Particle Simulation on Merging Processes of Two Spherical Tokamak-Type Plasmoids in a Conducting Vessel

S. Usami[1,2], R. Horiuchi[1], T. Moritaka[1], Y. Ono[2], M. Inomoto[2], H. Tanabe[2]

1)National Institute for Fusion Science, NINS, 2)University of Tokyo

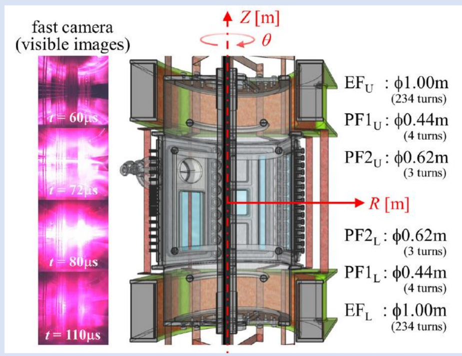
usami.shunsuke@nifs.ac.jp

ABSTRACT

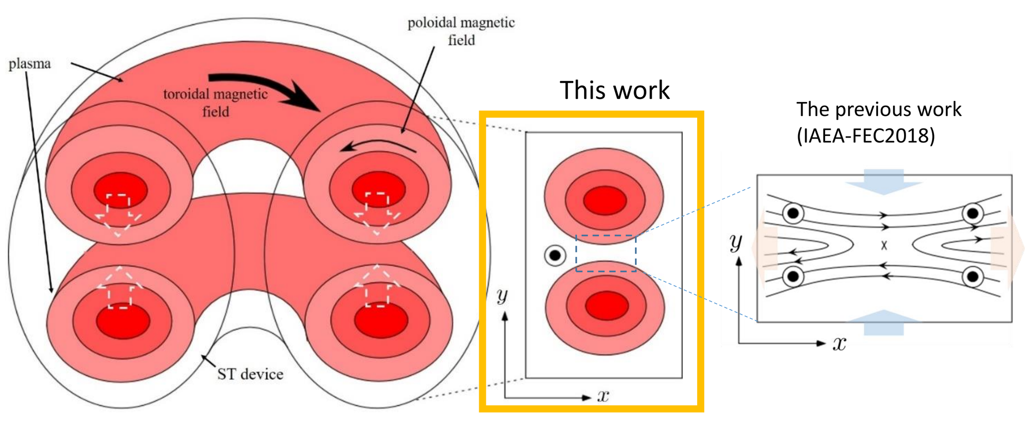
The merging processes of ST-type plasmoids confined in a conducting vessel are studied by means of particle simulations, which compute the entire region of a poloidal surface in an ST device. Our simulations demonstrate that ion heating is a global phenomenon, simultaneously related to kinetic microscopic processes. From macroscopic viewpoints, it is interpreted that compressional heating dominantly works during merging, and then viscous heating occurs after merging. From microscopic viewpoints based on observation of velocity distributions, it is found that the compressional heating consists of genuine heating due to compression and effective heating by the Pick-Up-Like process, while the viscous heating likely corresponds to a different type of effective heating. In comparison with TS-6 experiment results, ion temperature profiles and dependence of the ion temperature on the toroidal magnetic field observed in our simulation are consistent with those in the experiment.

BACKGROUND

- The ST attracts the attention as a candidate of future fusion reactors.
- Through magnetic reconnection, two torus plasmas are merged together to form single torus plasma with high temperature. (TS-6, β ~5% to ~40%)[1]
- Clarifying the heating mechanism in ST merging will lead to higher-performance of ST fusion reactors.
- In previous works, heating near the reconnection point have been focused on.
- However, the merging of STs is global system, where new features appear.
- In this work, we investigate the merging processes of STs, by means of a new particle simulation.

