Improvement of Plasmoid Acceleration Performance by Increased Magnetic Pressure Gradient for High-Mach Number Shock Generation*)

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The field-reversed configuration (FRC) collisional merging experiment in the FAT-CM device at Nihon University has been conducted for the generation of collisionless shock waves that are considered to cause the generation of nonthermal particles. Two FRC-like plasmoids with extremely high-beta formed by field-reversed theta-pinch are translated directly toward each other and collide at super-sonic/Alfvénic velocity. The acceleration performance is improved to generate high-Mach number shocks by generating the high-magnetic pressure gradient at the boundary between the formation and confinement sections. In this study, an increase in the translation velocity in the shortened coil geometry is presented. Changing of coil geometry may affect not only the velocity but also other parameters.

Keywords: collisionless shock, high-Mach number, field-reversed configuration, high-beta plasma, acceleration

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1. Introduction

Collisionless shockwaves are known to occur in low-density/high-temperature cosmic plasmas [1]. Collisions between particles rarely occur in these shockwaves, and energy is dissipated through electromagnetic interactions. This process may contribute to the generation of high-energy particles such as cosmic rays [2]. Fermi acceleration is thought to be the production mechanism of these high-energy particles which are generated in astrophysical shock waves. Although research on the mechanism of this phenomenon is still actively conducted, the research methods are mostly limited to simulations and astronomical observations. Moreover, expansion of experimental approaches is required.

Experimental research on the high-Mach number shock in laboratory experiments has been performed using intense lasers [3]. Intense lasers sublimate metal foils, and the resulting shockwave is formed by the collision of the generated plasma flow.

Another experimental research method that has been proposed is collisionless shock generation using field-reversed configurations (FRCs) collision [4]. This FRC collision experiment has been conducted in the FRC Amplification via Translation-Collisional Merging (FAT-CM) device at Nihon University [5]. Two FRC-like plasmoids generated by the field-reversed theta-pinch method are accelerated up to super-Alfvénic/sonic relative velocity and collide with each other. The experimental conditions mast be expanded to simulate high-Mach number collisionless shockwaves in supernova remnants.

This study focuses on the improvement of acceleration performance for the generation of high-Mach number shockwaves. Super-sonic/Alfvén translation of an FRC-like plasmoid has been observed in previous experiments [6]. The plasmoids are accelerated by the magnetic pressure gradient. In this study, improved acceleration performance is verified in the case of the single (one side) translations by increasing the magnetic pressure in the formation section, as shown in Fig. 1. To increase coil current density and apply high-magnetic pressure in the formation section, the theta-pinch coil length is reduced. This change was conducted to simulate high-Mach number shocks in a supernova remnant where its expansion velocity achieves several thousand kilometers per second.

The details of the FRC acceleration and FAT-CM device are explained in the next section. Improvement of acceleration performance by application of high-magnetic pressure gradient will be explained in Section 3. Section 4 describes the results of this experiment.

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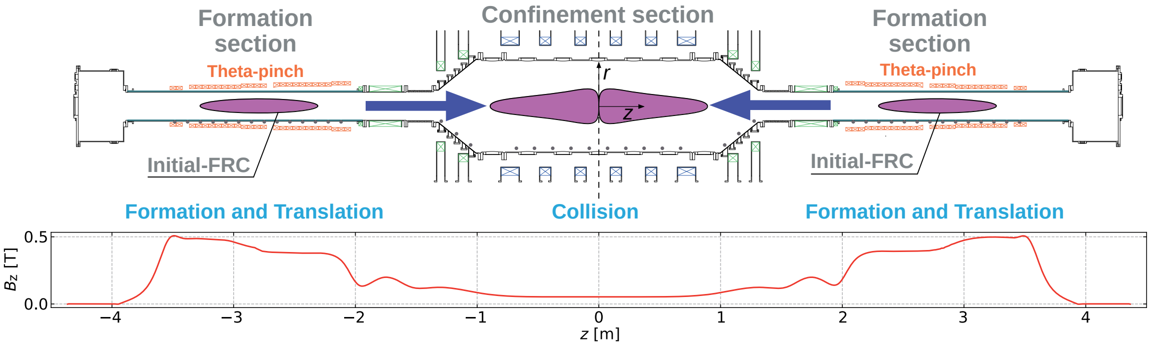

Fig. 1 Schematic of FAT-CM device and axial magnetic field profile.

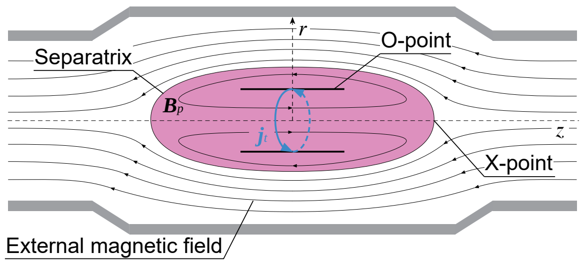

Fig. 2 Schematic of field-reversed configuration.

