EX/P7-20

Global Ion Heating/Transport during Merging Spherical Tokamak Formation

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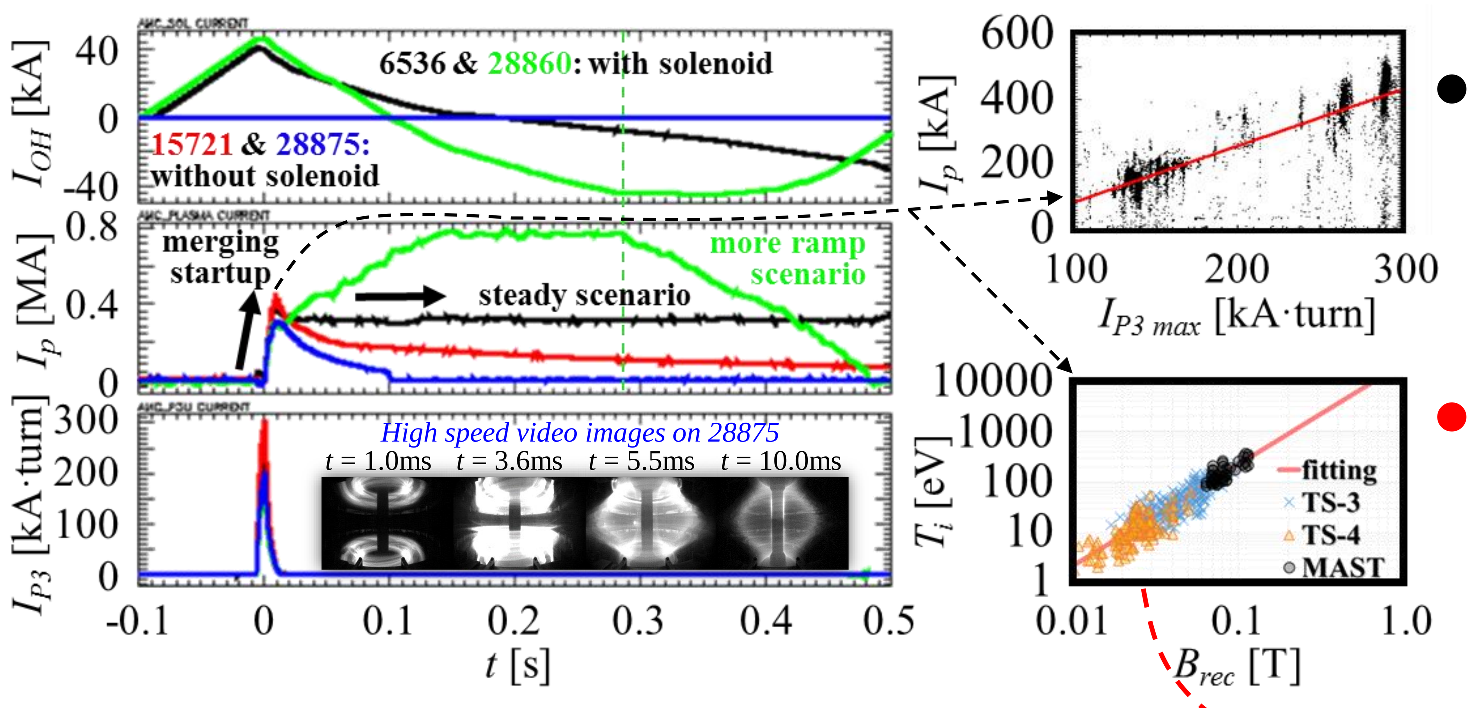
1. Introduction: ~ *application of merging/reconnection heating for CS-free plasma startup for spherical tokamak* ~

