COLLISIONAL MERGING OF A FIELD-REVERSED CONFIGURATION IN THE FAT-CM DEVICE

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Abstract

The collisional merging experiments of field-reversed configurations (FRCs) at super Alfvénic velocity have been successfully initiated in the FAT-CM device at Nihon University. A drastic increase of the excluded flux leading to the improved confinement performance of FRC has been observed. This process has an important role in realizing an FRC based high-beta reactor core to capture high-energy beam ions, and it has been clearly observed by magnetic diagnostics of excluded flux and internal probe array. The experimental results are compared with two-dimensional MHD simulation results computed for the typical conditions of the FAT-CM experiments. In order to investigate the collisional merging process of an FRC at super Alfvénic velocity, the FAT device has recently been upgraded to FAT-CM, consisting of two field-reversed theta-pinch (FRTP) formation sections and a central confinement section. Collisional merging of the two separately translated FRCs causes a conversion of the kinetic energy to mostly thermal ion energy, which contrasts with the spheromak merging dominated by magnetic energy, resulting in an increase of the ion pressure that drastically expands the FRC volume. The confinement chamber of FAT-CM device is made of stainless steel (inner bore of 0.78m) serving as a flux conserver in the timescale of the translation and merging process. Quasi-static confinement coils (inner diameter of 1.03m) are placed along the confinement region. Initial FRCs are formed by the FRTP method in two formation sections. The initial FRCs are accelerated by the gradient of the external guide magnetic field and then injected into the confinement chamber. The translated FRCs collide in the middle of the confinement chamber at the relative velocity in the range of 300 - 400 km/s. During collisional merging, radial expansion of the plasma is clearly observed and the plasma size, in the quasi-equilibrium phase, the size increases more than twofold compared with the single translation case. The averaged electron density of the merged FRC is ~2.5 × 10²⁰/m³, which is ten times higher than the previous experiments performed in a C-2U device at TAE. The shape of the simulated FRC agrees with experimental results. This also indicates a successful merging of the FRCs and results in radial expansion and excluded flux increase due to the collisional merging, as observed in experiments.

1. INTRODUCTION

A field-reversed configuration (FRC) is a compact toroid which has the highest beta value (\(\beta > -1\)) among magnetically confined fusion systems [1]. Because of its high beta nature and simply-connected geometry, sustainment of FRC had not been realized because of the limitation of additional heating and current drive. The FRC, therefore, has been studied mostly for the formation technique of high-density magnetized plasmas as, for example, the target of magnetized target fusion [2]. Recently, high confinement performance of FRCs have been achieved on a C-2/C-2U device via collisional-merging, i.e. the kinetic energy of translation is larger than the thermal and magnetic energy of the plasmons being merged, process with large orbit high energy ions fed by neutral beam injection (NBI) [3]. However, details of the collisional-merging process at super Alfvénic velocity, such as rethermalization from kinetic to ion energy, details have not been investigated.
In order to investigate the collisional-merging process of FRC at super Alfvénic velocity, the FAT (FRC Amplification via Translation) device at Nihon University [4] has recently been upgraded to a FAT-CM (Collisional Merging), consisting of two field-reversed theta-pinch (FRTP) formation sections and the central confinement section [5]. Collisional-merging of the two separately translated FRCs causes a conversion of the kinetic energy to mostly thermal ion energy, which contrasts with the spheromak merging dominated by magnetic energy [6], resulting in an increase of the ion pressure that drastically expands the FRC radius and volume. This process has an important role in realizing an FRC based high-beta reactor core to capture high-energy beam ions while it is keeping its high-beta nature and simply-connected geometry.

In this work, expanded radius and volume have been clearly observed by magnetic diagnostics of excluded flux and internal probe arrays in the FAT-CM device. Other important plasma parameters, such as electron density and ion temperature have also been observed. The experimental results are compared with the numerical simulation results by two-dimensional (2D) resistive magnetohydrodynamics (MHD) code: Lamy Ridge [7] for better understanding of the dynamics of formation, translation and collisional merging processes.

### 2. EXPERIMENTAL DEVICE

Figure 1 shows a schematic diagram of the FAT-CM device and its external guide magnetic field profile. The device consists of the central confinement chamber and two FRTP formation sections, called “R-formation” and “V-formation”, respectively. The formation tubes are made of transparent quartz and the confinement chamber is made of stainless steel (inner bore is 0.78m; skin time ~5 ms) serving as a flux conserver in the timescale of the translation, collision and merging process. Quasi-static confinement magnetic field coils (inner diameter of 1.03m) are placed along the confinement region. Initial FRCs are formed by the FRTP method in two formation sections with D2 gas-puffing.