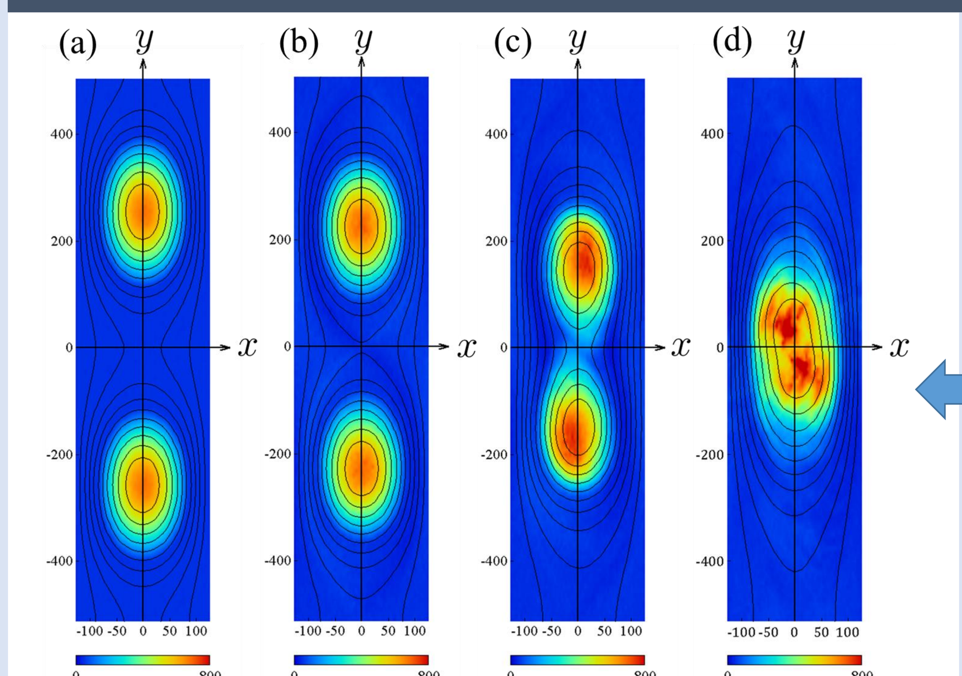


SIMULATION MODEL [2]

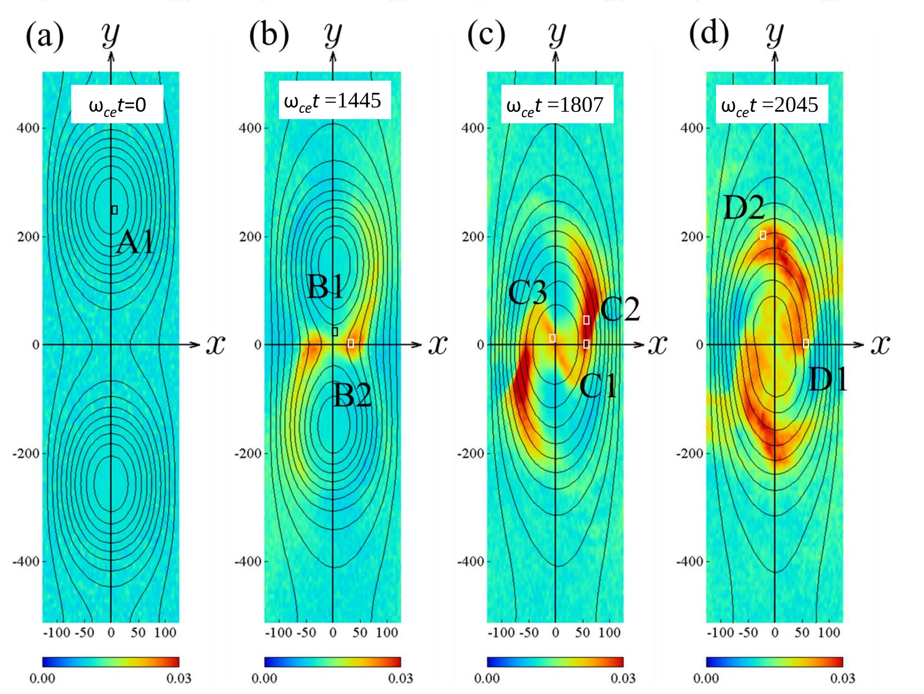


- PIC simulation in 2D Cartesian system
- No 3D effect or toroidicity
- Boundary conditions:
  - y: periodic
  - x: perfect conductor
- Initial state: MHD equilibrium is satisfied.

