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Investigation of ion heating/transport process of magnetic reconnection during CS-free merging plasma startup of spherical tokamak in TS-6

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1) Univ. Tokyo 2) Tokamak Energy Ltd. 3) CCFE

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THE UNIVERSITY OF TOKYO

TS-group

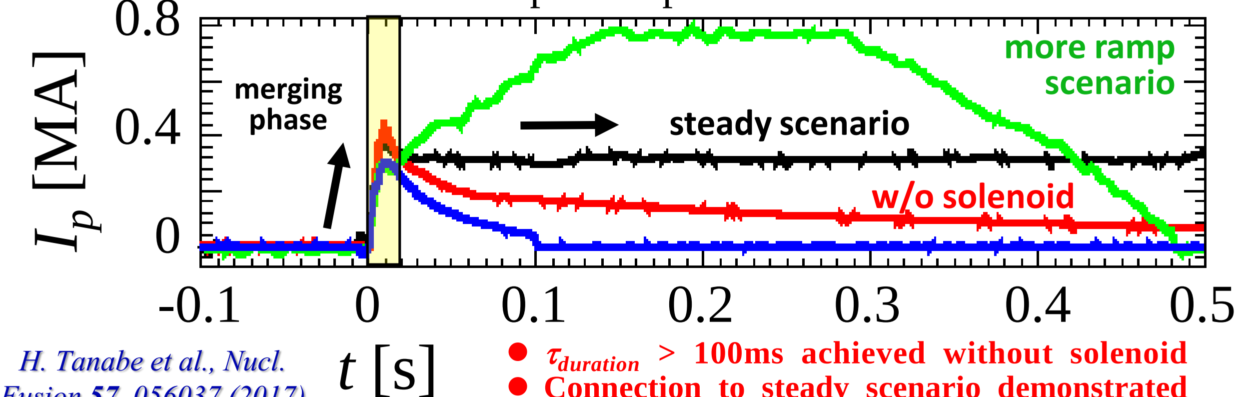
Merging/reconnection plasma startup

~ promising ST formation scheme without solenoid ~

Demonstration in MAST

- **~ 1keV plasma formation by merging**
- **Successful connection to long pulse scenario**

Plasma current (I_p) of merging startup plasma
~ reference for plasma performance & life time ~

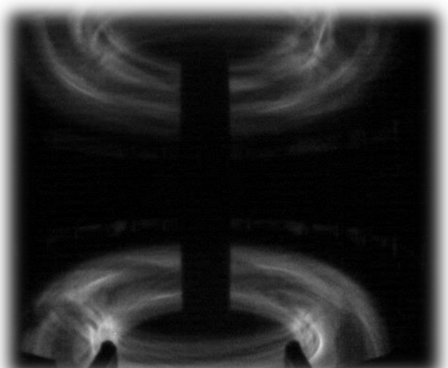


H. Tanabe et al., Nucl. Fusion 57, 056037 (2017)

- $\tau_{duration}$ > 100ms achieved without solenoid
- Connection to steady scenario demonstrated

> ***Merging + Ohmic***
—***More ramp scenario***
—***Steady scenario***

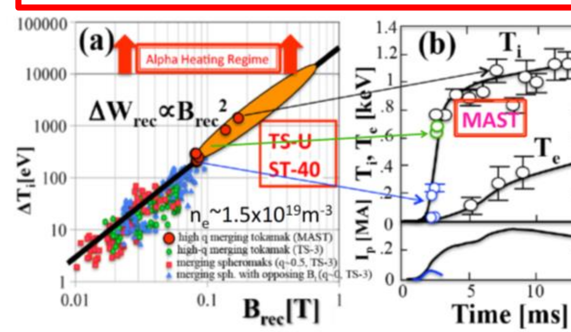
> ***Only merging***
—B_{rec} ~ 0.15T
—B_{rec} ~ 0.10T



Merging phase

Full operation

$\Delta T_i \propto B_{rec}^2$ → ~ 1keV achieved

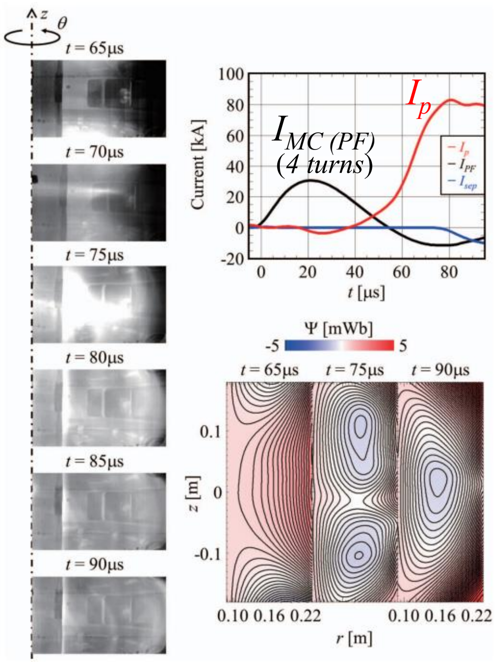


Y. Ono et al., IAEA FEC2018, EX/P3-24 (2018)
Y. Ono et al., Nucl. Fusion 59, 076025 (2019)

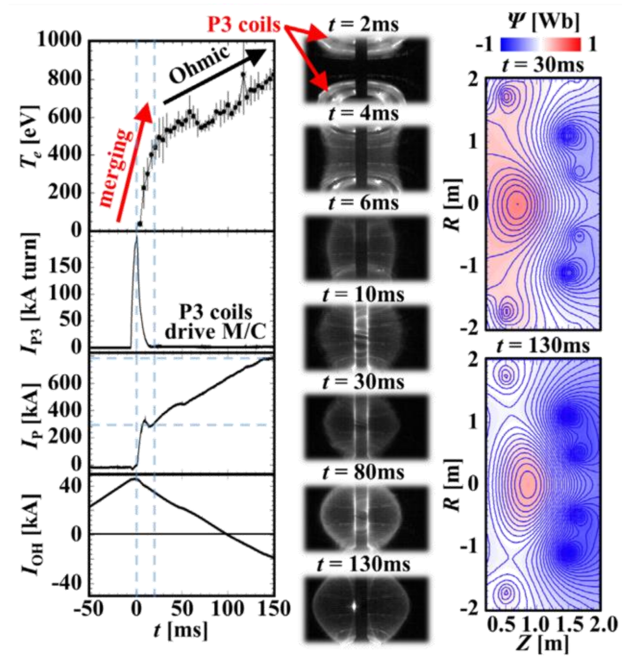
Merging/reconnection plasma startup

~ Many merging experiments reproduced the attractive startup performance ~

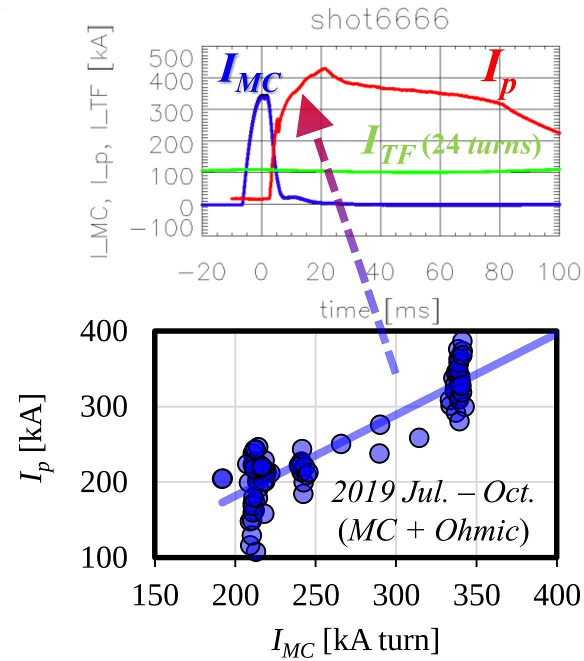
Ex1) TS-3 (U-Tokyo)