Successful demonstration of CS-free plasma startup scenario in MAST

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

H. Tanabe et al., Nucl. Fusion **57**, *056037 (2017)*



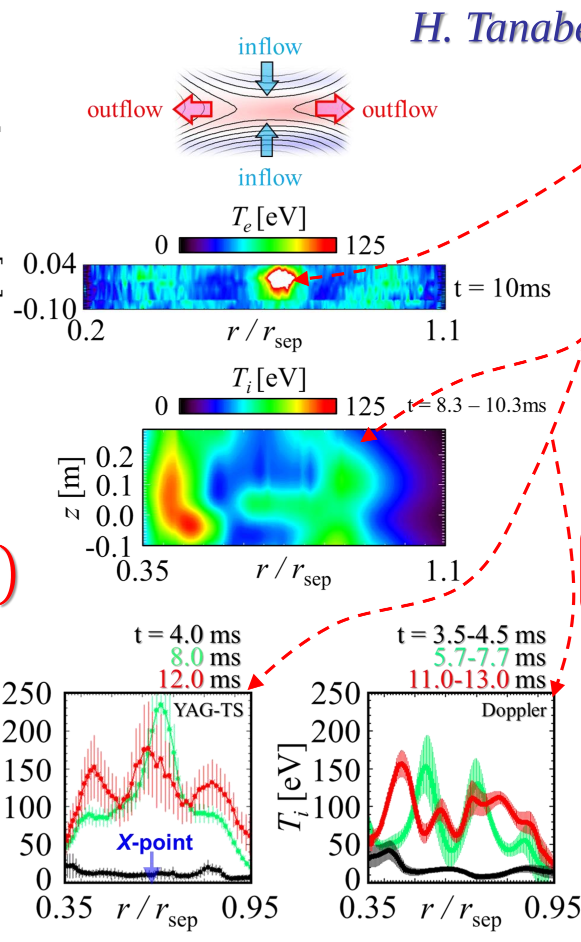
- Formation of two plasma rings by the induction of P3 coil (I_{P3}).
- In proportional to I_{P3}, initial plasma current I_P increases.
- Merging/reconnection heating increase in proportional to the square of reconnecting field B_{rec} (B_p for tokamak).

→ $\Delta T_i \propto B_{rec}^2 (\propto B_p^2 \propto I_P^2 \propto I_{P3}^2)$

- By exceeding radiation barrier of low Z impurity, the duration time exceeds 100ms. (merging → steady scenario has also been demonstrated)

Heating physics for high guide field merging experiment

H. Tanabe et al., Phys. Rev. Lett. 115, 215004 (2015)



Typical heating characteristics:

- 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 (τ^{E}_{ei} ~ 4ms delayed).

Sustainment of the characteristic profile | bulk electron heating over radiation barrier by i-e energy relaxation

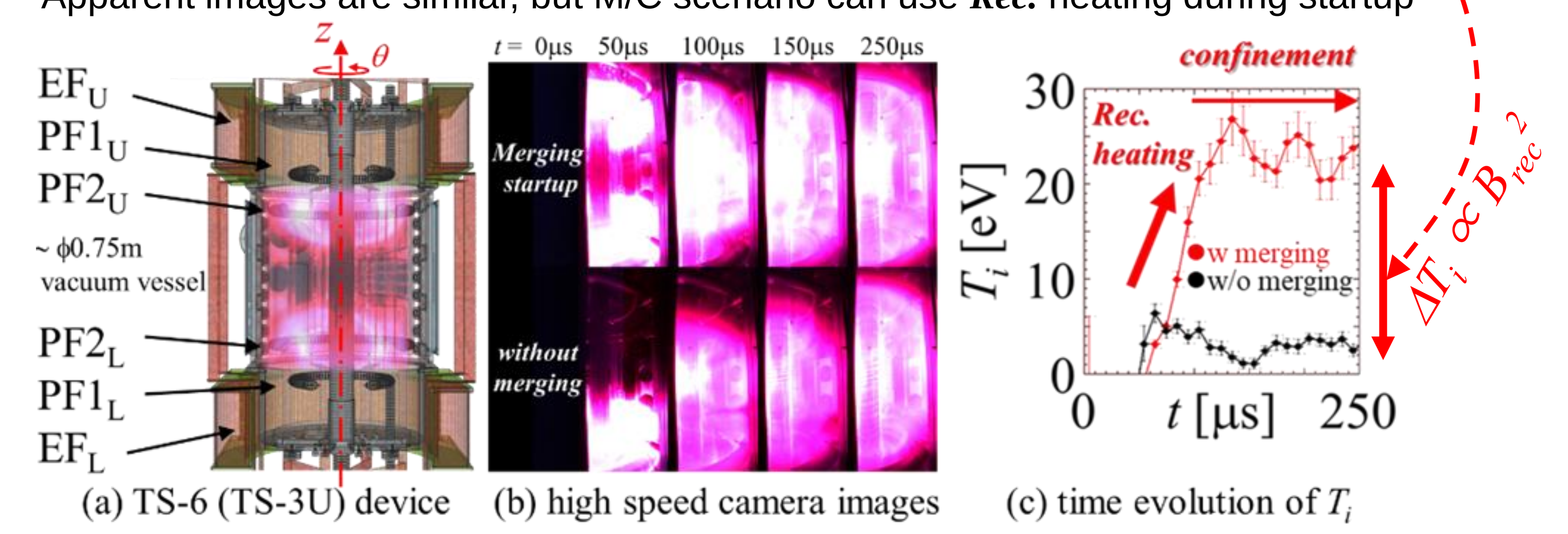
Successful connection to long pulse operation by high B_t guide field reconnection scenario

