



# Global Ion Heating/Transport during Merging Spherical Tokamak Formation

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## Global Ion Heating/Transport during Merging Spherical Tokamak Formation

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**1. Introduction:** ~ application of merging/reconnection heating for CS-free plasma startup for spherical tokamak ~

Successful demonstration of CS-free plasma startup scenario in MAST

MAST experiment successfully connects the merging startup plasma to steady and more ramp scenario.

Heating physics for high guide field merging experiment

**Typical heating characteristics:**

- Formation of two plasma rings by the induction of P3 coil ( $I_{P3}$ ).
- In proportional to  $I_{P3}$  initial plasma current  $I_p$  increases.
- Merging/reconnection heating increase in proportional to the square of reconnecting field  $B_{rec}$  ( $B_{rec}$  for tokamak).
- By exceeding radiation barrier of low Z impurity, the duration time exceeds 100ms (merging) → steady scenario has also been demonstrated.

Electrons are heated around the X-point mostly by sheet current dissipation. Ions are heated by the dissipation of reconnection outflow globally downstream.

Energy relaxation (collisional coupling) between electrons and ions also heats electrons globally ( $\tau_{ei} \sim 4ms$  delayed).

Stabilization of the characteristic profile

High electron heating over radiation barrier by energy relaxation

Successful connection in long pulse operation by high  $B_z$  wide-field reconnection occurs

Further upgraded projects have been started in ST40 and TS-3U based on high  $B_z$  merging startup scenario.

Proper supporting experiments must be required to investigate the detailed heating/confinement physics.

**2. CS-free plasma startup in TS-3U**

Comparison of M/C and CT-injection-like scenarios

Apparent images are similar, but M/C scenario can use Acc. heating during startup

TS-6 (TS-3U) device

High speed camera images

Time evolution of  $T_e$

MAST-like heating characteristics are routinely reproduced

Based on outflow heating mechanism, doubly-peaked profile is formed ~

Radially double-peak  $T_e$  profile

Hollow profile formation on the closed flux surface

**3. Diagnostics upgrade on TS-3U project:**

~ 96CH & 320CH ultra high resolution ion Doppler tomography ~

High-resolution & high-throughput multi-slit spectroscopy technique

Gen. I: single-slit

Gen. II: 3-slit type 96CH Doppler tomography (2016-)

Gen. III: 5-slit type 320CH Doppler tomography (2018-)

Multi-slit spectroscopy technique enables both global/microscopic fine structure measurement

Full-2D ion temperature measurement of Rec. heating

Highlight of the advanced diagnostics from the last IAEA meeting

Full-2D imaging of  $T_e$  without assumption of poloidal symmetry

2D imaging of ion heat flux in experiment

FT typically has large radial component downstream but cross-field radial thermal transport is strongly suppressed (higher  $v_{\theta}$  by larger  $\omega$ ) and ion heat flux propagates mostly along closed flux surface

**4. Global ion heating/transport process during M/C**

Full-2D imaging of ion temperature profile during magnetic reconnection

Reconnection heating and transport model

Merging/acceleration phase

Disruption/reconnect phase

Propagation of high  $T_e$  area

Reference results from MAST

Poloidally ring-like structure formation mechanism has clearly been visualized

**Experimental new finding: poloidally asymmetric global structure formation during M/C**

Negative  $B_z$

Positive  $B_z$

TF current reversed

$T_e$  profile flipped

Clockwise polarity of  $T_e$

anti-clockwise polarity of  $T_e$

**5. Characterization of the poloidally asymmetric profile**

~ Why does the higher  $T_e$  appear in the positive potential region? ~

Particle energy gain from quadrupole potential does not explain the results

E-B drift profile partially explains inboard/outboard asymmetric heating

Parallel acceleration mostly by reconnection electric field explains the polarity

The negative distribution of parallel electric field component mostly from E<sub>z</sub>:

- High field side ( $B_z$  is positive): vertically downward acceleration
- Low field side ( $B_z$  is negative): vertically upward acceleration