**FIG.1. Schematic view of the experimental device FAT-CM consisting of two FRTP formation sections and central confinement section (top) and axial profile of the external guide magnetic field.**

In the typical FAT-CM operation, an FRC, which has ~$1\times10^{21}$ m$^{-3}$ of electron density, is generated by the main compression field of ~0.40 T. The one-turn theta-pinch coil in each formation section consists of coil elements which have 4 different diameters of 36, 34, 32, and 30 cm. The taper angle can be changed by the combination of coil elements. The maximum taper angle is about 1degree. The initial FRCs, ~0.06 m in radius and ~1.0 m in length with 0.4~0.5 mWb of trapped magnetic flux, are accelerated by the gradient of the external guide magnetic field formed by the tapered theta-pinch coil and then injected into the confinement chamber. The translated FRCs collide in the middle of the confinement chamber at the relative velocity in the range of 200~500 km/s at around $t \sim 50$ µs from the main reversal. To globally investigate and characterize the dynamics of the FRC formation, translation and collisional-merging process, a number of in-/ex-vessel magnetic probes and optical measurements are installed along the device [8, 9].

A two-dimensional internal magnetic probe array is installed in the FAT-CM device. The two-axis probe array consists of 32 hand-wound pickup coils: 16 coils in each of the $z$ and $\theta$ directions (for $B_z$ and $B_\theta$ measurements), spaced 3 cm apart. Therefore, the probe array covers a total of 45 cm in space as shown in Fig. 2. The L/R penetration time for both $B_z$ and $B_\theta$ fields is less than 0.1 µs. As a plasma facing material and electrical insulation
of the probe housing, AX05 grade boron-nitride jackets (OD ~6.35 mm) are mounted. Figure 2 illustrates the probe assembly installed in the mid-plane of the FAT-CM confinement vessel. With the long actuator and the probe housing, the probe array passes the center of the confinement vessel (r = 0) and can be fully retracted outside the vessel wall whose radius (r_w) is ~39 cm.

![Diagram](image)

**FIG. 2. Illustration of a cross-sectional view of the installed probe assembly with probe locations (marked as red dots) in the mid-plane of the FAT-CM device.**

3. EXPERIMENTAL RESULTS

Figure 3 shows the time evolution of plasma parameters of both single and collisional merging FRCs in the FAT-CM device. The estimated excluded flux radius \( r_{\Delta \phi} \) at mid-plane, which is shown in Fig 3(a),

\[
r_{\Delta \phi} = r_{w} \sqrt{1 - \frac{B_{0}}{B_{e}}}
\]

(1)

is known to be comparable to the separatrix radius reflecting the poloidal flux for ideal FRC equilibrium with negligibly small plasma pressure in the scrape-off layer. Where, \( r_{w} \) is the radius of the metal confinement chamber (r ~0.4 m), \( B_{0} \) is the magnetic field in vacuum, and \( B_{e} \) is the external magnetic field. Figure 3(b) shows the estimated poloidal magnetic flux \( \Phi_{\phi} \)

\[
\Phi_{\phi_{\text{eq}}} = 0.31 \pi B_{e} r_{\Delta \phi} / r_{w}
\]

(2)

assuming the rigid-rotor (RR) equilibrium model [10] that is consistent with the internal field measurements for translated FRCs [11]. Both plasma radius \( r_{\Delta \phi} \) and poloidal flux \( \Phi_{\phi} \) are estimated using B-dot probes near the mid-plane, and line-integrated electron density is measured by a He-Ne laser interferometer system in the mid-plane of the confinement chamber. Figure 3 only shows one single-sided FRC case because the global behavior/performance of each FRC from the R- and V-formations are quite similar.

In the case of single-sided FRC formation/translation (red dashed lines in Fig. 3), the FRC is typically accelerated and ejected at a speed of 150–200 km/s into the confinement region; the FRC is then decelerated and bounces back-and-forth between the mirror regions. In the case of collisional-merging FRCs (black solid lines in Fig. 3), radial expansion of the plasma is clearly observed and the plasma size, in the quasi-equilibrium phase, increases more than twofold compared with the single translation case as observed and discussed in the C-2/C-2U experiment at TAE [12]. The averaged electron density \( \langle n_{e} \rangle \) of the merged FRC, \( \sim 2.5 \times 10^{20} \text{ m}^{-3} \), is ten times higher than the C-2U FRC (Fig.3(c)). The oscillating signal on the line-integrated electron density of merged FRC (#1736) in Fig. 3(c) represents the rotational instability with toroidal mode number \( n = 2 \), which is typically observed in FRC plasmas without stabilization.
This apparent increase in the plasma radius (diamagnetic signal) is due to a thermalization of the collisional-merging FRCs, in which the kinetic energy of the translated FRCs (relative speed up to ~400 km/s) gets converted into thermal energy by the collisional merging process, as also seen in C-2 experiments [12].

