Collisional Merging Process of Field-Reversed Configuration Plasmas in the FAT-CM Device*)

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(Received 28 December 2017 / Accepted 8 July 2018)

In order to investigate the collisional merging process of field-reversed configurations (FRCs), the FAT device has recently been upgraded to FAT-CM, consisting of two field-reversed theta-pinch (FRTP) formation sections and the confinement section. Collisional merging of the two FRCs causes a conversion of the kinetic energy to mostly thermal ion energy, resulting in an increase of the ion pressure that greatly expands the FRC size/volume. This increase of the FRC size is observed by magnetic diagnostics in the confinement region, leading to an increase in the excluded flux; on a side note, these characteristics/phenomena have also been observed in C-2/C-2U experiments at TAE Technologies. The process of FRC formation, translation and collisional merging in FAT-CM has been simulated by Lamy Ridge, 2D resistive magnetohydrodynamics code, in which the same phenomenon of the excluded-flux increase via FRC collisional merging has been observed. Simulation results also indicate that there is an importance of the external magnetic field structure/profile in the confinement region, clearly affecting the FRC merging. Steeper magnetic field gradient by a strong mirror field appears to suppress the axial expansion of collided FRCs and lead a merged FRC to higher temperature.

Keywords: magnetically confined plasma, field-reversed configuration, high beta plasma, FRC merging, 2D resistive MHD simulation

DOI: 10.1585/pfr.13.3402098

1. Introduction

A field-reversed configuration (FRC) is a compact toroid (CT) that has predominantly poloidal magnetic field with zero or small amount of self-generated toroidal field [1, 2]. FRC has a potential as a feasible fusion reactor because of its simple geometry, ease of translation, natural diverter, and extremely high beta value. The averaged beta of FRCs is near unity: $\langle\beta\rangle = 2\mu_0\langle p\rangle/B_\mathrm{e}^2 \sim 0.9$ (p is plasma pressure and B_e is the external magnetic field, respectively).

Recently, the C-2/C-2U device at TAE successfully demonstrated a quasi-static sustainment of merged FRCs by fast ions which are introduced via ~ 10 MW neutral-beam injection [3]; also, the collisional merging process clearly exhibited an increase of the diamagnetic signals [4, 5]. However, the collisional merging process itself and its effect on FRC performance have not yet fully been studied in detail.

Field-reversed theta-pinch (FRTP) is the conventional method to produce hot and high-density plasma [6]. The FAT (FRC Amplification via Translation) device at Nihon University has been upgraded to FAT-CM to have two FRTP formation regions in order to investigate the collisional merging process of FRCs. In parallel with FAT-CM experiments, a simulation research has started to better understand the dynamics of formation, translation and collisional merging processes of FRC's. We have employed Lamy Ridge [7] that is 2D resistive magnetohydrodynamics (MHD) code with real experimental boundary and initial conditions.

In this paper, we report initial results of the FAT-CM experiments and numerical simulations.

2. FAT-CM Device

Figure 1 illustrates a schematic of the FAT-CM device. It consists of the central confinement vessel and two FRTP formation sections, called "V-formation" and "R-formation". Formation tubes are made of transparent fused quartz, and the confinement chamber is made of stainless steel (inner wall radius 0.39 m; skin time ~ 5 ms). It serves as a flux conserver in the timescale of the translation pro-

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*) This article is based on the presentation at the 26th International Toki Conference (ITC26).

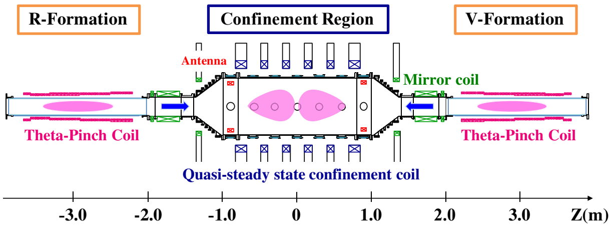

Fig. 1 Schematic view of the FAT-CM device.

cess at Alfvénic velocity. Quasi-static confinement coils are placed along the confinement region.

Initial FRCs are formed by the FRTP method in two formation sections. In a typical FAT-CM operation, the theta-pinch circuits generate the negative bias field of ~ 0.038 T, followed by the main reversal/compression field of ~ 0.40 T with the rise time of ~ 4 μs. The formation process also employs a pre-ionization method by ringing theta discharge. The quasi-steady state confinement coils create a forward field of 0.03 ~ 0.07 T to confine plasmas. A working gas of D_2 is puffed into the both formation sections at 6 ms before the start of the bias field. Initial FRC plasmas, ~ 0.07 m in radius and ~ 1.0 m in length, are formed at ~ 6 μs after the initiation of the compression field in the both formation sections, and are ejected from the respective formation regions at ~ 30 μs. The translated FRCs collide each other in the middle of the confinement chamber, the merged FRC plasma state is obtained at ~ 60 μs, at which the plasma radius is ~ 0.22 m and the length is ~ 2 m.