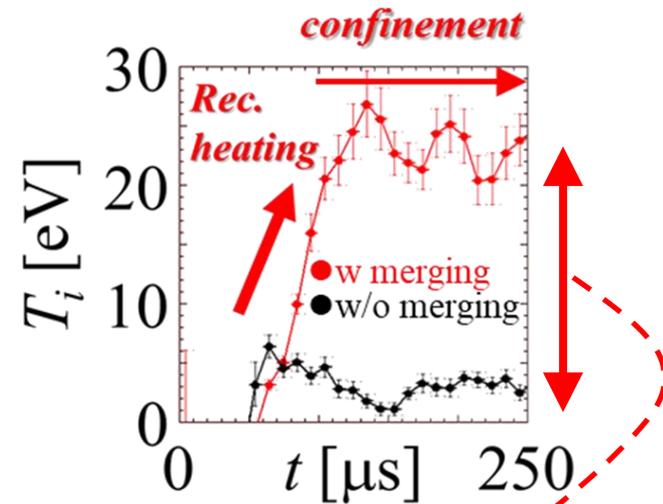
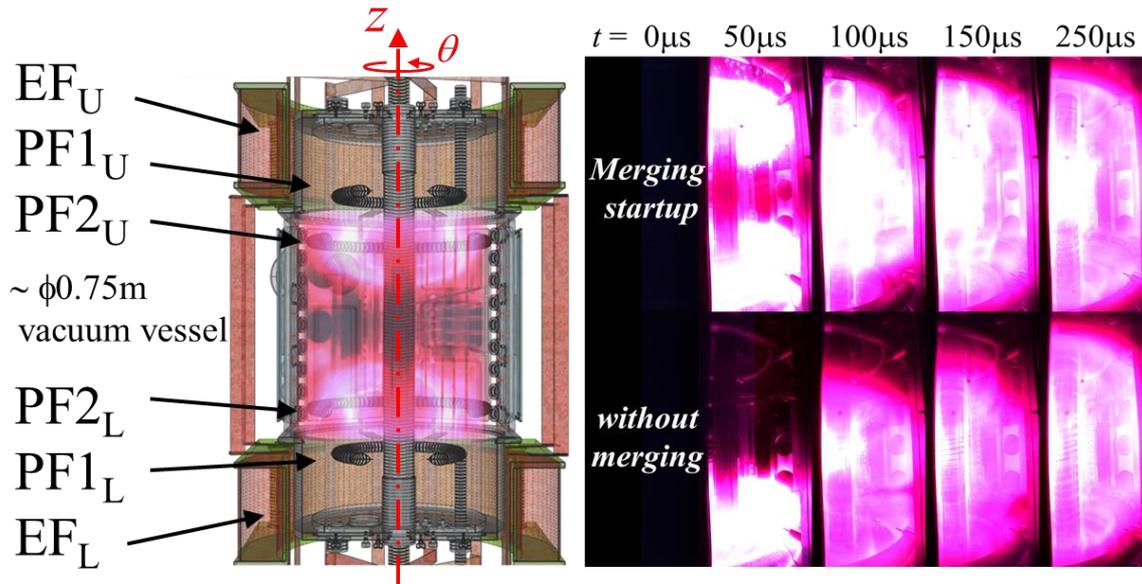
Poloidally anti-clockwise  $T_e$  distribution is formed through the parallel acceleration by E<sub>z</sub>

**6. Summary and conclusion**

Global ion heating/transport of magnetic reconnection has been investigated in TS-3U merging plasma startup experiment using full-2D high resolution imaging diagnostics

