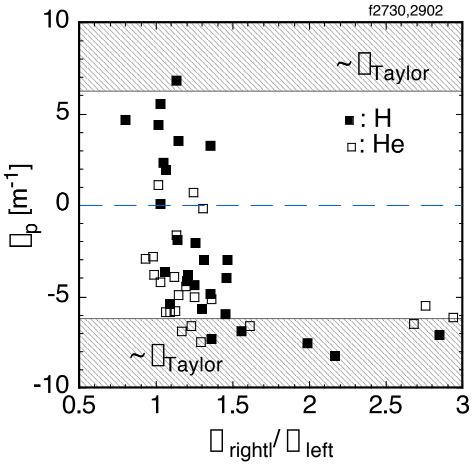

Fig. 5 $\square_p$ is plotted as a function of $\square_{right}$/ $\square_{left}$ in the light ion cases.

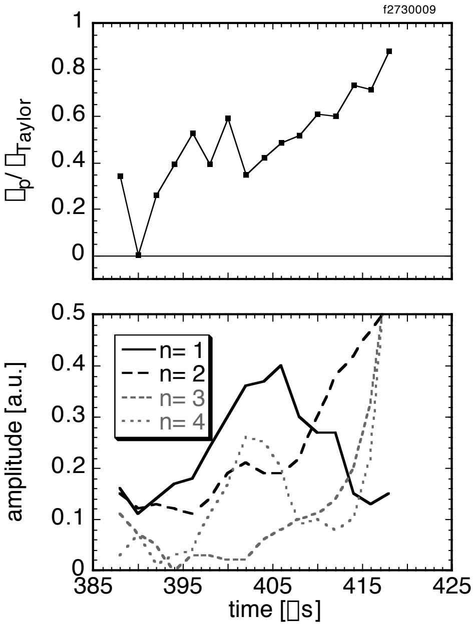

Fig. 6 Time evolution of $\square_p$/ $\square_{Taylor}$ and toroidal mode amplitudes.

3.2. Relaxation of merging spheromaks with reversed B_t polarities

The counterhelicity merging experiment was carried out under the condition that the B_t polarities of merging spheromaks were reversed (Fig. 7 case(b)). The experiments shown in the section 3.1 are the case of the normal B_t polarities(case(a)). The directions of the troidal plasma current I_t were same in both cases.

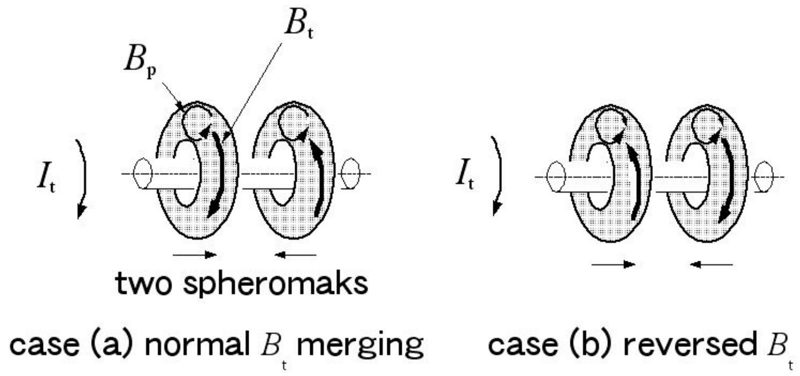

Fig. 7 The counterhelicity merging with normal and reversed B_t polarities.

Time evolution of the normalized poloidal eigen value $\lambda_p/\lambda_{Taylor}$ is shown in Fig. 8. When initial $\lambda_p/\lambda_{Taylor} < 0.3$ (triangle), λ_p became zero for a short time. However λ_p finally approached λ_{Taylor}. In TS-4, the merged CTs tended to relaxed to the configuration of $\lambda_p \sim \lambda_{Taylor}$ in reversed B_t merging.