3. Initial Results of Collisional Merging Experiment

Figure 2 shows the comparison of single FRC translation (from each formation) and collisional merging one in the typical FAT-CM experiment. The data are measured by magnetic pick-up coil near the mid-plane of the confinement chamber ($z = +8$ cm). The excluded-flux radius is estimated as

$$r_{\Delta\phi} = r_{\rm w}\sqrt{1-\frac{B_0}{B_{\rm e}}}, \tag{1}$$

where, $r_{\rm w}$ is the radius of the metal confinement chamber, B_0 is the magnetic field without plasma, respectively. The estimated excluded-flux radius is known to be comparable to the radius of flux null surface for equilibrium. As shown in Fig. 2, global behavior of each FRC in the R- and V-formation are comparable. In the case of single FRC formation/translation, FRC is ejected at a speed of ~ 70 km/s and accelerated by the external magnetic field gradient. When the FRC enters into the confinement region, it immediately expands radially from ~ 6 cm to ~ 12 cm in radius, as shown in Fig. 2 (b). After passing through the midplane, the FRC with the accelerated speed of ~ 150 km/s is then decelerated and bounced off back-and-forth between

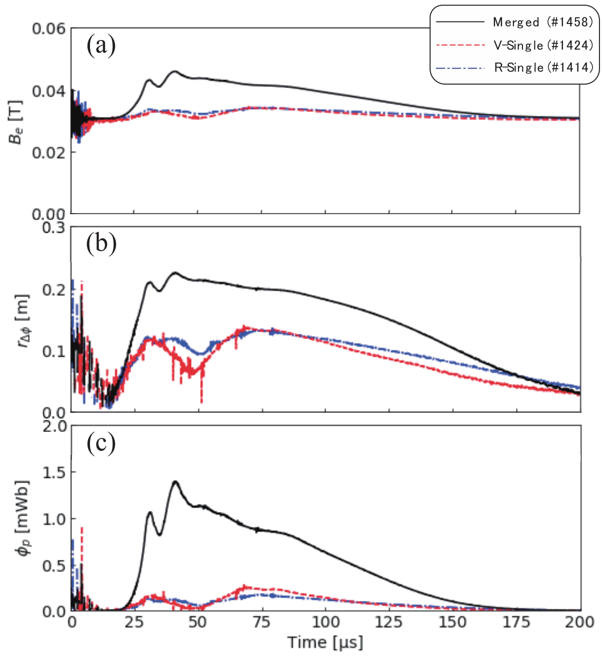

Fig. 2 Comparison of the single translated and merged FRCs; showing time evolutions of (a) external field $B_{\rm e}$, (b) excluded flux radius $r_{\Delta\phi}$, and (c) estimated poloidal flux $\varphi_{\rm p}$ near the midplane ($z = +8$ cm).

the magnetic mirrors. In the case of collisional merging, radial expansion of the plasma is clearly observed and the plasma size/flux remains large compared with the single translation case.

Ion Doppler spectroscopy is employed to estimate the ion temperature of FRC plasmas. The estimated temperature of the merged FRC is 50 ~ 120 eV for an emission spectrum of C-III. The emission intensity in the single translated FRC case appears to be insufficient to estimate temperature. The electron density, measured by laser interferometry, is $0.5 \sim 1 \times 10^{20}\ \mathrm{m^{-3}}$ in both cases. The relative speed of the colliding two FRCs is ~ 300 km/s that is faster than Alfvénic speed of ~ 200 km/s calculated by the electron density and external magnetic field. Therefore, shock heating may occur in the collisional merging FRC.

The poloidal flux is estimated as

$$\phi_{\rm p} = 0.31\pi B_{\rm e} r_{\rm s}^3 / r_{\rm w}, \tag{2}$$

assuming rigid-rotor (RR) profile that is consistent with the internal field measurements for translated FRC [8]. Here, $r_{\rm s}$ is the separatrix radius. The apparent increase in the excluded-flux radius and the estimated poloidal flux, seen in Figs. 2 (b) and 2 (c), indicates that the collisional merging process has thermalized the initial kinetic energy of the two translating FRC's.