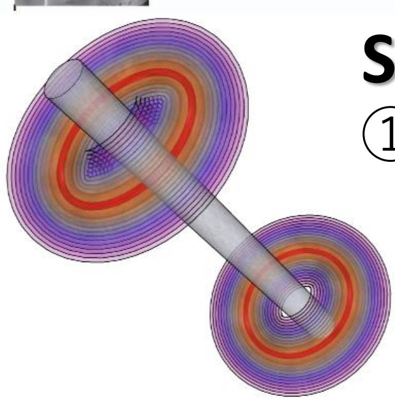


Ex2) MAST (CCFE)



Ex3) ST40 (Tokamak Energy)





Startup process of M/C plasma formation:

①Formation of 2 plasma rings (induction of MC coils)

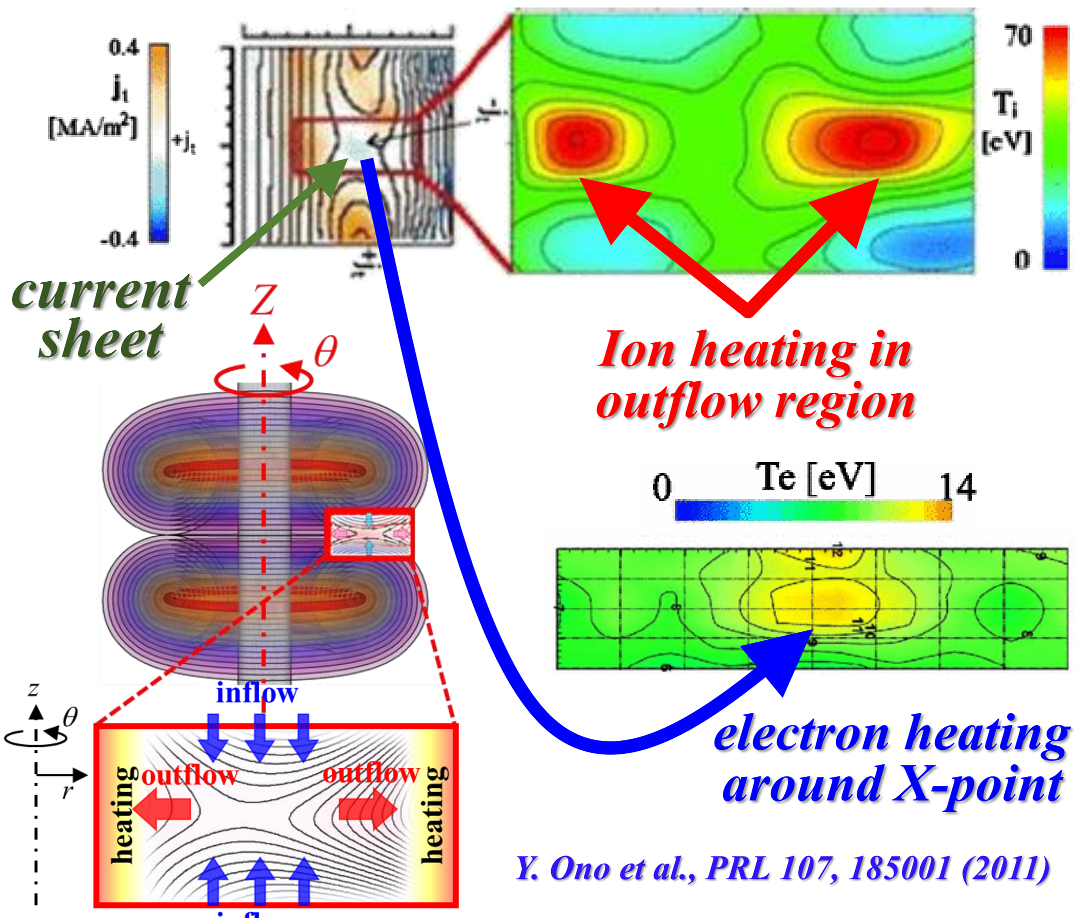
②Merging/reconnection starts around midplane

③Significant ion and electron heating by *Rec.*

④connection to steady scenario (OH/NBI, etc…)

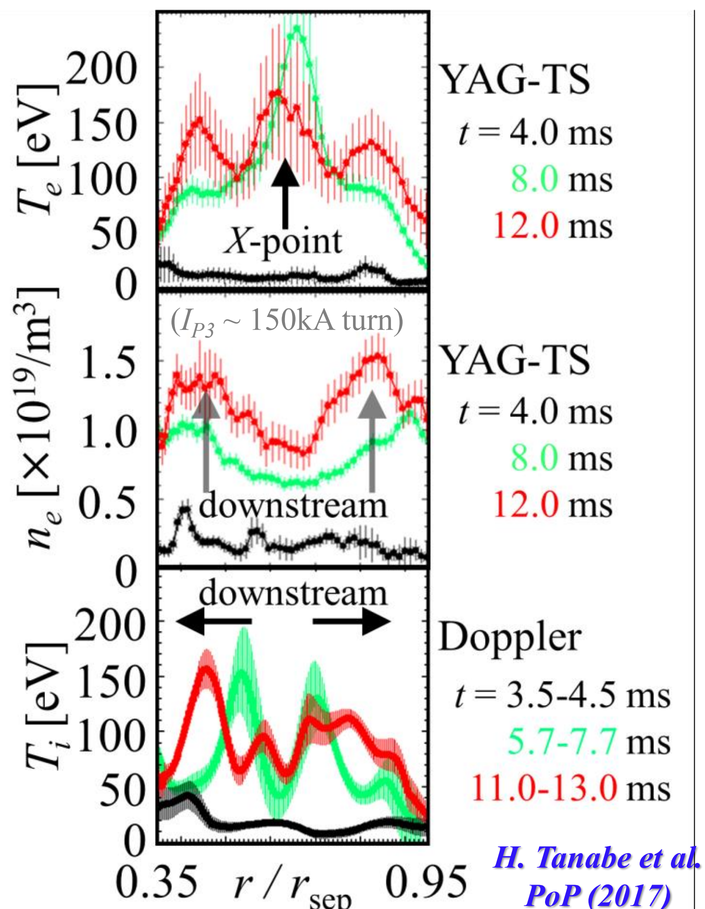
Typical feature of electron and ion heating characteristics during merging plasma startup

T_i, T_e and flux profile during merging in TS-3



Y. Ono et al., PRL 107, 185001 (2011)

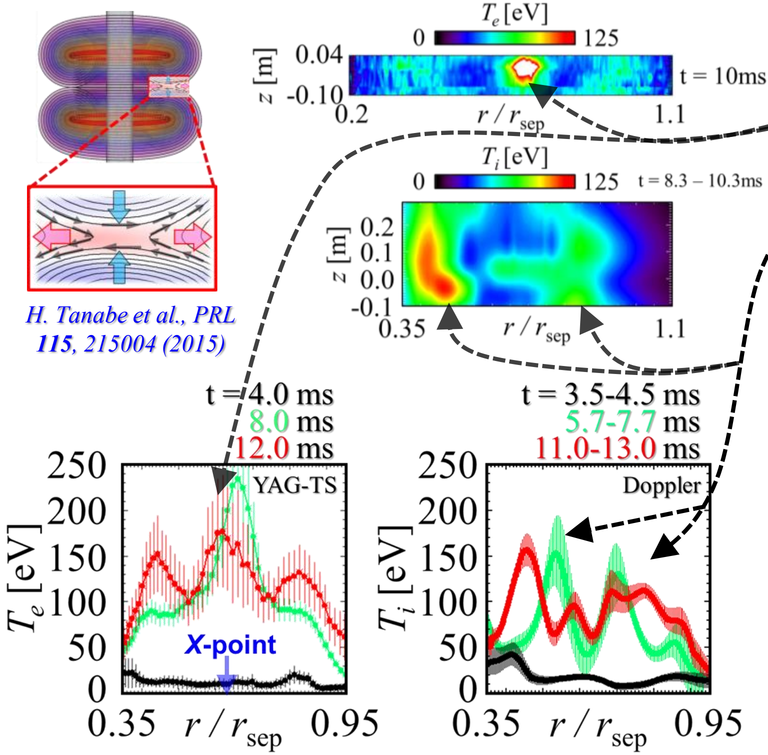
T_e, n_e and T_i profile in MAST



H. Tanabe et al. PoP (2017)

- T_e increases around X-point
- T_i increases downstream
- n_e increases in the outflow region
- T_e-T_i energy relaxation (triple peak) (τ^E_{ei} ~ 4ms)

Clearer characteristic fine structure has been pioneered in MAST high power merging *Exp*.