2. FRC Acceleration in FAT-CM Device

An FRC, as shown in Fig. 2, is an extremely high-beta compact toroid that only has a poloidal field with toroidal current [7,8]. The beta value inside of an FRC, except near the edge of the separatrix, is over unity. As the inside of an FRC is only slightly magnetized, the Larmor radius inside of the separatrix exceeds the separatrix radius. The closed magnetic fields localized in the separatrix region behave as an MHD container, with the population of unmagnetized plasma particles being confined inside the separatrix radius [6]. FRCs that have this characteristic can be translated in the axial direction because there are no structures at the center of the plasma in the FRC configuration.

Figure 1 is the schematic of the FAT-CM device at Nihon University and shows the axial profile, z-direction, of the magnetic field B_z. This device has one confinement section at the center and two formation sections, one at each end. The formation sections consist of a quartz tube and the conical theta-pinch coils, which are comprised of a set of one-turn coils, connected in parallel to the discharge circuit. These coils are lined up in the axial direction to produce a magnetic field of ~0.5 T. At the confinement section, multi-turn coils on the outside of a stainless-steel chamber provide a quasi-static confinement magnetic field of ~0.06 T. Deuterium gas is puffed from solenoid valves on both ends of the device and used for plasma generation. FRC-like plasmoids are generated by the field-reversed theta-pinch method in each of the formation sections [9]. The difference in magnetic pressure between the formation and confinement section is crucial to the high-Mach translation. The translation velocity exceeds Alfvén and ion sonic velocity when a plasmoid reaches the confinement section [6]. The translation velocity at the confinement section is 100 - 200 km/s in standard operation.

3. Applying a High-Magnetic Pressure Gradient

The axial direction difference of external magnetic field pressure accelerates the FRC-like plasmoids. The axial magnetic pressure is unbalanced in the FAT-CM device; the magnetic pressure in the formation section is higher than that in the confinement section. Therefore, the plasmoids are accelerated toward the confinement section from the formation sections. The kinetic energy of an accelerated plasmoid is described as follows:

$$\int \frac{1}{2}\rho {v_0}^2 dV + \int \frac{\Delta B^2}{2\mu_0} dV = \int \frac{1}{2}\rho (v_0 + \Delta v)^2 dV, \tag{1}$$

where ρ, v_0, V, ΔB, and Δv are the mass density, initial velocity, plasmoid volume, magnetic field gradient, and velocity increment, respectively.

Improvement of acceleration performance by applying a high magnetic pressure is evaluated using three configurations of theta-pinch coil geometry, namely, 26, 21, and 18 coils. The set of theta-pinch coils consists of one-turn coils connected in parallel. When shortening the coil geometry by removing coils, the current density of each remaining coil is increased, and higher magnetic pressure is applied. Figure 3 shows the external magnetic field profile in the cases of the 26, 21, and 18 coil geometries. The set of 26 coils generates the magnetic pressure gradient at the formation section in standard operation. To apply high magnetic pressure, theta-pinch coils are removed from the end of the formation section. Figure 4 indicates the time evolution of the magnetic field in the formation section. In the case of 18 coils, the magnitude of the main magnetic field reversal, when the FRC formation and translation begins (t = 0), increases by approximately 34% compared with that during standard operation (26 coils).

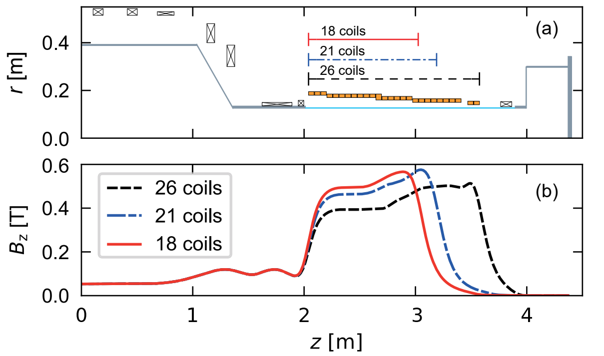

Fig. 3 (a) Axial location of theta-pinch coils, and (b) axial magnetic field profile.