RESULTS-1



Lines are poloidal field lines, and color contours indicate ion density



Lines are poloidal field lines, and color contours indicate ion temperature

Merging process of STs

- Two STs (plasmoids) approach each other by an attractive force *JxB*.
- Through magnetic reconnection, a single large ST is generated.

Ion heating

- Magnetic energy → kinetic energy → thermal energy
- Plasma heating is not only due to reconnection, but a global phenomenon.

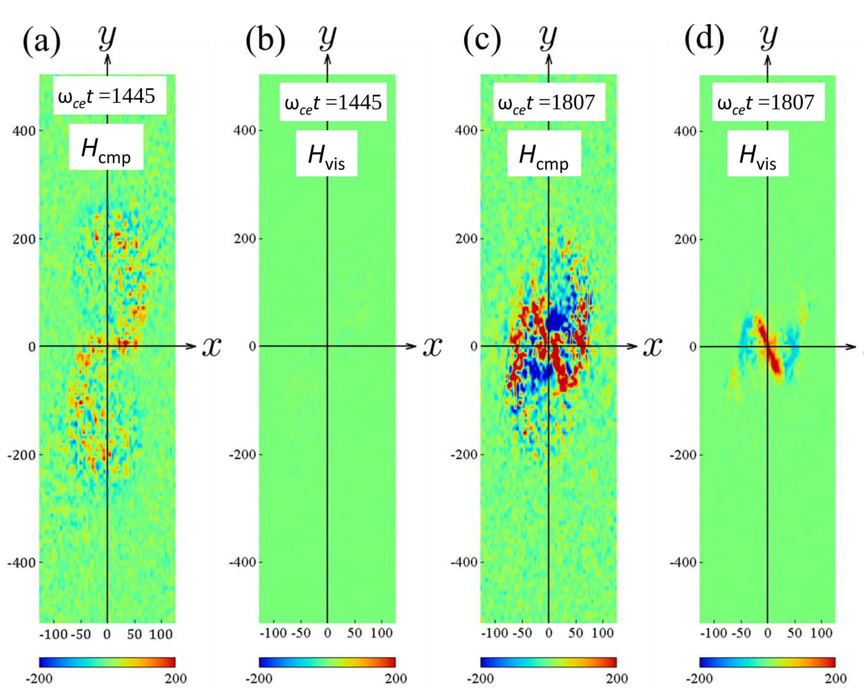
(a): Initially, the ion temperature is low and uniform.

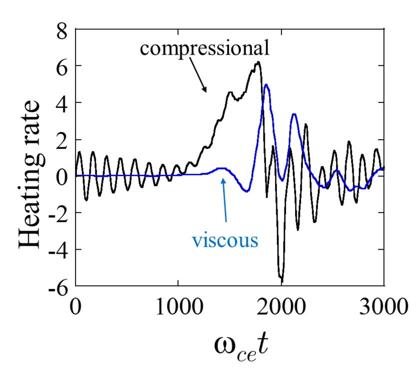
(b): The ion temperature becomes high in parts of the downstream (30<x<70, -70<x<-30), where ions are heated.

(c): High-temperature ions are expanded to upper-right area and lower-left area. In addition, a new high-temperature region is generated around the central position.

(d): High-temperature ions are further expanded to wider regions due to diffusion/transport.