New findings in MAST:

- Highly peaked T_e *around X-point*
- Global ion heating downstream
- Local ion-electron energy relaxation to form triple peak distribution
- Finally both ions and electrons are globally heated
  → Exceeding radiation barrier and successful connection to long pulse scenario by saving CS flux consumption

Future works suggested from MAST results:

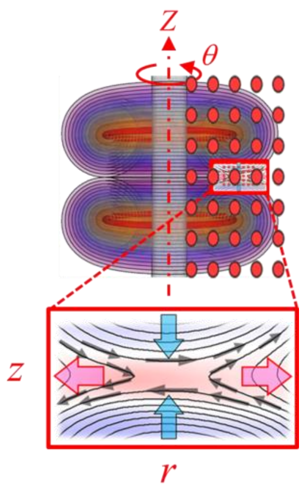
- If this research could be done with local magnetic diagnostics, underlying physics could be more clearly understood.
  → U-Tokyo M/C *exp.* starts TS-3 upgrade "TS-3U" (TS-6) with MAST-like ultra-high resolution diagnostics

Highlight of this talk:
MAST-like detailed profile measurement in *Lab. Exp.*

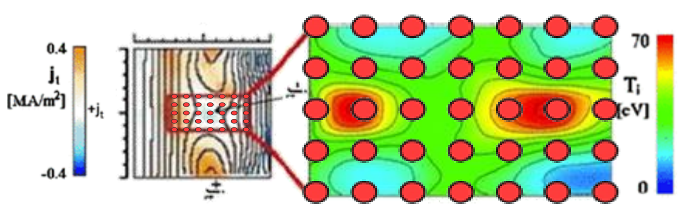
To investigate reconnection process, diagnostics needs to satisfy gyro-scale spatial resolution as presented by Y. Ono.

List of ion Larmor radius ρ_i [mm] vs B [T] and T_i [eV]

Larmor radius ρ_i [mm]				Atomic mass: A		1
B [T]↓ T_i [eV] →	1	10	50	100	150	200
0.05	2.00	6.32	14.14	20.00	24.49	28.28
0.1	1.00	3.16	7.07	10.00	12.25	14.14
0.2	0.50	1.58	3.54	5.00	6.12	7.07
0.3	0.33	1.05	2.36	3.33	4.08	4.71



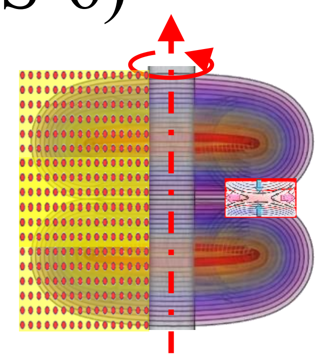
Previous TS-3: 35CH



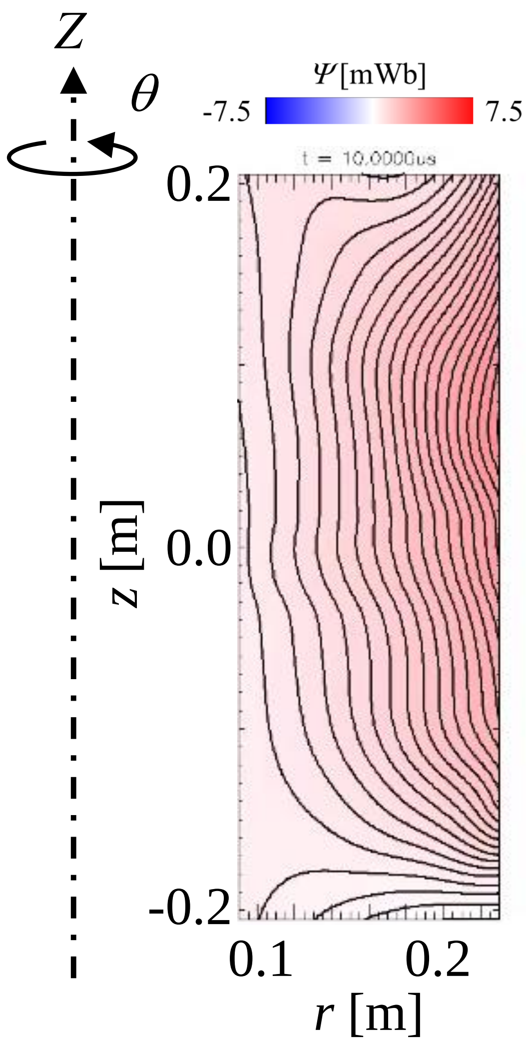
$\Delta r \sim 35mm >> r_i$

TS-3U (TS-6)

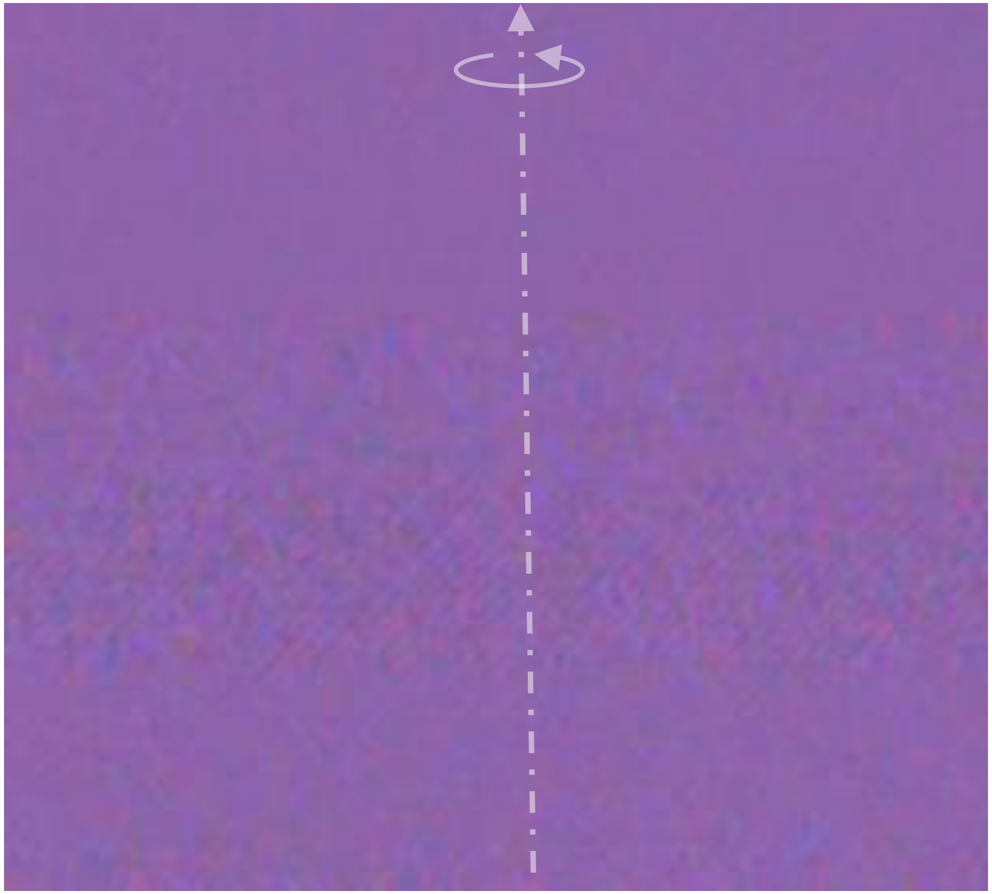
- 96CH (2016-2018)
- 320CH (2018-2019)



