# Super-sonic/Alfvénic collision and merging of field-reversed configuration plasmas

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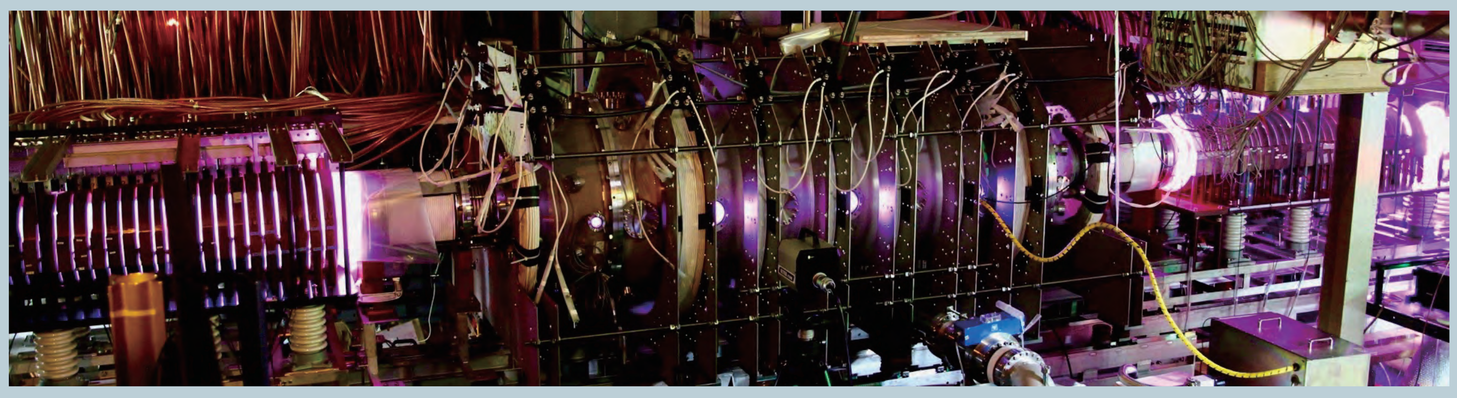
T. Asai[1], D. Kobayashi[1], T. Seki[1], Ts. Takahashi[1], N. Sahara[1], M. Nagata[1], Y. Nagayama[1], S. Okada[1], K. Iwamoto[1], H. Gota[2], R. Magee[2], T. Roche[2], S. Dettrick[2], Y. Mok[2], M. Tuszewski[2], M.W. Binderbauer[2], T. Tajima[3], T. Matsumoto[3], M. Inomoto[4], N. Mizuguchi[5], To. Takahashi[6], J. Morelli[7]

1) College of Science and Technology, Nihon University, Tokyo, Japan
2) TAE Technologies, Inc., California, USA
3) Department of Physics and Astronomy, University of California at Irvine
4) Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Japan
5) National Institute for Fusion Science, Toki, Japan
6) Graduate School of Engineering, Gunma University, Kiryu, Japan
7) Department of Physics, Engineering Physics & Astronomy, Queen's University at Kingston Canada