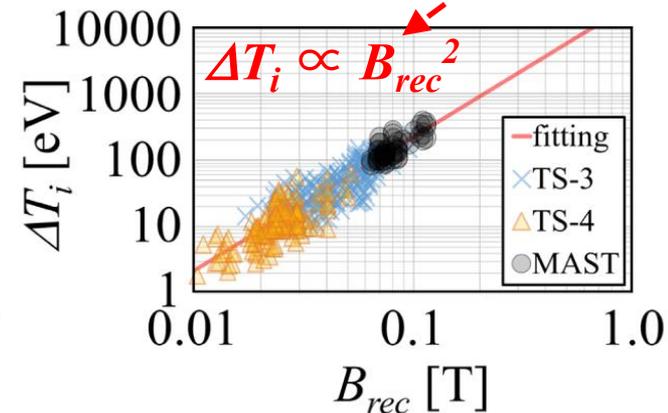
- Magnetic reconnection heats ions globally downstream of outflow jet and forms a hollow  $T_e$  profile with inboard/outboard asymmetry to have higher temperature in the high field side
- Perpendicular heat conduction is strongly suppressed by guide field and becomes negligibly small to enable the connection to quasi-steady sustainment of double-peak profile after merging
- Full-2D heating measurement clearly reveals that downstream ion heating forms poloidally ring-like global structure surrounding the merging flux tubes
- The global heating profile forms poloidally asymmetric structure by parallel acceleration mechanism and the poloidally rotating structure is flipped when toroidal field is reversed.