Dedicated *Lab.* experiment with in-situ magnetic measurement helps detailed understanding of the startup process (non-EFIT)

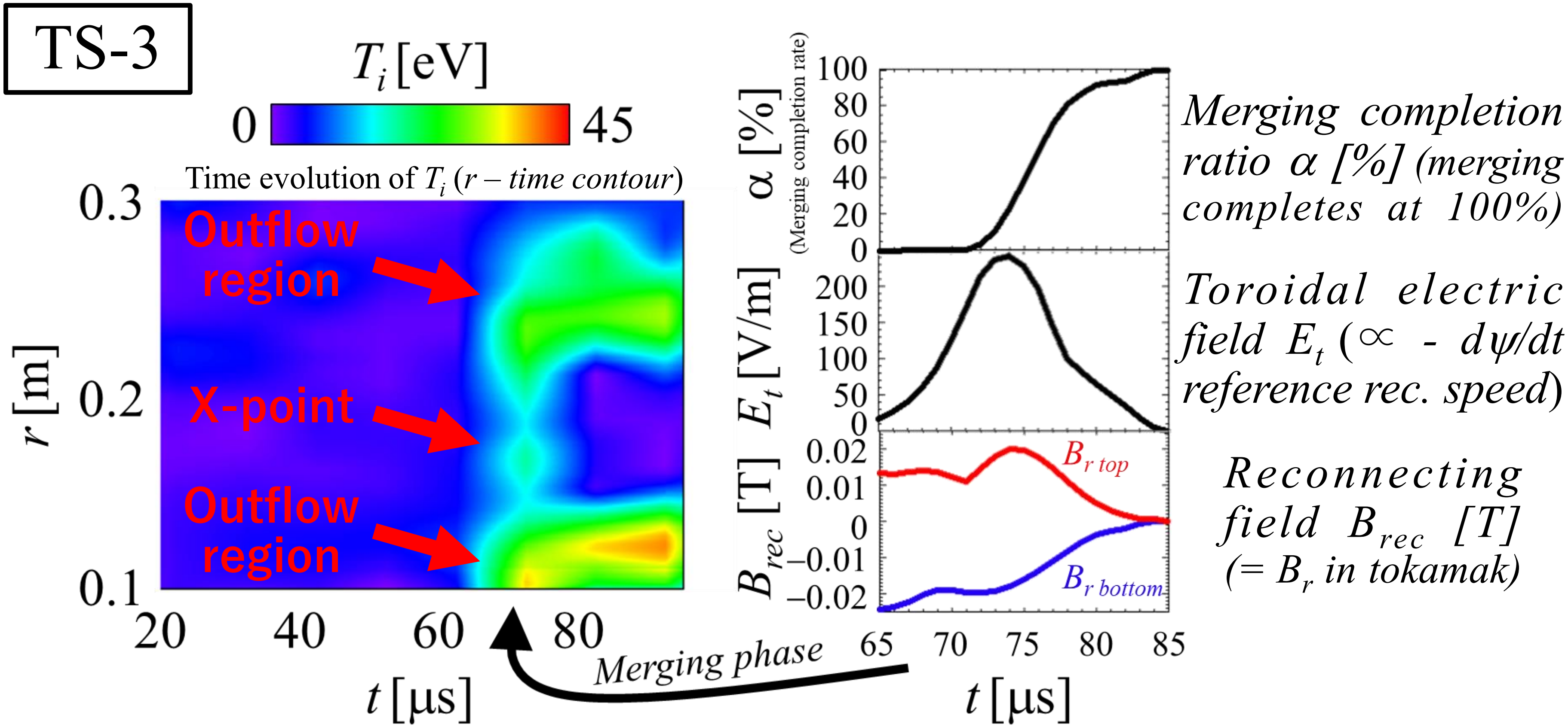


Tokamak merging in TS-3 (2μs/frame)



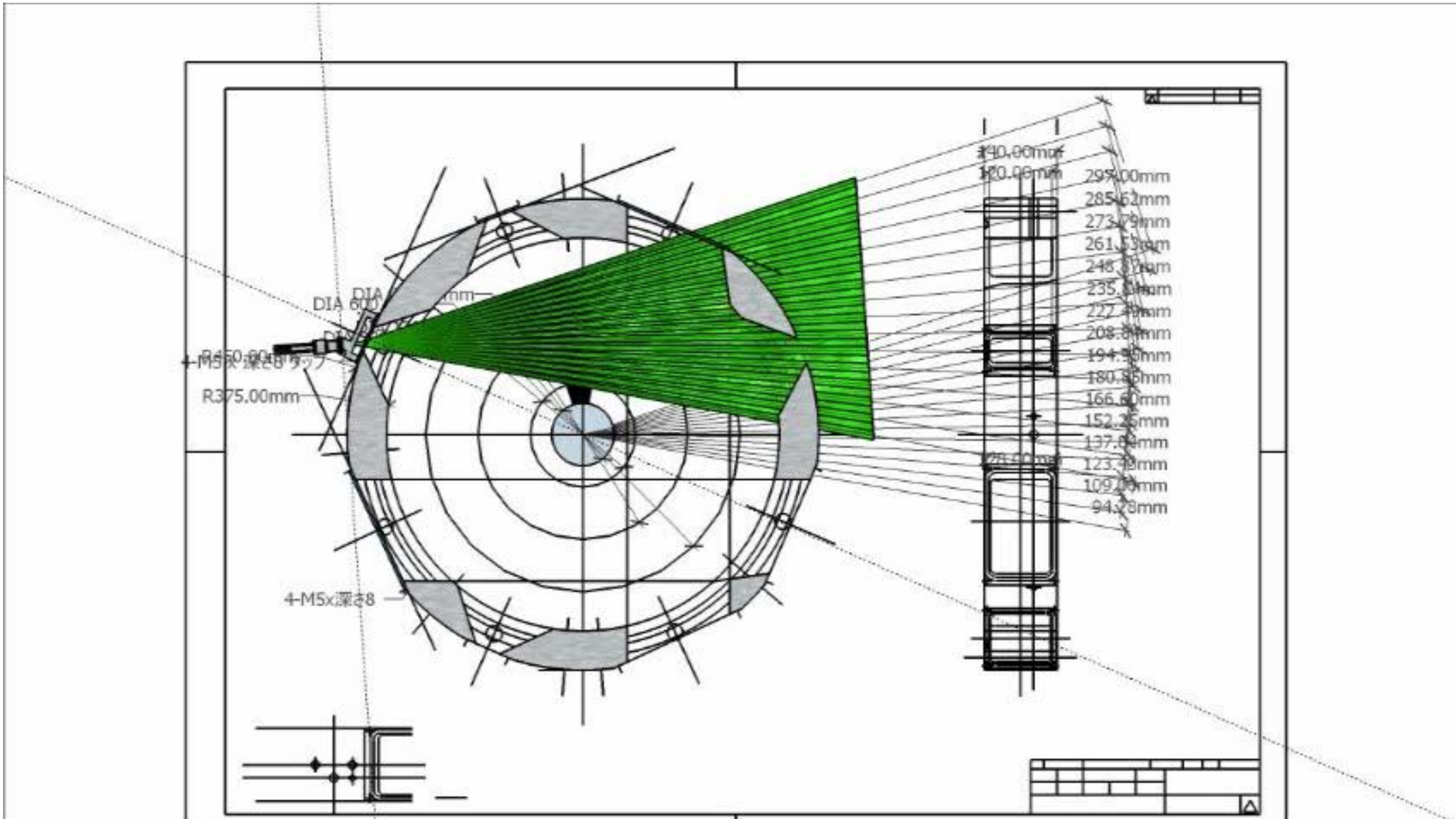
Typical merging/reconnection heating time scale in TS-3