4. Simulation Results

Figure 3 shows 2D MHD simulation results computed for the same discharge conditions as experiments, shown in Fig. 2. The simulation results approximately agree with

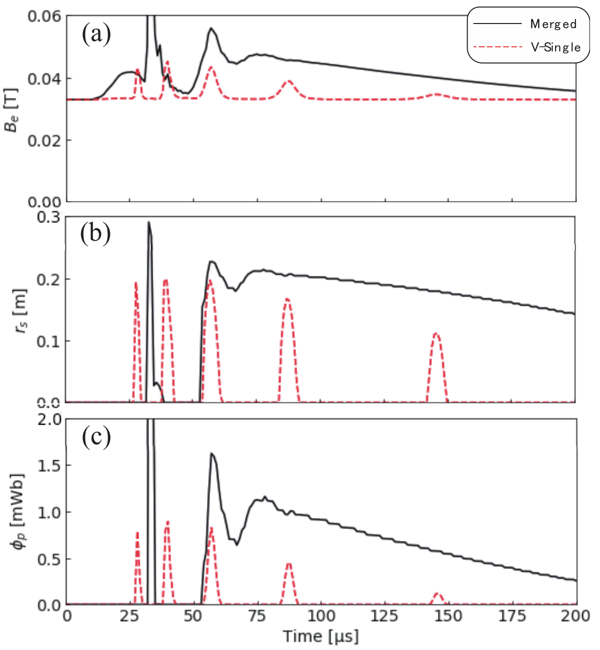

Fig. 3 Comparison of the single translated and merged FRCs in 2D MHD simulations; showing time evolutions of (a) external field B_e, (b) separatrix radius r_s, and (c) estimated poloidal flux φ_p.

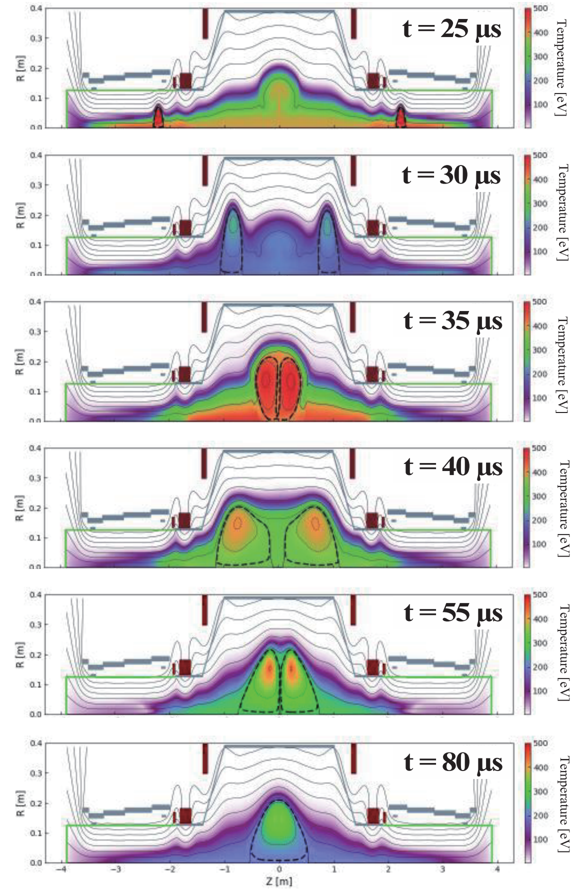

Fig. 4 Simulation of FRC formation, translation and collisional merging dynamics for the experimental condition. Solid line shows flux surface and color contour represents total temperature ($T = T_i + T_e$).

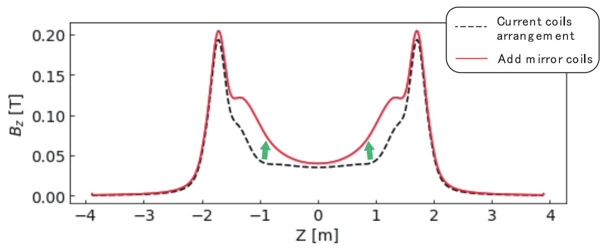

Fig. 5 Axial confinement magnetic field profile. Black dashed line is the field profile of current coil arrangement (same as Fig. 4), and red solid line shows the profile with an additional set of mirror coils.

experimental results: separatrix radius ~ 0.23 m, electron density ~ 1×10^{20} m^{-3}, and translated velocity in the confinement region ~ 200 km/s. The separatrix radius is directly obtained from the simulation output and the trapped poloidal flux is estimated using the same method as experiments, assuming RR profile. In the simulation, the single translated FRC bounces off four times as indicated in pulsating separatrix radius (Fig. 3 (b)) but the pulsating peak is not observed in the experiments (Fig. 2 (b)). The simulation is more ideal than the experiment; thus the simulation does not perfectly describe the experiments. Collided FRCs bounce off each other once at the midplane and two separate FRCs reflect at the magnetic mirror end. Finally, merged FRC is formed through a second collision of FRCs (Fig. 3 and Fig. 4). Collisional merging of FRC have advantage in point of suppressing the bouncing. The bouncing is observed clearly.