Macroscopic view: compressional and viscous heating terms





$$H_{cmp} = -\frac{5}{2} p \nabla \cdot \boldsymbol{u}$$

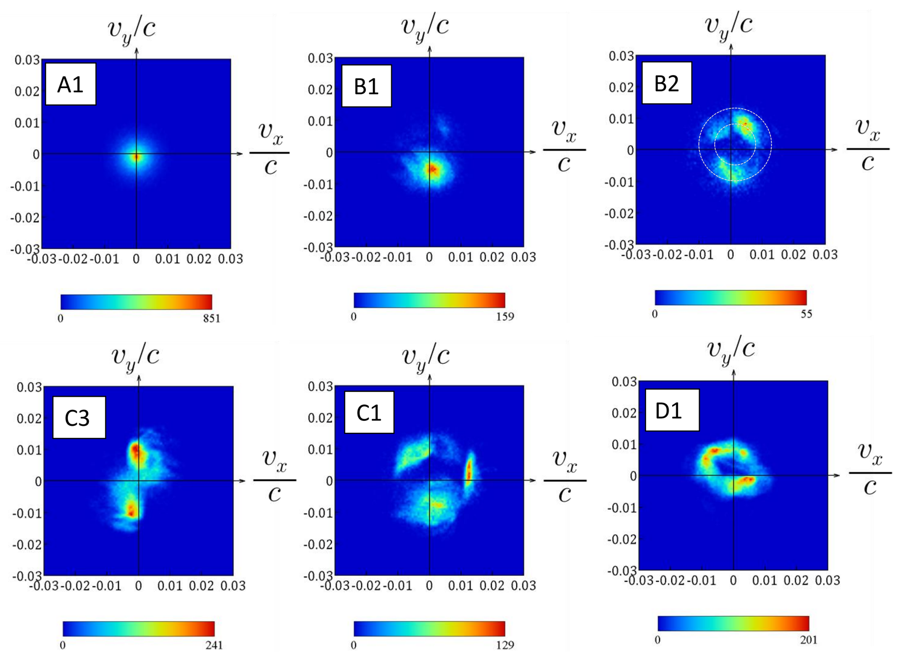
$$H_{vis} = -\pi_{i,j} \partial_i u_j$$

At first, compressional heating predominantly acts on ions and then viscous heating plays a main role.

- At $\omega_{ce}t$ = 1445, compressional heating is dominant, because the confinement region shrinks by the merging of the two STs, whereas viscous heating is quite weak throughout the entire region.
- At $\omega_{ce}t$ =1807, both compressional heating and viscous heating play important roles around the central region. Viscosity heating is generated since the merging system has a net angular momentum around the geometric axis and thus large velocity shear is produced.

RESULT-2

Microscopic view: ion velocity distributions



The two terms are strong in C3

C3: Maxwellian does not hold.

→ A different type of effective heating (under investigation)

A1: Initially, a Maxwellian holds.

The compressional term is large in B1 and B2

B1: Keeping Maxwellian, the distribution is spread.

→Actual heating due to compression.

B2: The distribution shape is a part of a circle.

→Effective heating by the Pick-Up-Like process [3,4]

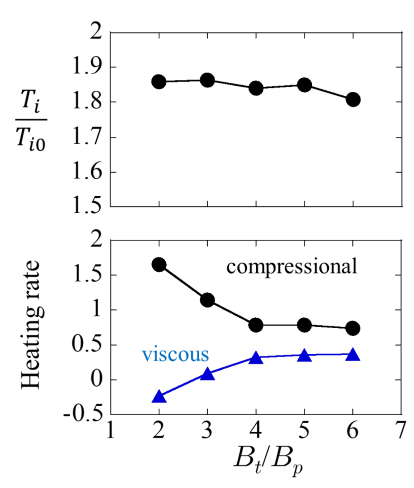
The compressional heating consists of actual heating and effective heating.

C1 and D1:

Examples for showing that part-of-circle distributions are ubiquitous.