T_i profile rapidly changes during M/C in the order of $\tau_{Alfven} \sim 10\mu s$



When merging completion ratio α increases around $t \sim 70\mu s$, magnetic reconnection occurs and it rapidly changes ion temperature profile to be doubly peaked structure downstream

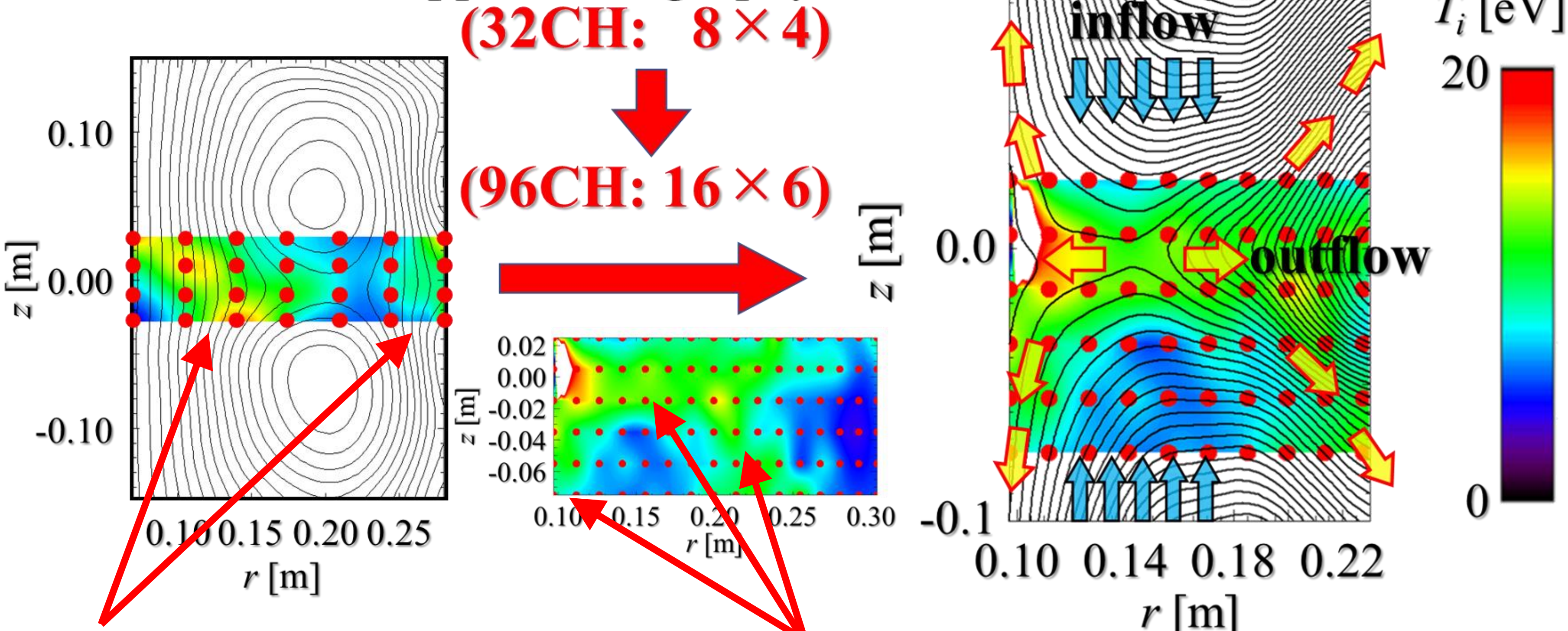
To approach the microscopic scale, a new 96CH 2D ion Doppler tomography has been developed



Results from the new 96CH spectroscopy system

~ MAST-like feature was successfully resolved by the new system ~

Previous 2D ion Doppler tomography:



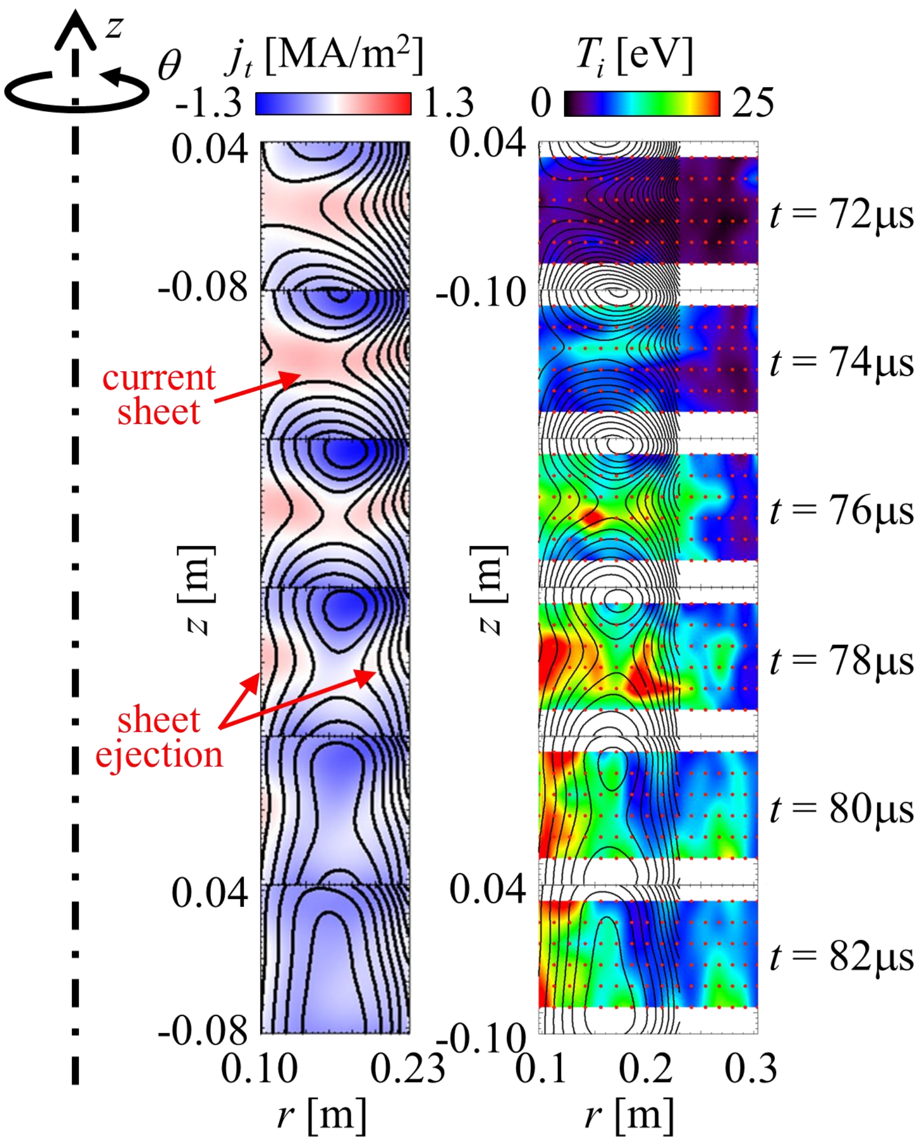
Previous system:

It only detects double-peak structure downstream.