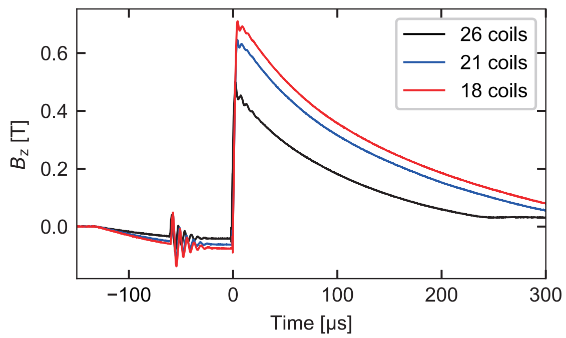

Fig. 4 Time evolution of the axial magnetic field in the formation section in the 26, 21, and 18 coil geometries.

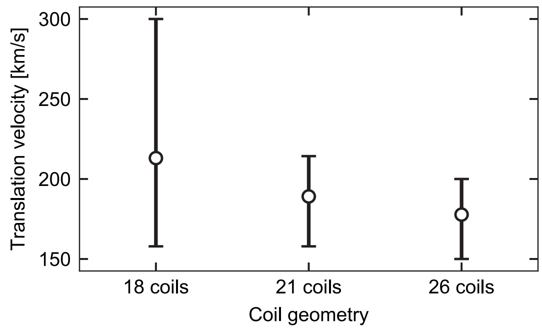

Fig. 5 Comparison of translation velocity in the 26, 21 and 18 coils geometries.

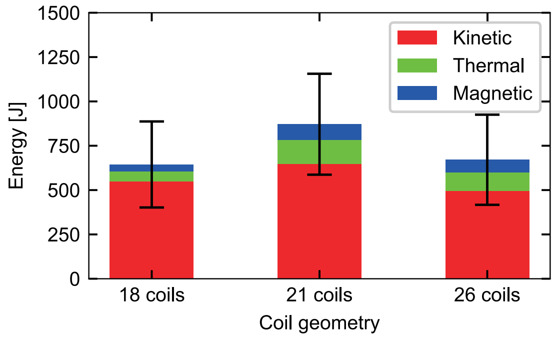

Fig. 6 Total energy in the 26, 21 and 18 coils geometries.

4. Experimental Results

4.1 Translation velocity

Translation velocity in each of the 26, 21, and 18 coils geometries is estimated by the peak timing of the excluded magnetic flux measured by axially arranged magnetic probes in the confinement section.

Figure 5 indicates the translation velocity averaged over several shots in each coil geometry. The error bars represent the minimum and maximum velocity observed. In the case of 18 coils, the translation velocity averaged over 23 shots is up to 20% higher than the average of 26 coils. The maximum velocity reached 300 km/s and the relative velocity was 600 km/s. Translation velocity was successfully increased by applying the high-magnetic pressure gradient.

The dispersion of velocity in the case of 18 coils is larger than that of the other cases. The theta-pinch coils were removed from the end without changing the arrangement to simplify the evaluation of the dependence of the magnetic pressure gradient, and the distance between the gas puff valves and the formation region became longer. Because of the long gas diffusion time, there is the possibility that the location where the plasmoids were generated was not sufficiently consistent within the shots for the 18 coils case.

4.2 Energy of a plasmoid

The radial plasma pressure of a prolate FRC balances with external magnetic pressure. The internal magnetic energy of an FRC can be estimated as Nk_BT_{total} [10]. Here T_{total} is the sum of ion and electron temperature. The total energy E_{total} of a translated plasmoid with the velocity v is,

$$E_{total} = \frac{3}{2}Nk_BT_{total} + Nk_BT_{total} + \frac{1}{2}Nm_iv^2, \qquad (2)$$

where N, k_B, and m_i are total particle inventory, Boltzmann's constant, and ion mass respectively. The sum of the first and second terms is the internal energy (thermal energy + magnetic energy); the third term is the kinetic energy of a translated plasmoid [11].

The averaged total energy of each coil geometry case estimated from Eq. 2 is shown in Fig. 6. In the case of 18 coils, the contribution of kinetic energy to total energy is larger than that of the 26 coils case. The amount of total energy in the case of 21 coils is larger than that in the other cases. Since the theta-pinch coils act both for the plasmoid generation and translation, changing the theta-pinch coil geometry affects not only the translation velocity but also pre-ionization and the amount of poloidal flux. For one example, the thermal energy of 21 coils is the largest in these results as shown in Fig. 6. The shortened coil geometry formed a smaller plasmoid. However, it seems these changes did not depend only on coil geometry length.

Table 1 Comparison of translation velocity in the experiment and MHD simulation.