## Abstract

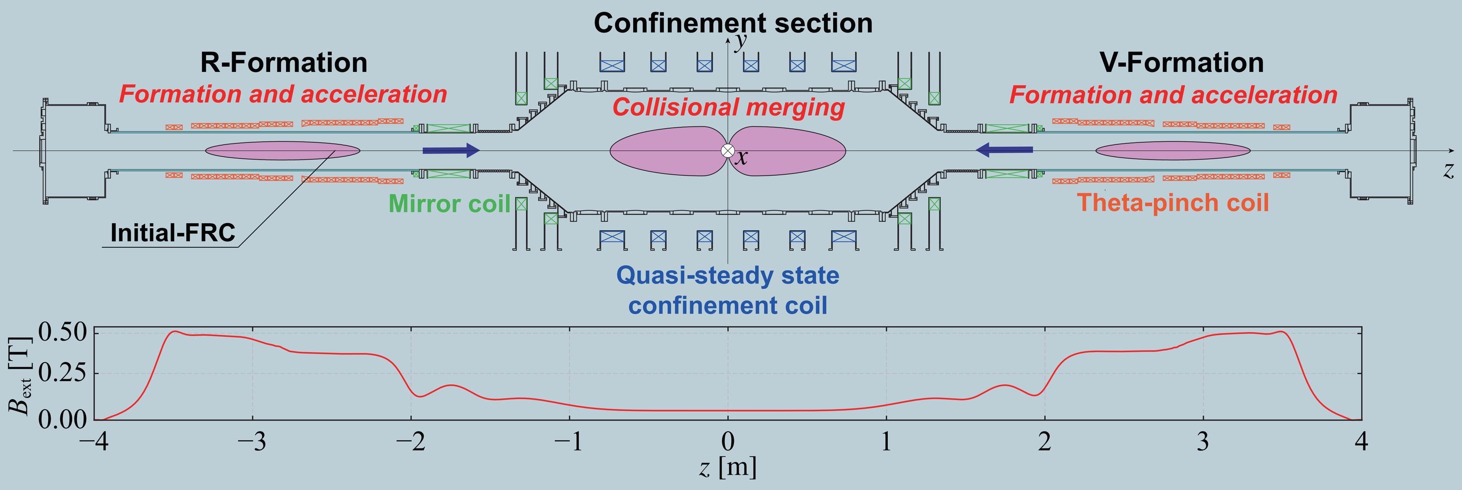

- A D-D fusion reaction during the super-Alfvénic collisional merging formation process of a field-reversed configuration (FRC) plasma has been detected by the developed fast response neutron detector in the FAT-CM device at Nihon University.
- The neutron radiation and its dependency on the translation velocity of FRC plasma have been observed as an experimental evidence of an excited shock heating in the collisional merging of the oppositely-translated FRCs. Two dimensional MHD simulation does not predict high enough ion temperature that produces fusion reaction, thus the observed significant amount of neutron radiation indicates the rapid acceleration of non-thermal ions through the excited shock as one of the regeneration channels from the kinetic to the internal thermal energy.
- Self-organized FRC formation has also been observed after the merged plasmoid experienced destructive disturbance during the supersonic collision and merging process. After the collision, the merged FRC lose its configuration and even toroidal rotation is not conserved. However, a magnetic configuration of FRC is self-organized within a few tens of microseconds after the impact.


## FAT-CM device



*The FAT-CM device at Plasma Physics Laboratory, Nihon University.*

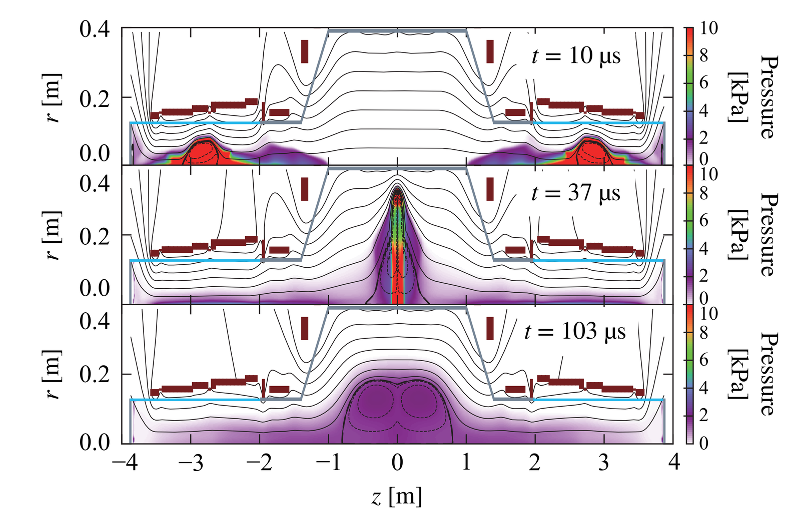
- The experiments had been conducted in the FAT-CM device. The device has a stainless-steel cylindrical confinement chamber of 0.8 m in diameter with quasi-steady state external magnetic field. Initial FRCs are formed by the field-reversed theta-pinch (FRTP) method with deuterium gas-puffing in the two formation sections connected at both ends of the confinement section.
- Initially formed FRCs with electron density of ~$1\times10^{21}$ $m^{-3}$ are typically generated by the main compression field of ~0.4 T, after which they are accelerated by the gradient of the external guide magnetic pressure. The translated FRCs collide in the middle of the confinement chamber at the relative velocity in the range of 200 – 400 km/s.