New system:

Both <u>inside current sheet</u> and <u>globally downstream</u>

More detailed heating structure around X-point
～Initially heated around X-point and then downstream～



Phase 1:

Maximum apparent E_{rec}
(resistivity is not so high)

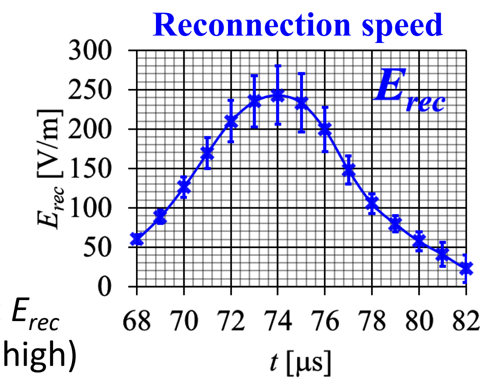
(Externally driven/ accelerated phase)

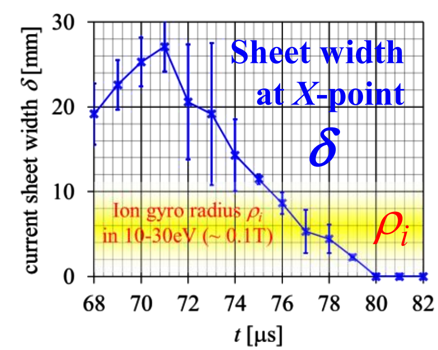
Phase 2:

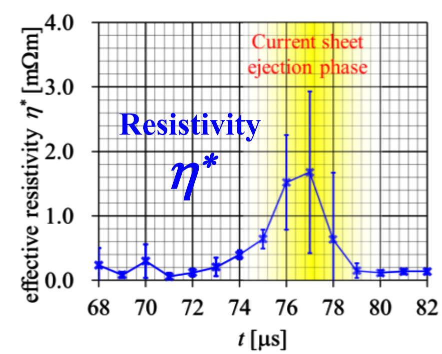
Anomalous resistivity phase

(Spontaneous fast reconnection phase)

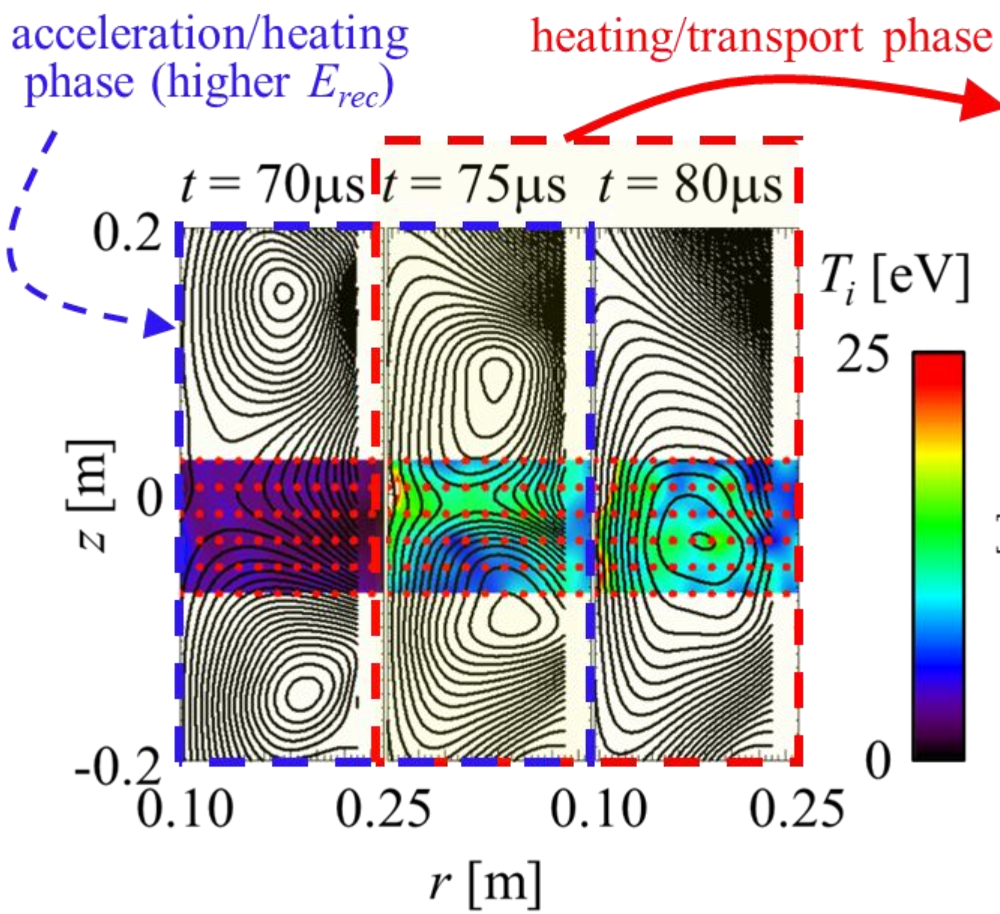
H. Tanabe et al., Plasma and Fusion Res.14, 3401110 (2019)

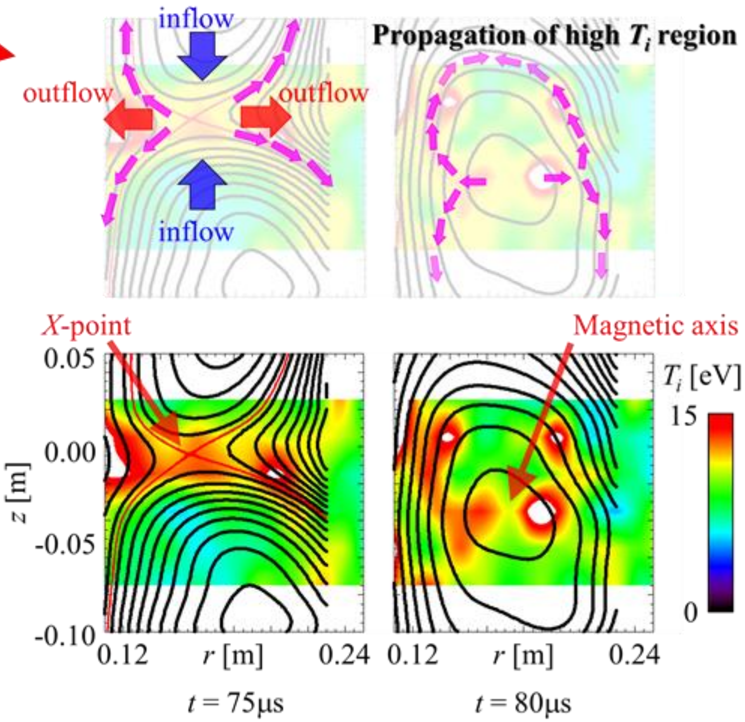






In global geometry, downstream outflow heating is trapped by thick layer of closed flux surface formed by reconnected flux





Poloidally double-ring-like global structure is formed after merging

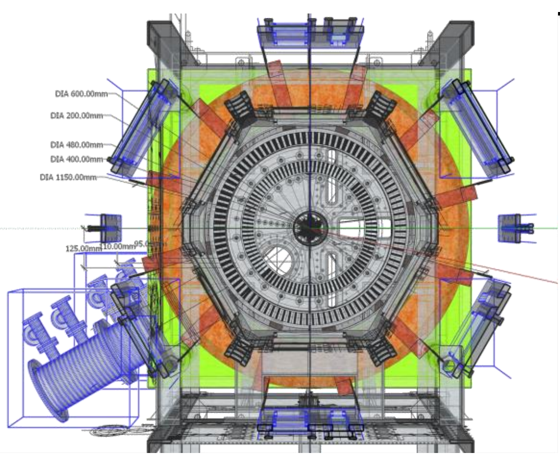
Outflow heating initially increases T_i downstream.

→ ion heat flux driven by $-\nabla T_i$ propagates on closed flux surface under the influence of higher $\chi^i_\perp/\chi^i_{//} \sim 2(\omega_{ci}\tau_{ii})^2 >> 1$ when high guide field exists.