Further upgraded projects have been started in ST40 and TS-3U based on high B_t 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

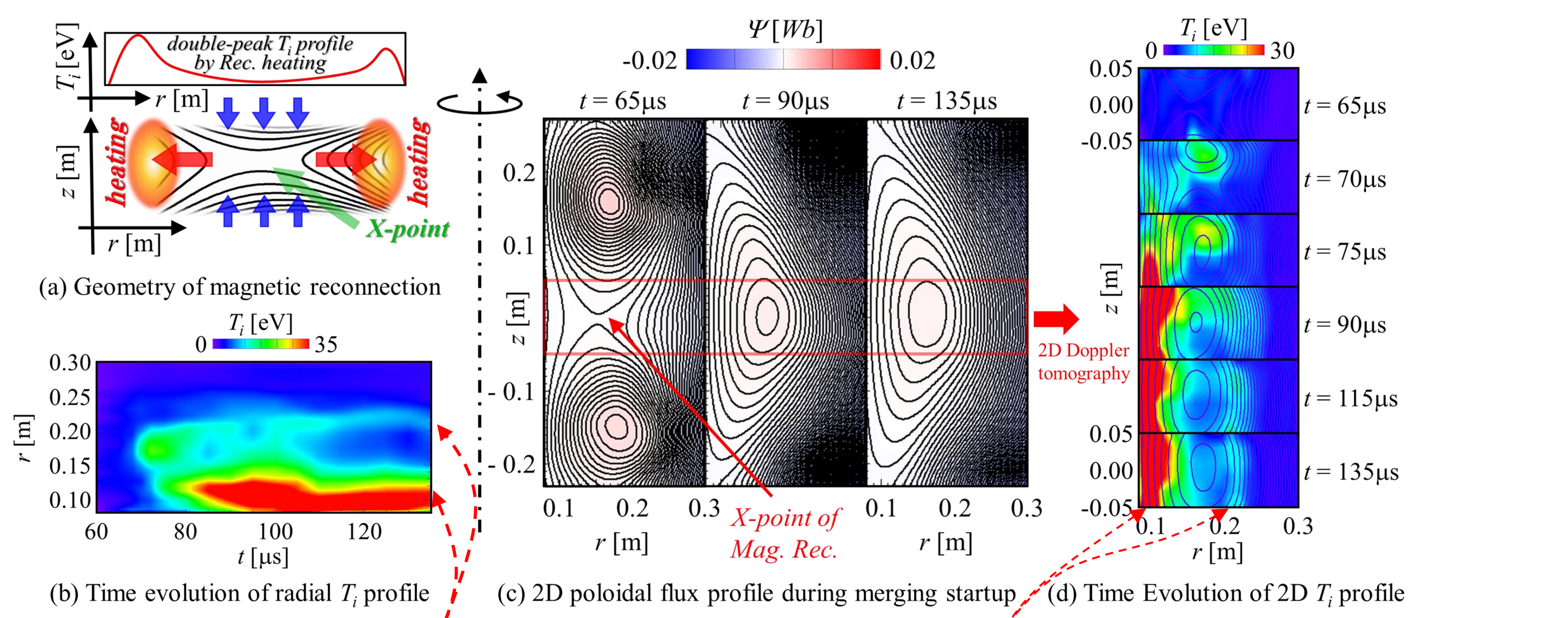
~ Apparent images are similar, but M/C scenario can use *Rec.* heating during startup ~