# Merging/reconnection heating experiment in the TS-3U (TS-6) spherical tokamak



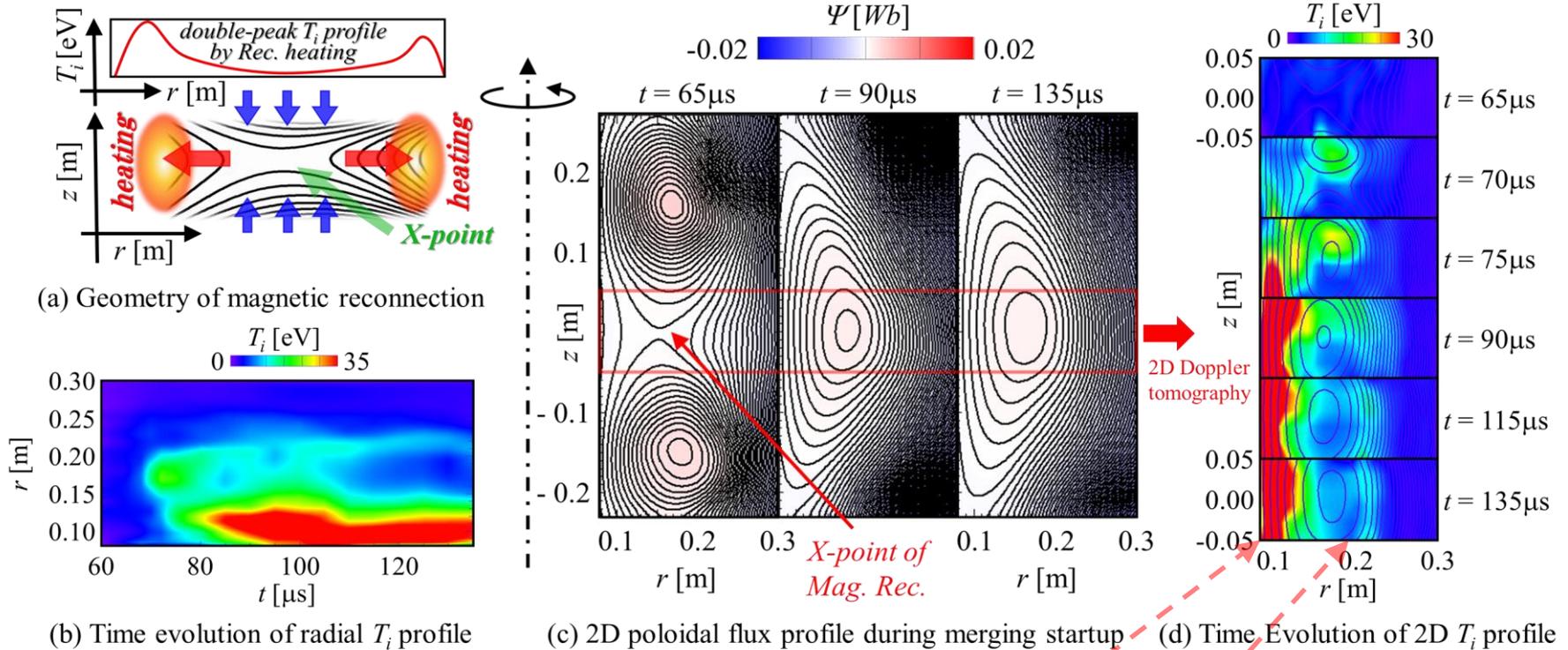
## Merging spherical tokamak formation

- Central solenoid free (CS-free) plasma startup method
- In comparison with CT-injection startup scenario, MW-GW scale ion heating is also available through reconnection



# Reconnection heating during Merging plasma startup typically forms double-peak hollow $T_i$ profile

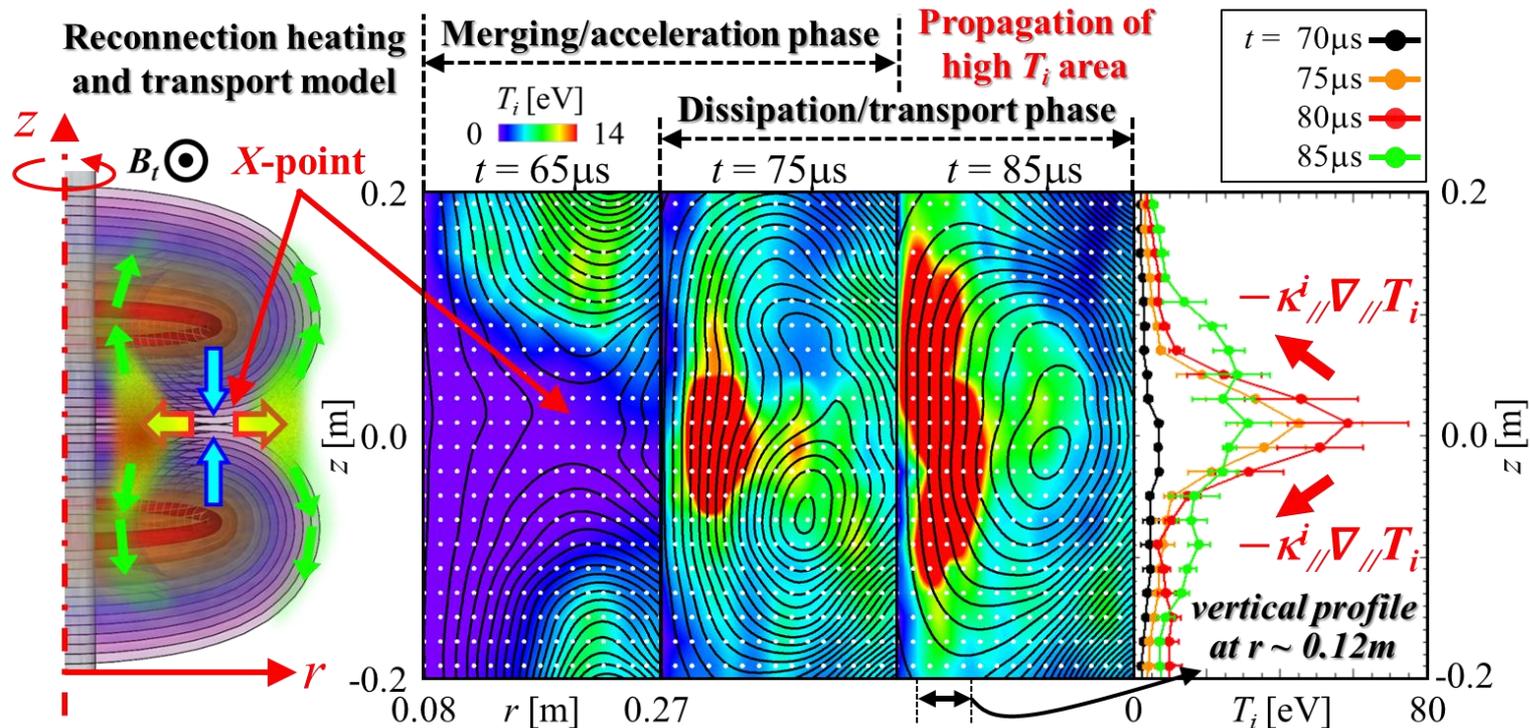
Based on outflow heating mechanism, ion temperature increases in the downstream region of outflow jet