FIG. 3. Time evolutions of (a) excluded flux radius $r_{ef}$ (b) trapped poloidal flux and (c) line-integrated electron density. The hatched area indicates standard deviation.

In order to investigate internal magnetic field structures of FRC plasmas for typical collisional-merging FRCs, the internal magnetic probe array is inserted into the FRC as illustrated in Fig. 2. The FRC plasma is translated through the probe array and its $B_z$ profile clearly exhibits a field-reversed structure during the first pass of the translation ($t \approx 35$–$50$ µs). The FRC then bounces off the mirror region of the confinement section, and then the second pass of the FRC is also observed at around $t \approx 75$ µs.

FIG. 4. Contour maps of magnetic-fields ($B_z$ and $B_t$) radial profiles as a function of time in the collisional-merging FRC plasma, measured by the internal magnetic probe array in the FAT-CM mid-plane.
Figure 4 shows the contour maps of the poloidal and toroidal magnetic field evolution measured by the internal magnetic probe array in the mid-plane of the FAT-CM device. As shown in Fig. 4, clear field-reversed structures of the $B_z$ profiles are successfully observed in the quiescent equilibrium phase. However, FRC performance and lifetime are obviously affected by the presence of the invasive internal probe array. The configuration lifetime was shortened to ~150 μs compared with ~300 μs in the longer-lived FRC without internal probe array. In the collisional-merging FRC, each of the two-translated plasmoids appears to carry significant toroidal magnetic fields with opposite helicity, and the strong $B_z$ observed during the collisional-merging process still remains at the quiescent phase of the merged FRC.

Figure 5 shows the radial profile of axial magnetic field at the midplane measured by the internal probe array. The observed poloidal magnetic profile clearly shows the field-reversal. The inflection point of the profile at $r = 0.2 m$ approximately agrees with $r_{\Delta \phi}$. An RR model is a well-known and adequate profile model for the magnetic field and density of FRCs in the equilibrium phase as well as for the translated plasmoid. The poloidal flux ($\phi_p$) of the FRC can be approximately estimated from the excluded flux measurement with the RR model, expressed as Eq. (2). By contrast, a direct measurement of the magnetic field profile yields a relatively simple poloidal flux estimation as

\[
\phi_p = -\frac{r_s}{R} \int_0^R 2 \pi r B_z dr = \frac{r_s}{R} \int_0^r 2 \pi r B_z dr.
\]

where, $R$ is the radius of magnetic field null point ($B_z = 0$), and $r_s$ is the separatrix radius of FRC that is approximately equal to the excluded flux radius $r_{\Delta \phi}$. In the ideal FRC, the poloidal flux amounts inside and outside $R$ are equal to each other. Using Eqs. (2) and (3) the poloidal flux inside the FRC can be estimated as: $\phi_p, RR \sim 1.5$ mWb and $\phi_p \sim 0.6$ mWb. The discrepancy between the two estimates could be due to the FRC radial shift/motion that is not properly taken into account, in particular the case when FRC is shifted perpendicularly away from the probe array.

4. MHD SIMULATIONS

Figure 6 shows contour maps of electron density computed by the 2D resistive MHD code for the typical conditions of the FAT-CM experiments. The shape of the simulated FRC approximately agrees with the experimental results: separatrix radius ~0.23 m, and translated velocity in the confinement region ~200 km/s (relative velocity ~400 km/s). Collided FRCs bounce off each other once at the midplane and two separate FRCs reflect at the magnetic mirrors. Finally, merged FRC is formed through a second collision process of FRCs. Collisional-merging of FRC has an advantage in point of suppressing the bouncing and reduces axial asymmetry compared to single-sided translation. Reduced expansion at the downstream mirror enables us to install in vessel antennas for wave excitation [13].
FIG. 6. Two dimensional MHD simulation, indicating collisional merging process of FRCs in the typical condition of FAT-CM experiments.

5. SUMMARY

The collisional merging experiments of FRCs at super Alfvénic velocity have been successfully initiated in the FAT-CM device. A drastic increase of the excluded flux leading to the improved confinement performance of the FRC, has been observed, as also seen in the C-2/C-2U. This indicates a successful merging of the FRCs and results in radial expansion and excluded flux increase due to the collisional-merging process, as observed in experiments. The MHD simulation also indicates that the increased volume is due to an efficient conversion of the translating FRC kinetic energy into the merged FRC thermal energy.

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