Machine upgrade for more investigation of global physics
~ TS-3 shutdown and replacement to TS-3U (TS-6) ~

To improve the limited diagnostics access on TS-3 (only around *X*-point), a new experimental facility was installed at the end of 2017 (full 2D accessible).

Poloidally full 360 degrees diagnostics access available



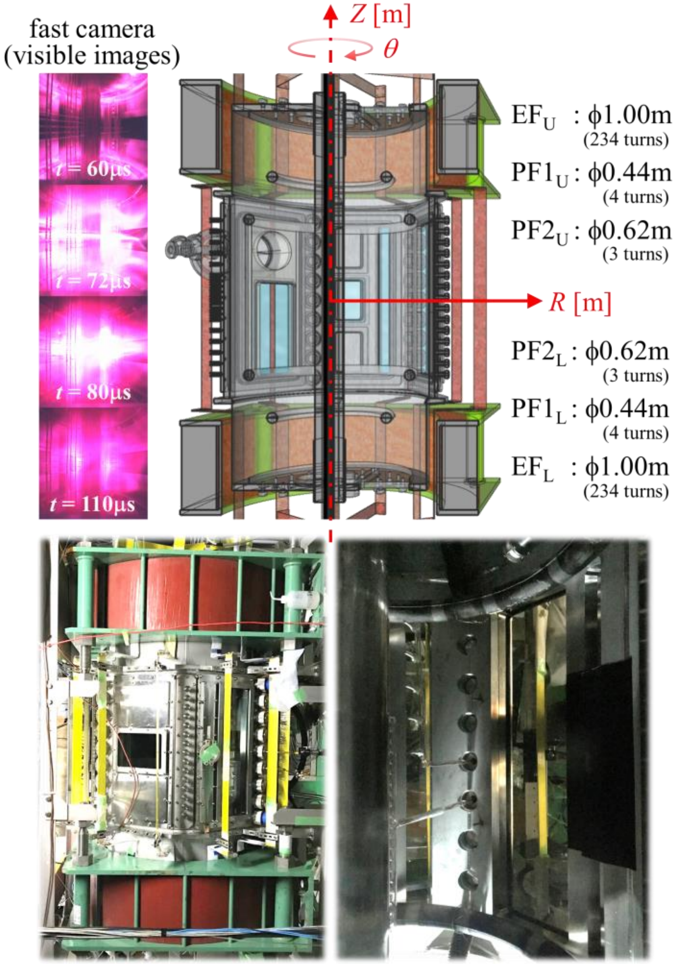
— Upgrade status: TS-3 → TS-3U (TS-6) —

- 2017/Oct. ： TS-3 shutdown
- 2017/Nov. ： the new vessel arrived
- 2017/Dec. – 2018/Feb. ：
  PF/TF/EF coil and TF return assembly, vacuum/gas, power supply connection, scenario development, etc…
- 2018/Mar. ： first plasma (low field operation)
- 2018/Apr.~ ： plasma commissioning (diagnostics test)
  --> 96CH/320CH ion Doppler tomography operational
- 2019/Summer ： installation of high field reconnection driving coils
- 2019/Nov. ~ : starting high field merging operation
- 2020 ~: construction of Ruby Thomson scattering system (96CH)

First plasma in TS-3U (TS-6)

~ The new experiment starts plasma commissioning from 2018 spring ~

TS-3U device (TS-6)

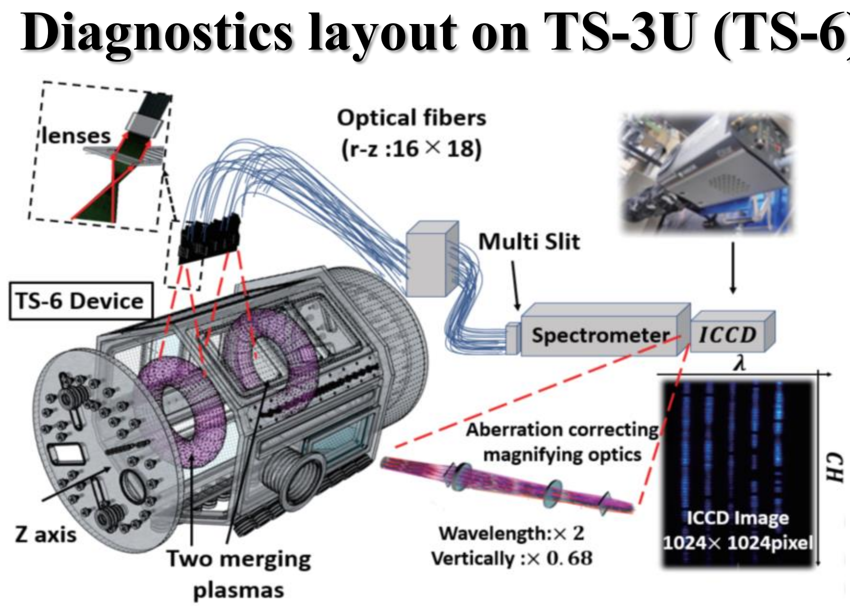


High speed camera (2μs/frame)

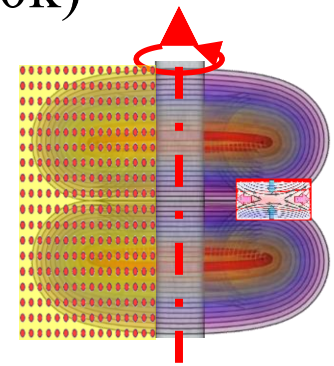
Development of 320 CH spectroscopy system

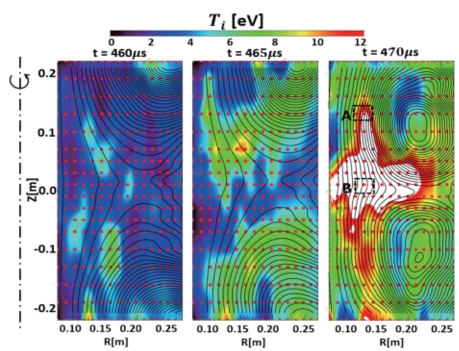
~ Global measurement with gyro-scale spatial resolution ~

Further diagnostics upgrade has been performed by *multi-slit spectroscopy technique* (upgrade cost < $20k)



