IAC

Self-Organized FRC Formation in Mirror Field Orthogonal to the Axis of Counter-Injected Plasmoids

T. Asai[1,2], T. Takahashi[1], Y. Miyamoto[2], Y. Takeuchi[1], R. Kikuchi[1], D. Kobayashi[1], T. Seki[1,2], T. Takahashi[3], M. Inomoto[4], Y. Kishimoto[5], N. Mizuguchi[6], M. Mizuguchi[2], and M. Sakamoto[2,7]

[1] College of Science and Technology, Nihon University, Tokyo 101-8308, Japan
[2] LINEA Innovations, Inc., Tokyo 106-6115, Japan
[3] Graduate School of Engineering, Gunma University, Gunma 376-0052, Japan
[4] Graduate School of Frontier Sciences, The University of Tokyo, Chiba 277-8561, Japan
[5] Graduate School of Energy Science, Kyoto University, Kyoto 611-0011, Japan
[6] National Institute for Fusion Science, Gifu 509-5292, Japan
[7] Plasma Research Center, University of Tsukuba, Ibaraki 305-8577, Japan

e-mail: asai.tomohiko@nihon-u.ac.jp

A novel method for self-organized FRC formation using counter-injected plasmoids in a mirror field is investigated. This orthogonal scheme enables direct access to end regions for divertors and direct energy conversion (DEC), improving reactor integration

FRC plasmas, with high beta ($\beta \sim 1$), are promising reactor cores for advanced fusion such as p-^{11}B[1], but conventional FRC merging experiments face significant design and operational challenges[2,3]. In these setups, the end regions crucial for divertor connection and/or DEC are often occupied by formation sections, limiting design flexibility[2]. Furthermore, FRC equilibrium and stability are strongly influenced by the density and temperature of surrounding open field line regions, the so-called scrape-off layer (SOL) or halo regions, which are difficult to control due to these constraints.

To address these challenges, this study explores a novel approach in which two high-speed plasmoids are injected orthogonally into the mirror magnetic field. This configuration cancels their momentum upon collision, forming a high-density plasma region directly within the mirror field. If successful, this method not only resolves the limitations of conventional FRC setups but also enhances confinement and stability.

The experiment was conducted using the FAT-CM device at Nihon University, which generates FRCs via the field-reversed theta-pinch method[3]. These FRCs were accelerated to a relative velocity exceeding 300 km/s[4] and injected into a confinement region with mirror magnetic fields orthogonal to the injection axis, as illustrated in Fig. 1.

Unlike axial FRC merging, this orthogonal scheme frees both end regions, improving access for DEC and divertors while allowing direct plasma control. Conventional methods required remote placement or rapid

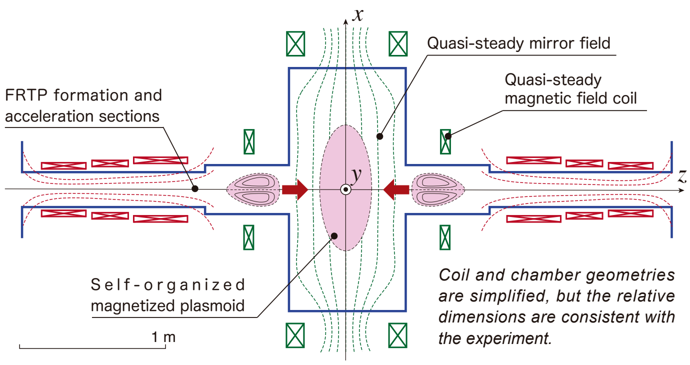

Fig.1 Schematic diagram of the FAT-CM device arranged for this experiment. The setup consists of two FRC formation sections and a confinement region with orthogonal mirror magnetic fields.

field switching. This approach also enables continuous or intermittent injection of additional FRCs.