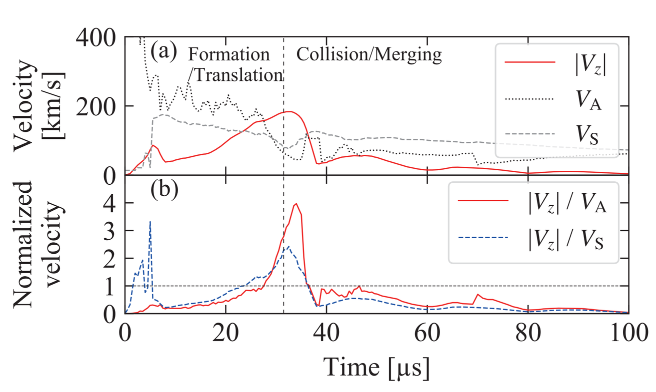

*Schematic view of the FAT-CM device and the axial profile of the external guide magnetic field.*

## Collisional Merging of FRCs

- The schematic of the collisional merging process is illustrated by two dimensional MHD simulation. FRCs formed in the formation region are accelerated immediately after the theta-pinch formation process. When the FRCs enter the formation section, they expand more than ten-fold in volume. The accelerated FRCs collide at around the midplane (z = 0) of the confinement chamber after which they reach quiescent equilibrium phase through the dynamic merging process.




*2-D MHD simulation indicating collisional merging process of FRCs. Two FRCs are accelerated into the confinement region and collide at mid-plane of the device.*

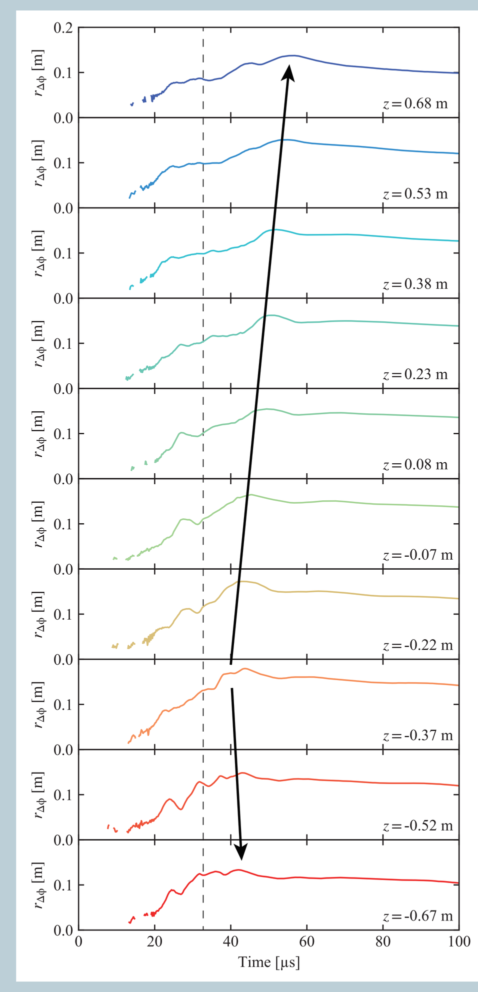



*(a) Time evolutions of translation $|V_z|$, Alfvénic $V_A$ and sound $V_s$ velocities from the MHD simulation. (b) Normalized value of $|V_z|$ by $V_A$ and $V_s$. Dashed vertical line denotes the timing when the whole FRC enters the confinement region.*