After merging, the high  $T_i$  region is surrounded by closed flux surface and field-aligned feature appears both inside and outside magnetic axis.

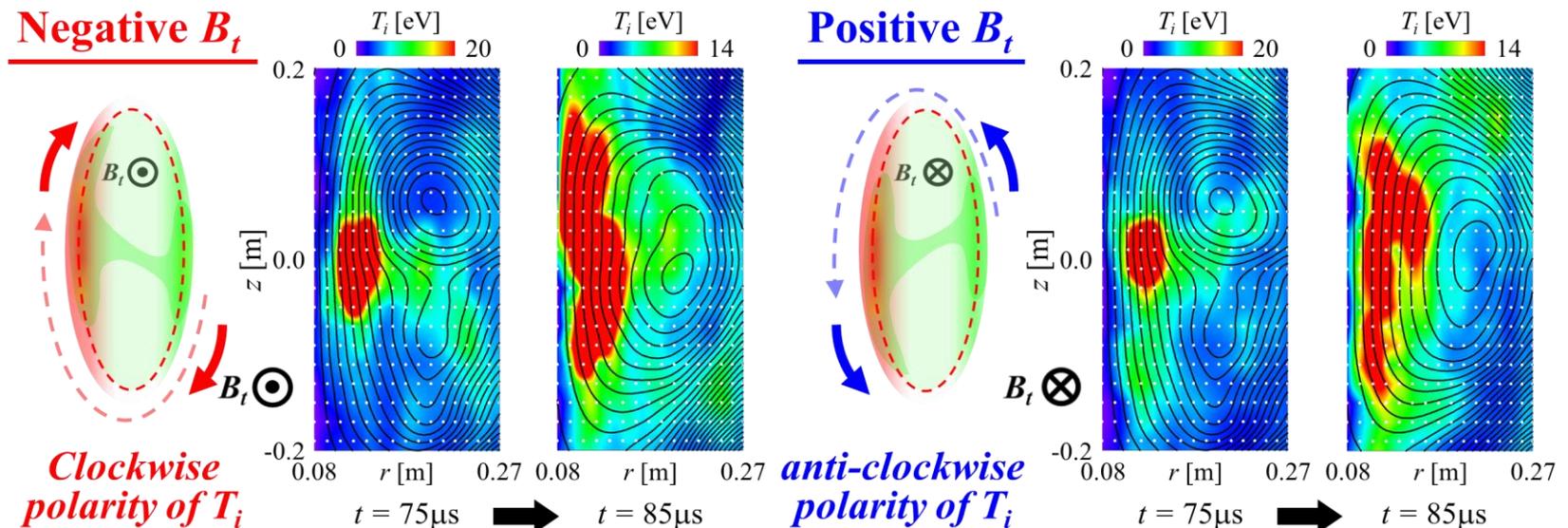
# Full-2D visualization of ion temperature profile during merging/reconnection in experiment

- Ions are heated globally in downstream region of outflow jet
- The impulsively formed hot spots in the downstream region is then transported mostly by parallel heat conduction
- *Field-aligned* heat transport leads to poloidally-ring-like hollow  $T_i$  structure as shown in the model profile