The separatrix radius is larger than the experimental result, thereby the estimated poloidal flux is overestimated. In contract, the estimated poloidal flux of merged FRC is almost equal to the experiments. Moreover, the collided FRC shows an increase of the flux value (Fig. 3 (c)), as also seen in the experiments. Experimental results and numerical simulations agree that there is a significant increase in the excluded flux, which was also observed in the C-2 experiments [4, 5]. To confine the high-flux plasma, the confinement magnetic field structure of the FAT-CM device is not optimum because the trapped flux increased twofold. Therefore, appropriate confinement magnetic field structure for FRC merging is being verified by the simulation.

The simulation demonstrates dynamic process of FRC formation, translation, and collisional merging, as shown in Fig. 4. Formed FRCs are ejected out from the formation regions at ~ 30 μs, FRCs collide at ~ 35 μs in the confinement chamber after translation, but the collided FRCs are immediately bounced off each other remaining as two separate FRCs; therefore, it is conceivable that the separated plasmas interact with the chamber wall, and it potentially deteriorates confinement performance. After bouncing at the mirror end, FRCs are collided again. Finally, merged FRC is formed at 80 μs. The structure of confinement magnetic field, as depicted in black dashed line of Fig. 5, may

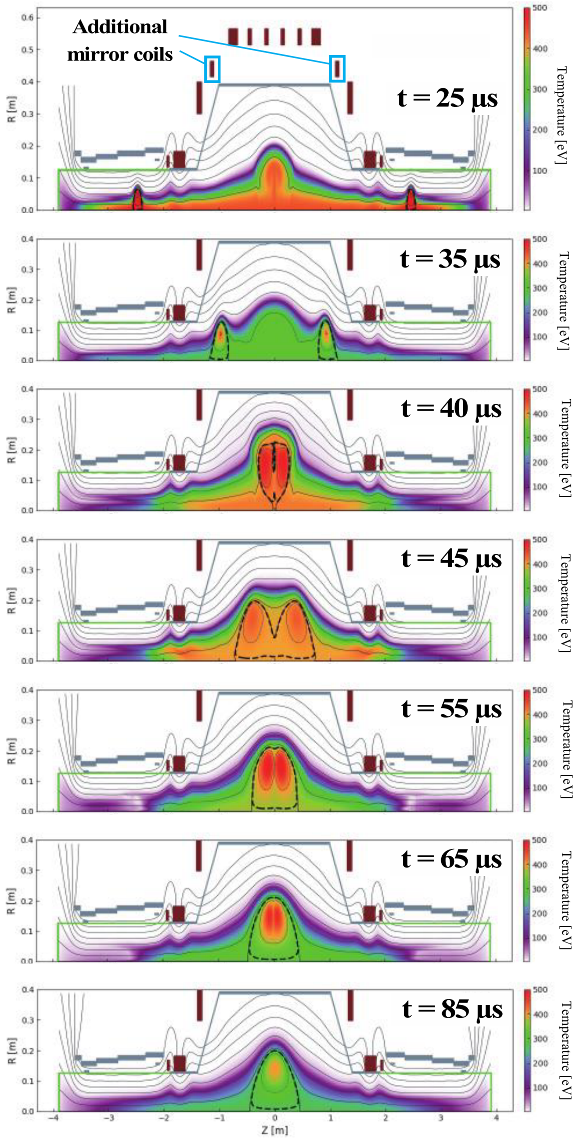

Fig. 6 Simulation result with an additional set of mirror coils, as shown in Fig. 5, clearly affecting FRC merging dynamics.

have inadequate field profile for effective FRC merging so that the collided FRCs do not merge but rather bouncing off axially.

To improve the FRC merging, a set of mirror coils is added at $z = \pm 1.13$ m in the simulation, whose field profile is shown in the red line of Fig. 5. The magnetic field gradient is increased towards the central confinement region. Figure 6 shows the simulation results of FRC dynamics using the modified magnetic profile by the additional mirror coils. In this case, the collided FRC does not bounce off completely unlike the case shown in Fig. 4; more importantly, merged FRC is successfully formed at 85 μs in the simulation without the bouncing and the merged FRC clearly have higher temperature. These simulation results suggest that the additional mirror coils shall help merging process of FRC's and may improve confinement property.

5. Summary

FRC collisional merging experiments have been started in FAT-CM. Experimental results and numerical simulations agree that there is a significant increase in the excluded flux of the merged FRC, compared to the single translated FRC. The simulation indicates that this increase is due to an efficient conversion of the translating FRC kinetic energy into the merged FRC thermal energy; it is similar to what was observed in C-2. The simulation also indicates that the structure of the confinement magnetic field is important for the merging process of FRCs, and final merged FRC state with higher temperature was successfully obtained by the additional mirror coils in the simulation.

Acknowledgements

The authors gratefully acknowledge the work of past and present member of our laboratory. This work was partially supported by JSPS KAKENHI Grant Number 16K06939.

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