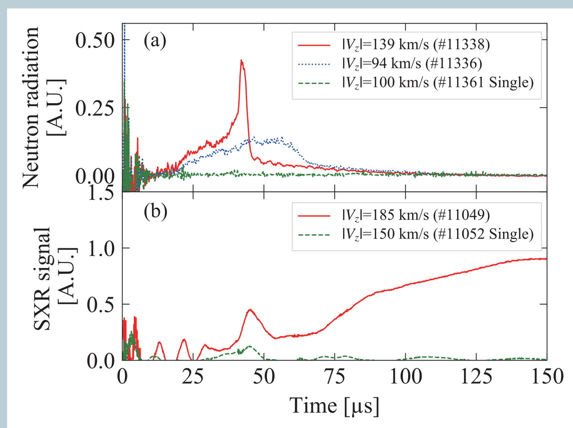
- The FRC in the formation region is accelerated by the external magnetic pressure up to $V_A$ and then translated into the confinement region while keeping the axial velocity.
- Therefore, the translation velocity exceeds $V_A$ and $V_S$ (typically ~50 and ~100 km/s, respectively) when FRC enters the confinement region.

## Shock Wave Excitation

- As the experimental evidence of the excited shock, neutron detection has been performed during and after the collisional merging process by the newly-built fast response neutron detector consisting of a columnar plastic scintillator and a photomultiplier tube.
- The neutron measurement indicates a quick rise of the neutron flux when FRC translation velocity is faster than the Alfven velocity as seen in red solid line. Here, blue dotted line denotes the collisional merging case with sub-Alfvén velocity, while green dashed line is single-sided FRC translation case without collision/merging.
- SXR radiation detected by a surface-barrier diode with 37.5 μm Be filter also shows a pulsed rise around t ~ 40 μs and following thermalization.



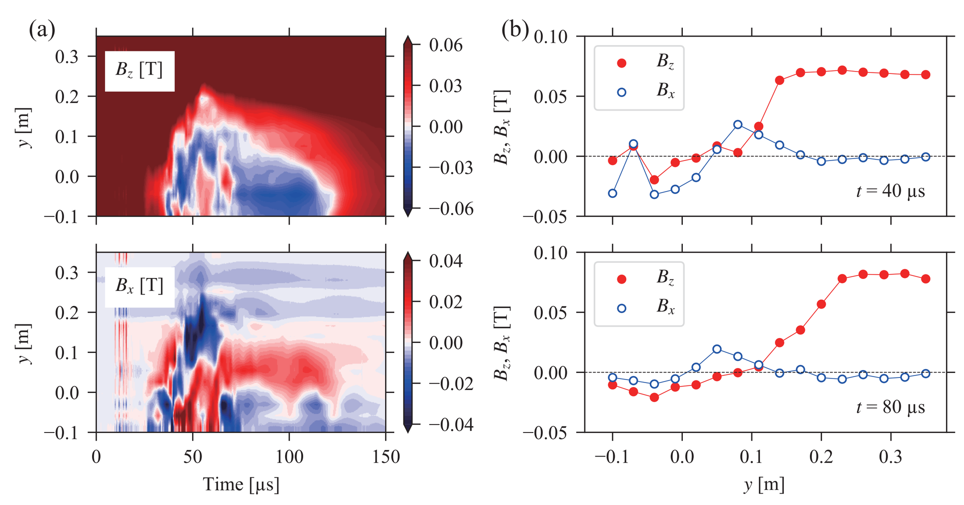

*Time evolutions of excluded flux radius at each point along z axis.*




*Time evolutions of (a) neutron radiation in the collisional merging for two different translation velocities and single translation (green dashed line). (b) SXR radiation. Steep peak is observed on neutron radiation only in the collisional merging with |Vz| significantly exceeds VA and VS (red solid line). Following the peak at the collision, the SXR intensity is increased by reflecting the thermalization of accelerated ions into electrons.*