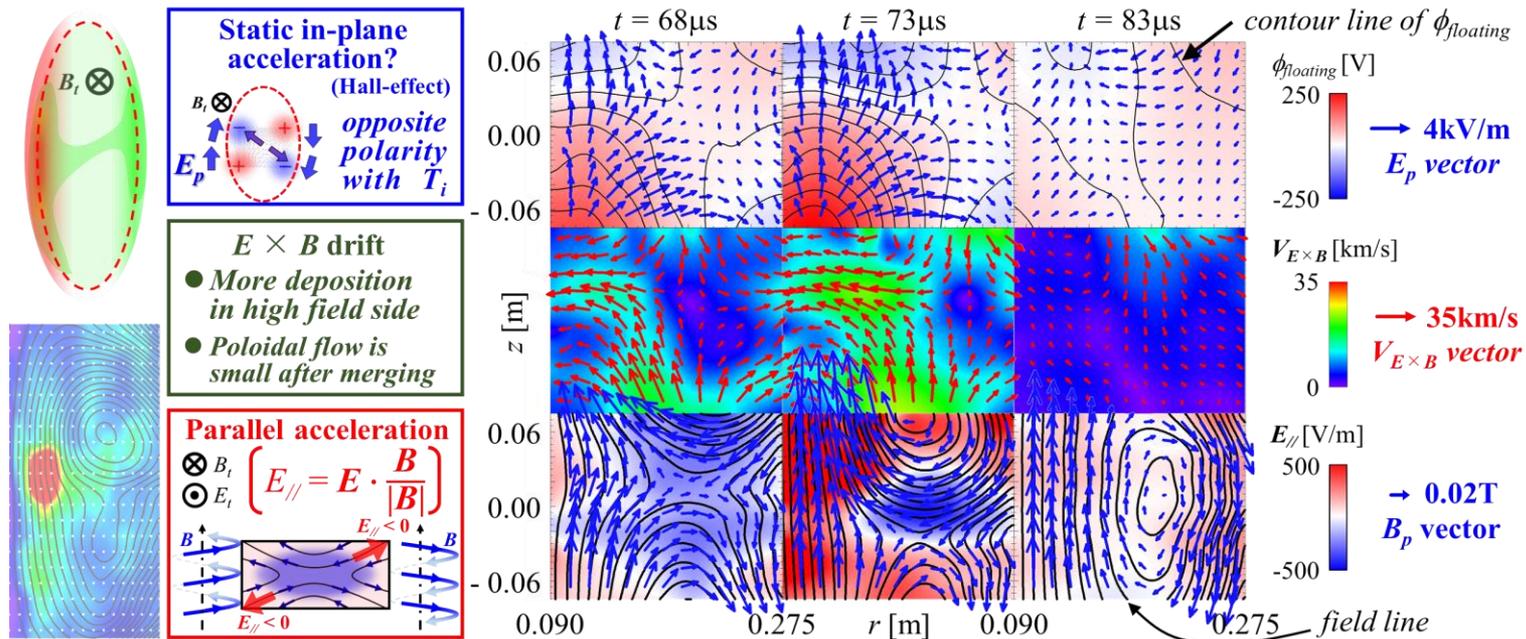
# The full-2D imaging diagnostics experimentally reveals **poloidally asymmetric global structure**

- Through merging/reconnection process, the characteristic ion temperature profile shows **poloidally rotating feature**
- The polarity of the rotation of  $T_i$  profile is flipped when TF current is reversed (positive/negative  $B_t$ )



# Characterization/interpretation of the measured poloidally asymmetric structure

- The rotating feature is **not driven by quadrupole potential drop** of guide field reconnection (opposite polarity with  $T_i$ )
- $E \times B$  drift distribution does not explain the poloidal rotation, while it has higher deposition of outflow heating in high field side
- **Parallel acceleration by reconnection electric field  $E_t$  explains the measured ion heating/transport polarity around the X-point**



# Summary and conclusion

Global ion heating/transport of magnetic reconnection has been investigated in TS-3U (TS-6) merging plasma startup experiment using full-2D high resolution imaging diagnostics

- Magnetic reconnection heats ions globally in the downstream region of outflow jet
- The downstream ion heating forms poloidally ring like global structure surrounding the flux surface
- The global heating profile forms poloidally asymmetric structure by parallel acceleration
- The poloidally rotating structure is flipped when toroidal field direction is reversed.