(a) TS-6 (TS-3U) device (b) high speed camera images (c) time evolution of T_i

MAST-like heating characteristics are routinely reproduced

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



(a) Geometry of magnetic reconnection (b) Time evolution of radial T_i profile (c) 2D poloidal flux profile during merging startup (d) Time Evolution of 2D T_i profile

Radially double-peak T_i ⇒ 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

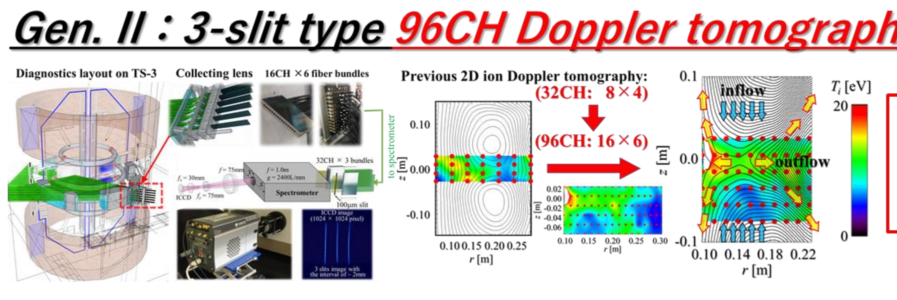
Gen. I: single-silt ⇒

- Usually spatial resolution is limited by the height of the entrance slit of spectrometers.
  - ✓ Number of CH
  - ✓ Fiber core width

  } trade-off problem

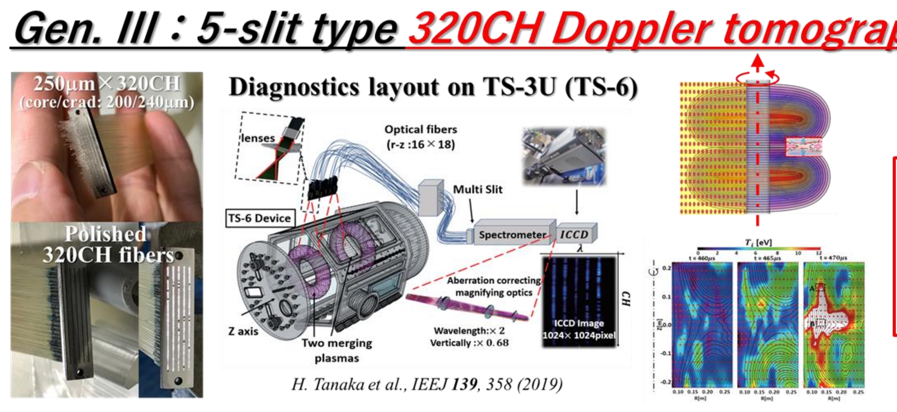
Note: upgrade cost ~ $20,000 for each

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



Fine-structure around X-point was resolved

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



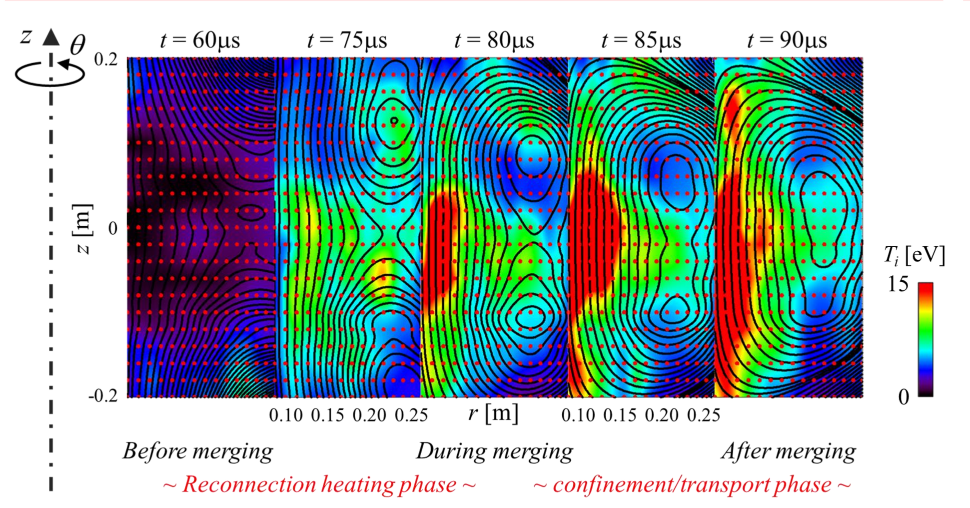
Multi-slit spectroscopy technique enables both global/microscopic fine structure measurement