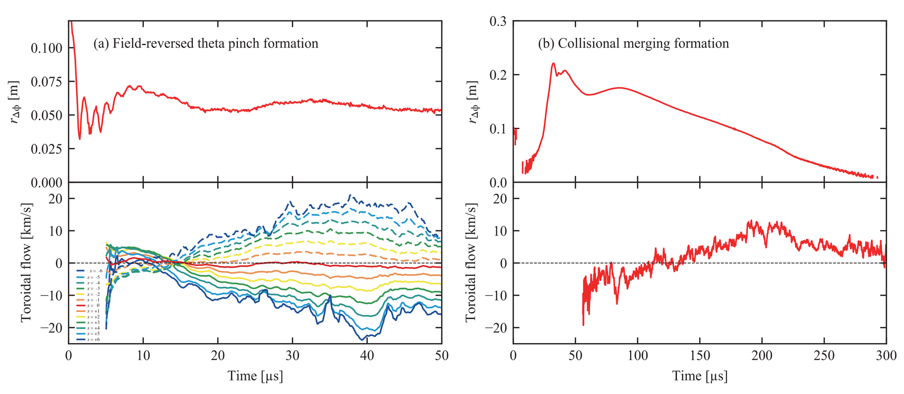
## Self-Organized FRC Formation

- In the collisional-merging FRC, each of the two-translated FRCs appears to carry significant toroidal magnetic fields with opposite helicity, and the strong Bx observed during the FRC collision. In this phase, field-reversed structure is not maintained in the merged plasmoid due to the destructive perturbation caused by the super-sonic/Alfvénic collision.
- After the collision/merging followed by relaxation process, a clear field-reversed structure of the Bz profile is observed.




*Position-shifted Bz radial profile of (a) Contour maps of magnetic-fields (Bz and Bx) 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, and (b) time slices of the radial magnetic field profiles at t = 40 and 80 μs (around FRC collision and quiescent phase, respectively).FRC at collision and quiescent phase.*

- The toroidal spin-up is known as a characteristic property of an FRC. An FRC in a theta-pinch formation region spins-up toroidally immediately after formation phase. The toroidal rotation velocity reaches the range of Alfven velocity within a few tens of microsecond.
- Remarkably, the toroidal angular momentum is not conserved during the super-sonic collision/merging process. After the "reformation" of FRC at around 80 μs, the FRC spins-up again in ion diamagnetic direction. The flow velocity reaches more than 10 km/s approximately 200 μs after the collision.




*(a) Time evolution of toroidal flow and separatrix radius in (a) and (b) the formation the confinement regions.*

## Summary

- In the super-sonic/Alfvénic collision and merging experiments, two FRCs are formed by a FRTP method in the formation regions.
- Two FRCs collide at the super-sonic/Alfvénic relative velocity of 200 – 400 km/s and then merge into one magnetized plasmoid. At the collision, shock wave rises and propagates in the plasmoid. Detected neutrons indicate the existence of accelerated particles in the generated shock wave.
- During the destructive collision/mering process, the plasmoid loses the field-reversal configuration and even toroidal rotation. However, an FRC is self-organized after the merging phase and then it spins-up in diamagnetic direction as generally seen in conventional FRCs.


Plasma Physics Laboratory, Nihon University
Department of Physics | College of Science and Technology
Office: 1-8-14 Kanda-Surugadai, Tokyo, Lab: 7-24-1 Narashino-Dai, Funabashi, Chiba
Tomohiko Asai (asai.tomohiko@nihon-u.ac.jp)



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