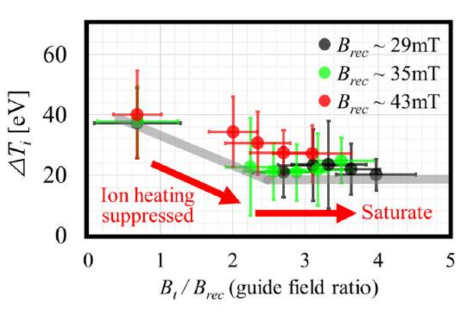
COMPARISON WITH EXPERIMENT

Dependence of ion heating on the toroidal field



- As the toroidal field is larger, the ion temperature is smaller, but the dependence is extremely small.
- As the toroidal field is larger, compressional heating becomes smaller, while viscous heating becomes larger.

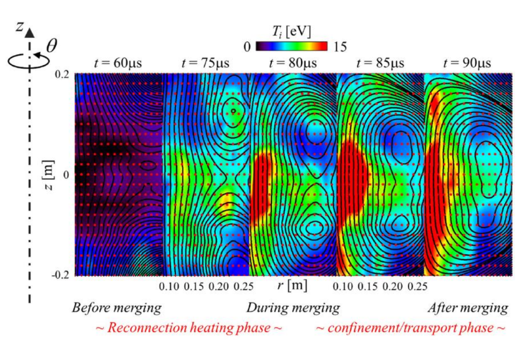
TS-6 experimental result (Fig. 4 of Ref. [5])



Both experiments and simulations indicate that the ion heating is suppressed in high toroidal field regime.

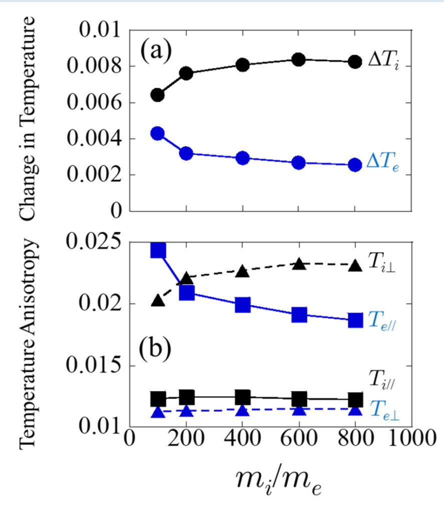
Ion temperature profile

TS-6 result (Fig. 6 of Ref. [5])



- "During merging" Exp: t=80μs, 85μs, Sim: $\omega_{ce}t$=1445
- "After merging" Exp: t=90μs, Sim: $\omega_{ce}t$=1807
- During merging, (focusing on the inner region in the radial direction), heated ions are conveyed along the field line mainly downward.
- After merging, there exists heated ions around the contact point, too.
- The behavior of high-temperature region in our simulations is consistent with one in a TS-6 experiment.

MASS RATIO m_i/m_e DEPENDENCE



- In order to clarify the roles of the ion dynamics, we carry out simulation runs for different values of m_i/m_e .
- As m_i/m_e increases…
  - (a)Thermal energy partition
    - ion: electron = 3 : 1
  - (b)Anisotropy
    - Ion heating: perpendicular
    - Electron heating: parallel

CONCLUSION

- We have developed a new particle-in-cell model to analyze physics in the entire region of a poloidal surface in an ST vessel.
- Macro: Compressional heating is dominant during merging, and viscous heating is dominant after merging, while high-temperature region is spread due to diffusion/transport.
- Micro: The compressional heating consists of genuine heating due to compression and effective heating by the Pick-Up-Like process, while the viscous heating likely is based on a different type of effective heating.
- Our simulation results are in a good agreement with TS-6 experimental results.
- By performing simulation runs under different mass ratio m_i/m_e, we have clarified that
  - Thermal energy partition ion: electron = 3:1
  - Heating anisotropy ion: perpendicular, electron: parallel

REFERENCES

[1] Y. Ono et al., Plasma Phys. Control. Fusion **54** (2012) 124039.
[2] R. Horiuchi, et al., Phys. Plasmas **26** (2019) 092101.
[3] S. Usami, et al., Phys. Plasmas **24** (2017) 092101.
[4] S. Usami, et al., Phys. Plasmas **26** (2019) 102103.
[5] H. Tanabe et al., Nucl. Fusion **59** (2019) 086041.