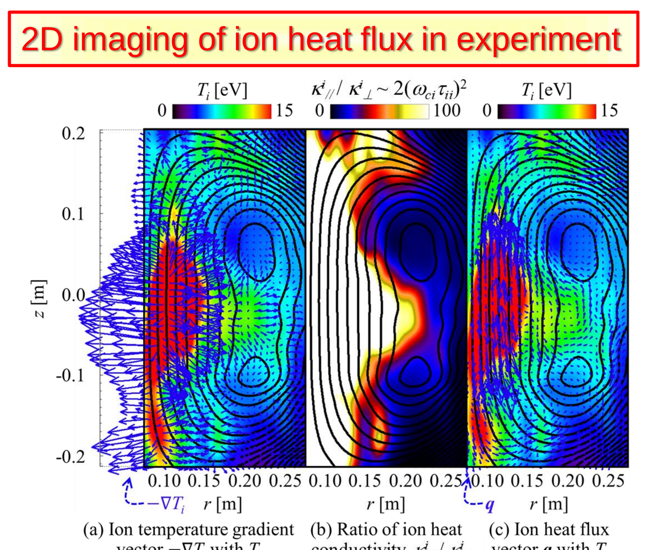
Gyro-scale spatial resolution satisfied ($dr \sim \rho_i$ = 10 - 20mm)

Full-2D ion temperature measurement of Rec. heating

Highlight of the advanced diagnostics from the last IAEA meeting

Full-2D imaging of T_i without assumption of poloidal symmetry | 2D imaging of ion heat flux in experiment





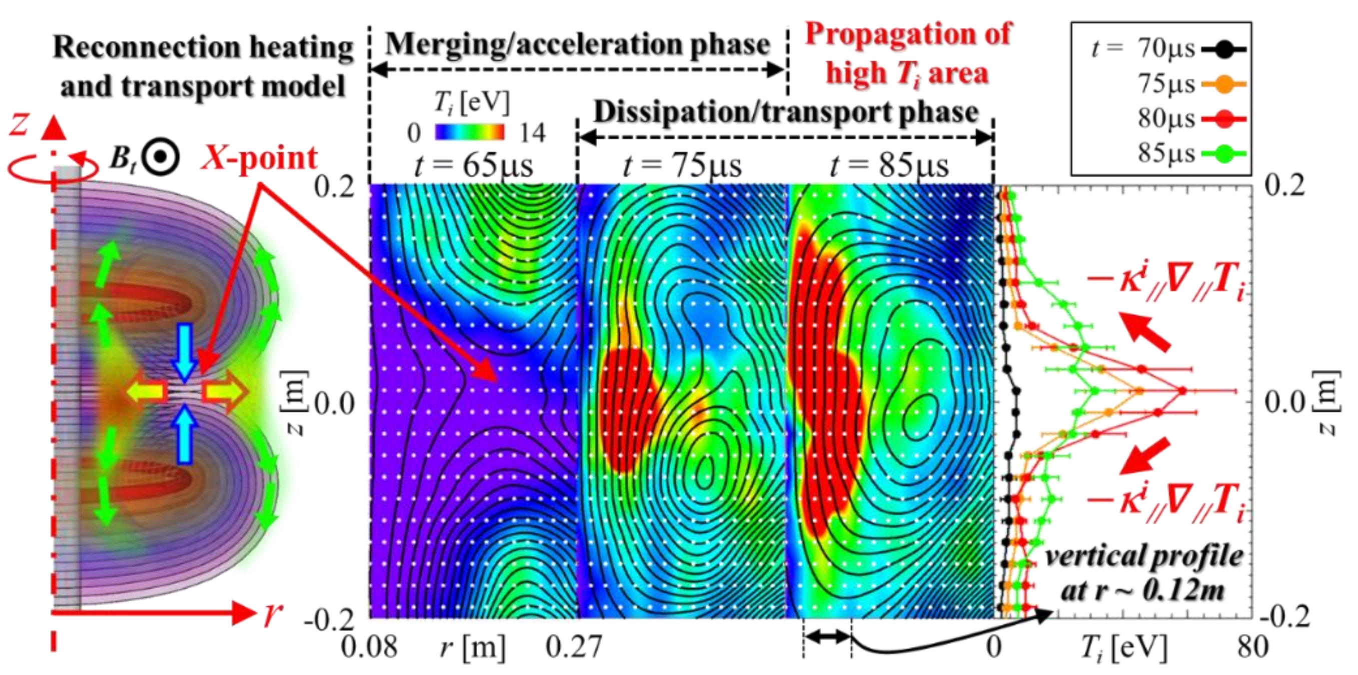
(a) Ion temperature gradient vector $-\nabla T_i$ with T_i (b) Ratio of ion heat conductivity $\kappa^i_{//}/\kappa^i_{\perp}$ (c) Ion heat flux vector q with T_i