The experiment revealed that plasmoids translated while rotating in the diamagnetic direction were observed to merge and spin up diamagnetically relative to the orthogonal mirror magnetic field after collision. Figure 2 shows plasma radius evolution, with an initial contraction followed by stable high-beta plasma formation. The plasmoid had an ion temperature of 100-200 eV and an electron density of $\sim 0.5 \times 10^{20}\ m^{-3}$. This dynamic reorganization indicates the formation of a high-beta plasmoid with a closed magnetic field structure distinct from that of simple mirrors (Fig. 2). The generated plasmoid was maintained for approximately 130 µs, more than 10 times longer than the diffusion time along magnetic field lines in a simple mirror configuration (11.2 µs, calculated for a mirror ratio of 2.9)[5]. A simple mirror confinement, even with optimistic assumptions, would not exceed 11.2 µs[5].

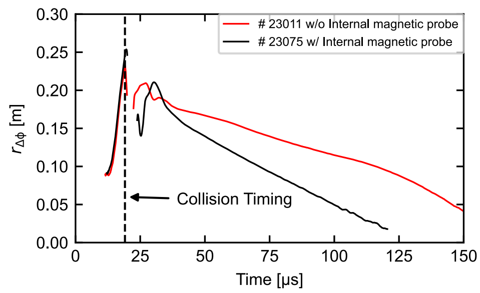

Fig.2 Time evolution of the plasmoid radius formed in an orthogonal mirror field. A stable high-density plasmoid (#23011) has a radius maintained over 130 µs, significantly exceeding the theoretical confinement time of a simple mirror configuration.

Though limited by the internal probe, Fig. 3 shows a sudden transition to a field-reversed configuration ~30 µs post-collision, supporting FRC formation. Initially perturbed, after 30 µs, a well-defined FRC emerges with two distinct poloidal field reversals, indicating self-organization.

Unlike conventional FRC setups, this method allows the end regions to remain accessible for additional functions such as a DEC, divertor systems, and/or advanced plasma control systems, offering new opportunities for optimizing FRC reactor design in linear magnetic field systems [2,3]. The observed self-organized formation of a high-beta plasmoid within a mirror magnetic field further enhances this flexibility, enabling better control of peripheral open field regions and facilitating the integration of advanced components such as DEC. The extended confinement time results from the FRC's closed magnetic field structure, which suppresses cross-field particle diffusion.

The 130 µs confinement time, though short for reactors, is tenfold that of a simple mirror and exceeds the MHD instability growth time (~10 µs), indicating a relaxed state. In the C-2 device (TAE Technologies), a stable seed FRC was sustained via neutral beam injection (NBI), demonstrating flexible reactor designs and marking a world-first achievement.

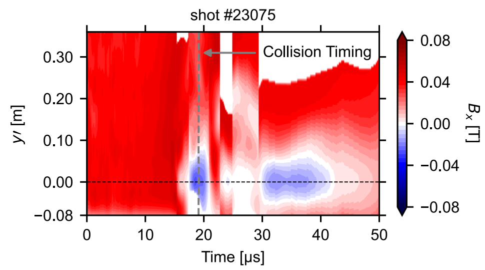

Fig.3 Time evolution of the poloidal magnetic field distribution measured by internal magnetic probes, presented as a contour plot.

REFERENCES

[1] R. Magee et al., Nat. Commun. **14**, 955 (2023)
[2] H. Gota et al., Nucl. Fusion **64**, 112014 (2024)
[3] T. Asai et al., Nucl. Fusion **64**, 096013 (2024).
[4] D. Kobayashi et al., Plasma Phys. Control. Fusion **66**, 065017 (2024).
[5] D.V. Sivukhin, Rev. Plasma Phys. **4**, 93 (1966).
[6] T. Asai et al., Phys. Plasmas **31**, 010703 (2024).
[7] R. Kikuchi et.al., Phys. Plasmas **32,** 010501 (2025).
[8] H. Gota et al., Nucl. Fusion **59**, 112009 (2019)