	Experiment	MHD simulation		
Coil geometry	Averaged translation Velocity [km/s]	Translation velocity [km/s]	Alfvén Mach number	Ion Mach number
26 coils	178	128	3	1.3
21 coils	189	205	9	1.5
18 coils	213	217	10	1.7

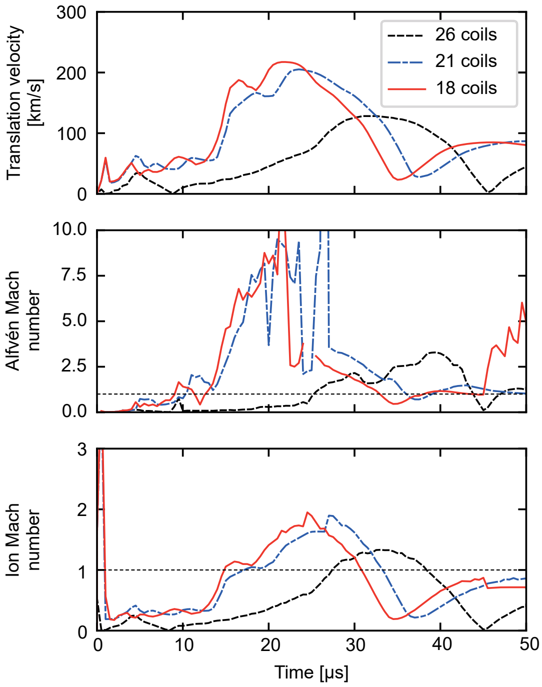

Fig. 7 Computed translation velocity and Alfvén/ion Mach number from MHD simulation.

4.3 Mach number during the translation

Alfvén and ion Mach numbers are the ratios of the translation velocity of the plasmoid to either the Alfvén or ion sonic velocity. In this study the Alfvén Mach number and ion Mach number are calculated using Alfvén velocity and ion sonic velocity obtained from MHD simulation. Figure 7 indicates the observed translation velocity and corresponding Alfvén and ion Mach numbers in the case of the 26, 21, and 18 coil geometries. When the translation velocity is at its maximum in each case, both Mach numbers are over unity. However, the timing of the maximum translation velocity in each case is not the same because the time that the plasmoid takes to reach the confinement region is different in each case. In the case of 18 and 21 coils, both Mach numbers increase compared with the 26 coils case.

Table 1 is a comparison of experimental results and MHD simulation values. The Alfvén Mach number from the simulation is increased to ~10 in the 18 coils case. In contrast, the ion Mach number remains in the same range in each case. Although Mach numbers are calculated with absolute translation velocity here, considering the relative velocity in the FRC collision, these Mach numbers are effectively doubled. In each case, the averaged translation velocity from the experiment is in the same range as the simulation. These results suggest the possibility of high-Mach number shock generation in future FRC collision experiments.

5. Summary

The FRC collision experiment has been conducted to generate collisionless shocks. Higher magnetic pressure gradients increase translation velocity. The maximum velocity reaches 300 km/s in the case of 18 coils. Both Alfvén and ion Mach numbers increase in the short coil length geometry. This acceleration technique successfully expands the experimental range for high-Mach number shock generation in the FAT-CM. To improve acceleration performance further, optimizing the theta-pinch coil geometry and discharge condition is required.

Acknowledgments

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[1] A.S. Novo, A. Bret, R.A. Fonseca and L.O. Silva, Plasma Phys. Control. Fusion **58**, 014005 (2015).
[2] A. Bamba, R. Yamazaki, M. Ueno and K. Koyama, Astrophys. J. **589**, 827 (2003).
[3] Y. Kuramitsu, Y. Sakawa, S. Dono, C.D. Gregory, S.A. Pikuz *et al.*, Phys. Rev. Lett. **108**, 195004 (2012).
[4] T. Asai, D. Kobayashi, T. Seki, Y. Tamura, T. Watanabe *et al.*, Nucl. Fusion **61**, 096032 (2021).
[5] T. Asai, T. Takahashi, J. Sekiguchi, D. Kobayashi, S. Okada, H. Gota, T. Roche, M. Inomoto, S. Dettrick, Y. Mok *et al.*, Nucl. Fusion **59**, 056024 (2019).
[6] D. Kobayashi and T. Asai, Phys. Plasmas **28**, 022101 (2021).
[7] M. Tuszewski, Nucl. Fusion **28**, 2033 (1988).
[8] L.C. Steinhauer, Phys. Plasmas **18**, 070501 (2011).
[9] Y. Ohkuma, M. Urano, M. Nakamura, Y. Narushima, T. Takahashi *et al.*, Nucl. Fusion **38**, 1501 (1998).
[10] D.J. Rej, W.T. Armstrong, R.E. Chrien, P.L. Klingner, R.K. Linford *et al.*, Phys. Fluids **29**, 852 (1986).
[11] D. Kobayashi, T. Asai, T. Takahashi, A. Tatsumi, N. Sahara *et al.*, Plasma Fusion Res. **16**, 2402050 (2021).