∇T_i typically has large radial component downstream but cross-field radial thermal transport is strongly suppressed (higher $\kappa^i_{//}/\kappa^i_{\perp}$ by larger ω_{ci}) and ion heat flux propagates mostly along closed flux surface

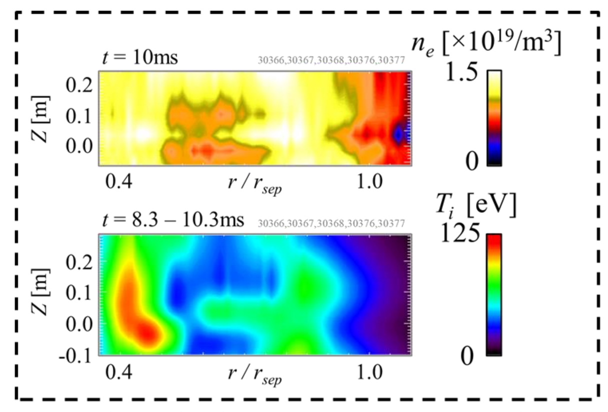
H. Tanabe et al., Nucl. Fusion, 59, 086041 (2019)

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

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



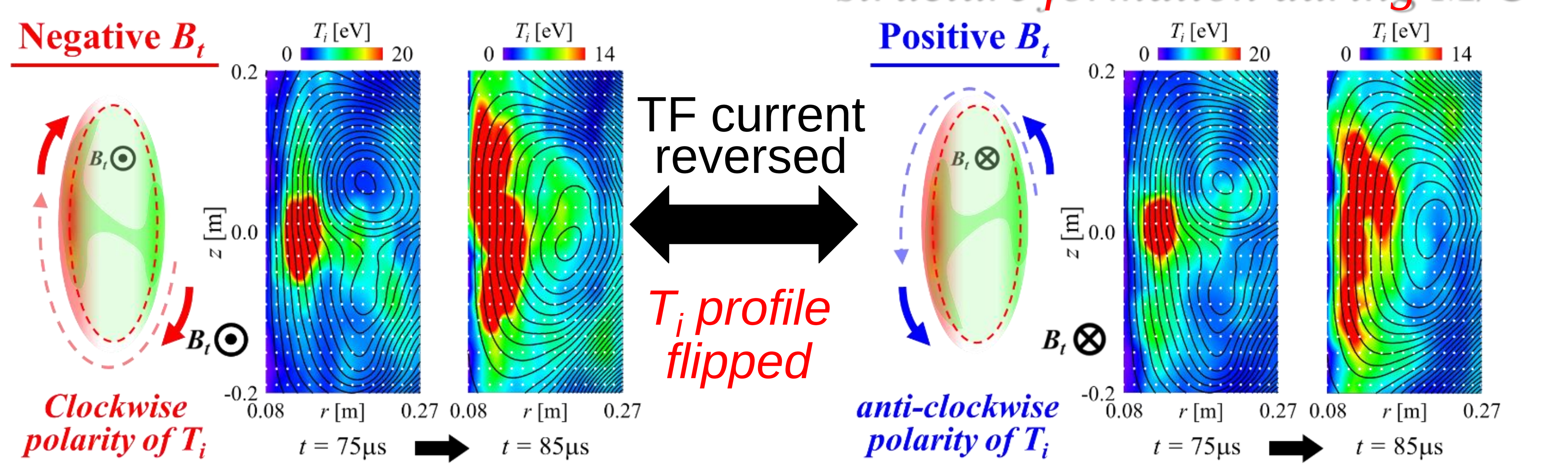
Reference results from MAST



H. Tanabe et al., Phys. Rev. Lett. 115, 215004 (2015)

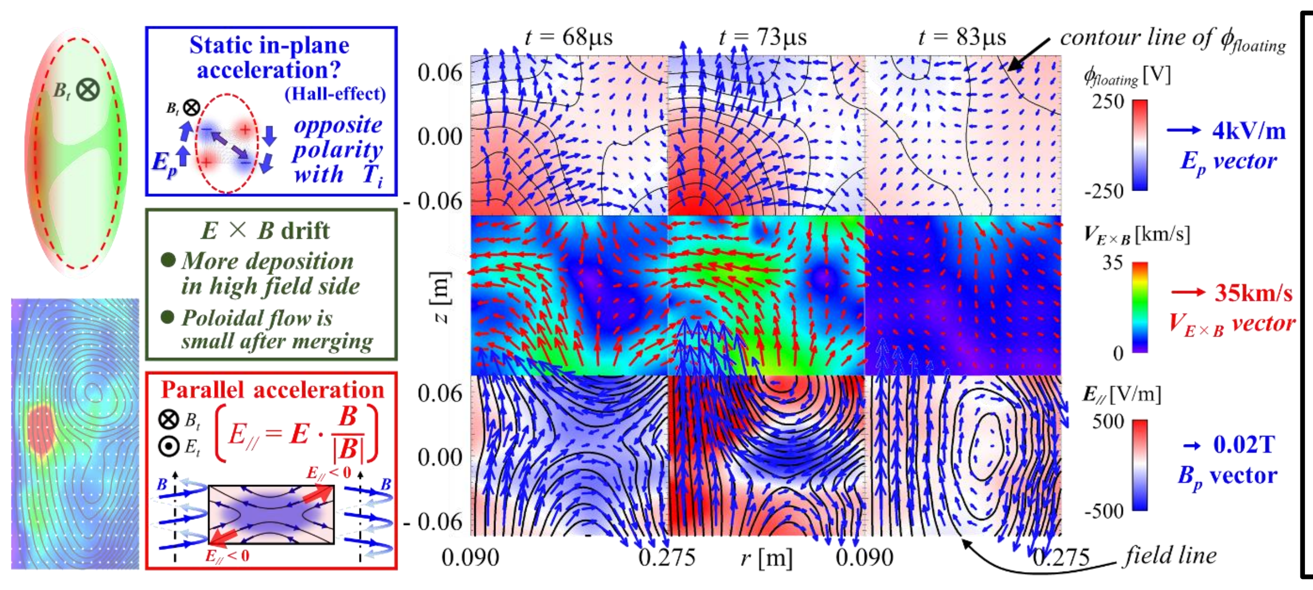
Poloidally ring-like structure formation mechanism has clearly been visualized

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



5. Characterization of the poloidally asymmetric profile

~ Why does the higher T_i 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_t:

→ High field side (B_z is positive) : vertically downward acceleration

→ Low field side (B_z is negative) : vertically upward acceleration

Poloidally anti-clockwise T_i distribution is formed through the parallel acceleration by $E_{//}$

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_i 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 imaging 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.

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