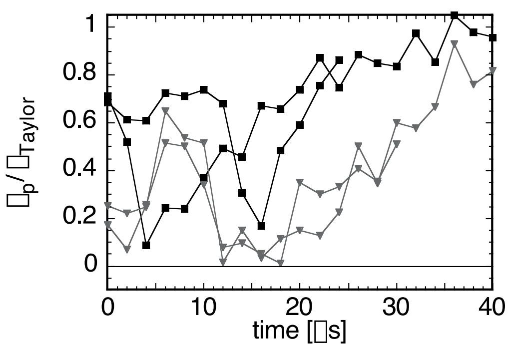

Fig. 8 Time evolution of the normalized poloidal eigen value $\lambda_p/\lambda_{Taylor}$.

One of the conceivable differences between the normal and the reversed B_t polarities is the polarity of the flow shear generated by magnetic reconnection as shown in Fig. 9. The flow shear polarities depend on B_t polarities of merging spheromaks, explaining the positive flow shear for the normal B_t case(a) and the negative one for the reversed B_t case(b). The generated troidal ion flow shear was experimentally observed in the TS-3 plasmas [3]. In TS-4, the relaxation into an FRC in the case(a) was more stable than that in the case(b). These facts suggest that the relaxation to FRC and its equilibrium correlate with ion flow parallel to I_t.

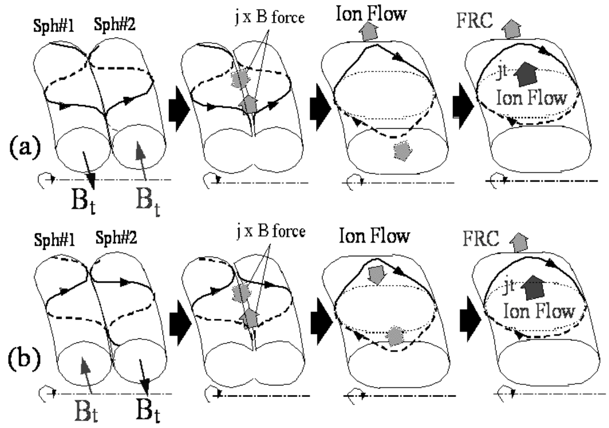

Fig. 9 B_t polarities dependence of generated flow shear polarities (the normal B_t case(a) and the reversed case(b)).

5. Summary

Effect of ion mass on the bifurcated relaxation was studied in TS-4. A window for the FRC relaxation was broad in the low *s* experiment (Ar case). The bifurcated relaxation of $\square_p \sim \square_{Taylor}$ and $\square_p \sim 0$ was clearly identified in this case. The process of the spontaneous FRC formation was stable and toroidaly symmetric. On the other hands, the regime for FRC relaxation is narrow in the high *s* case(H and He). The $\square_p \sim 0$ state was maintained for relatively shorter than that in the low *s* case. They tended to relaxed to the configuration of $\square_p \sim \square_{Taylor}$.

In order to investigate the effect of troidal ion flow shear on the equilibrium and the stability of an FRC, the counterhelicity merging experiment with reversed B_t polarities was carried out in TS-4. It was expected that the polarity of generated flow shear by the magnetic reconnection depends on the B_t polarities of merging spheromaks, explaining the positive flow shear for the normal B_t case and the negative one for the reversed B_t case. The preliminary result shows that the merged CTs tended to relaxed to the configuration of $\square_p \sim \square_{Taylor}$ when the merging spheromaks had reversed B_t polarities.

Acknowledgements

The authors are grateful to the members of the TS group for contributing data for this study and carrying out the experiments.

References

[1] Y. Ono, M. Inomoto, Y. Ueda, T. Matsuyama and T. Okazaki: Nucl. Fusion **39** 11Y, 2001 (1999).

[2] M. Tsuruda *et al*. : “Comparative Studies of CT/ST Configurations with Varied q-values in TS-4” *in Proceedings of this workshop*.

[3] T. Matsuyama, E. Kawamori, Y. Ono *et al*. : 19th IAEA Fusion Energy Conference, Lyon, Oct. 14-19, IAEA-CN-94/EX/P3-14 (2002) (*to be published*).