H. Tanaka et al., IEEJ **139**, 358 (2019)

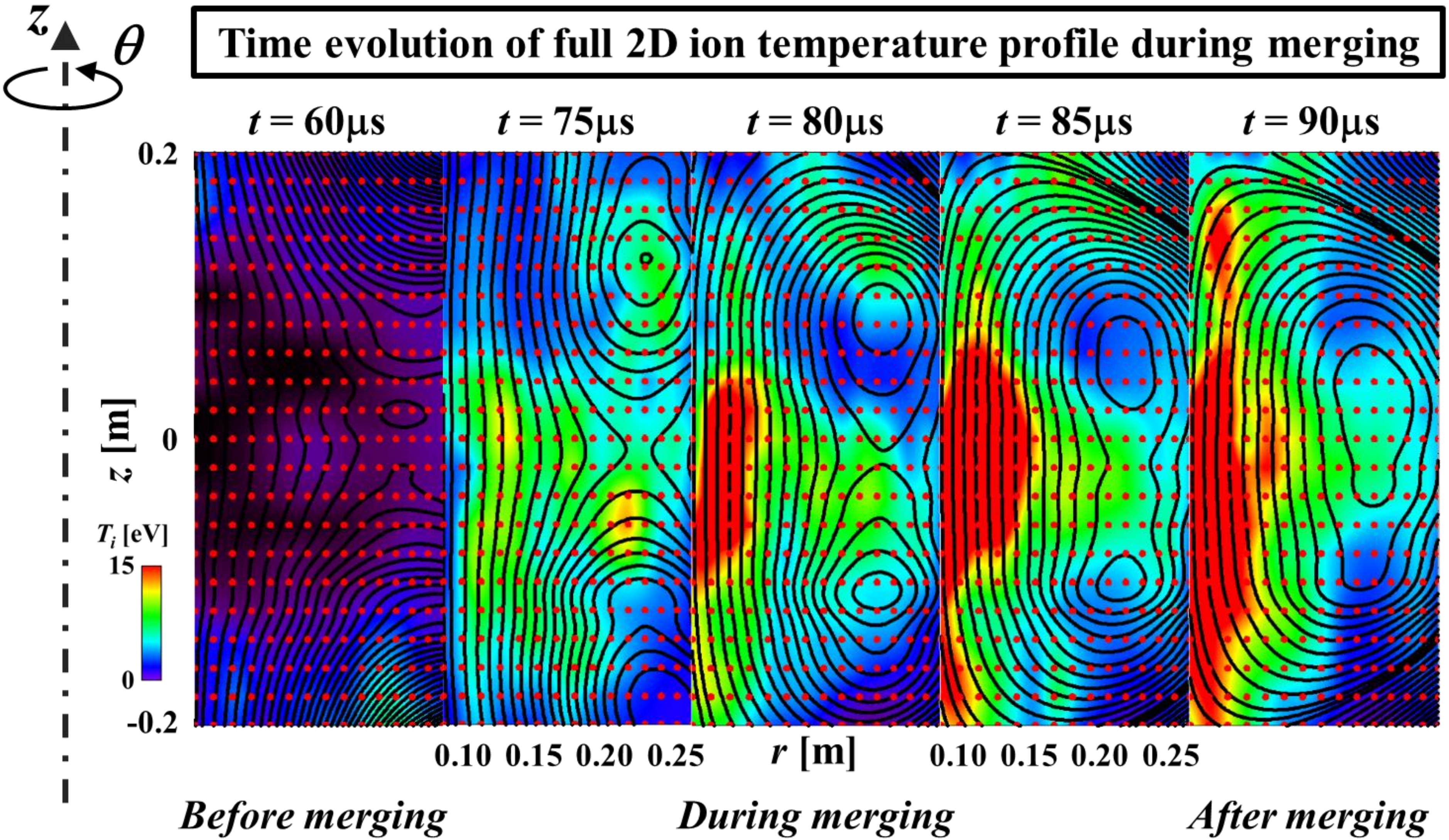




Diagnostics construction costs:

- Optical fibers: $2k
- Fiber bundle assembly: $3k
- Collecting lens: < $2.2k ($0.12k × 18)
- FC connecters/adapters: < $0.03k × 320)

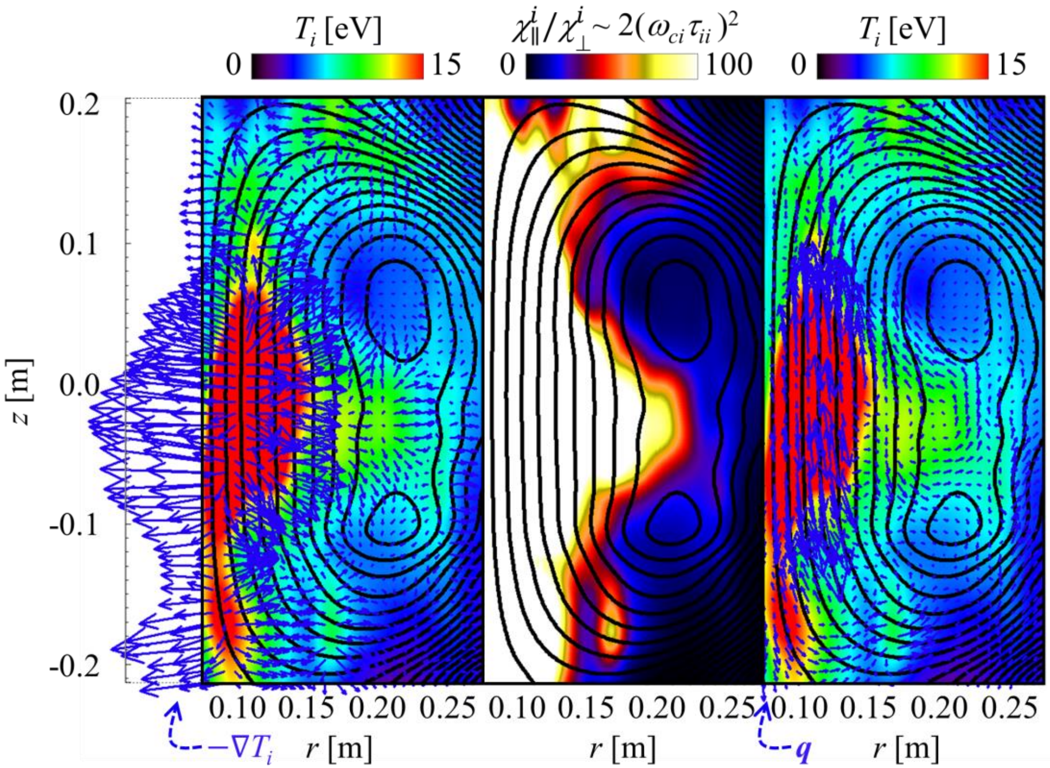
The new experimental facility enables full-2D imaging measurement of T_i profile



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

~ Reconnection heating phase ~ ***~ confinement/transport phase ~***

The hot spot formed by outflow heating forms higher ∇T_i downstream but its cross-field component is strongly suppressed by high guide field



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

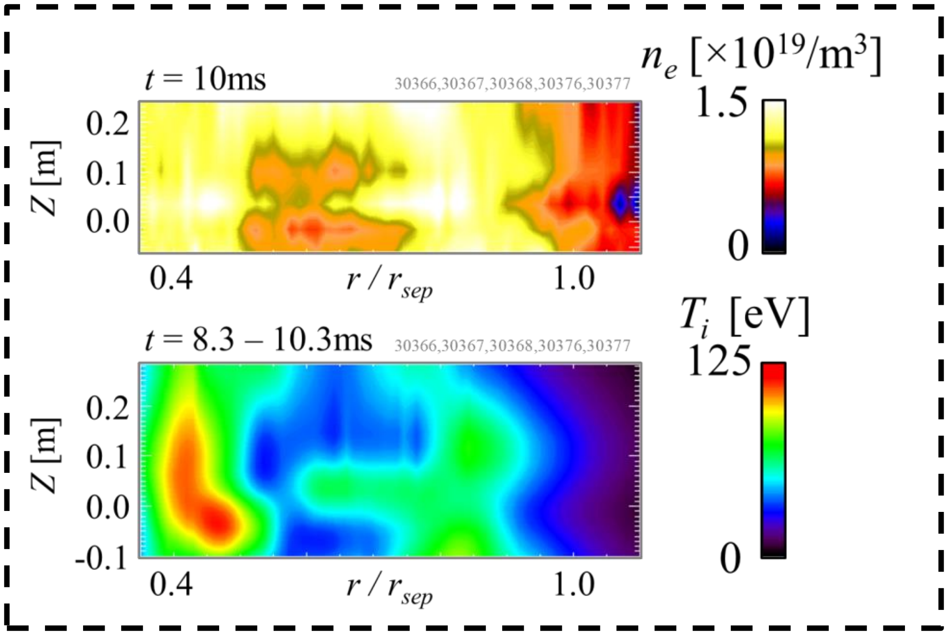
In comparison with no guide field experimental condition (typically $\chi^i_{\perp}/\chi^i_{//} \sim 1$), ion heat flux mostly propagates on field line direction for guide field reconnection.

→ From the view of application scenario, high guide field reconnection is more promising to develop a practical operation scenario than spheromak based one.

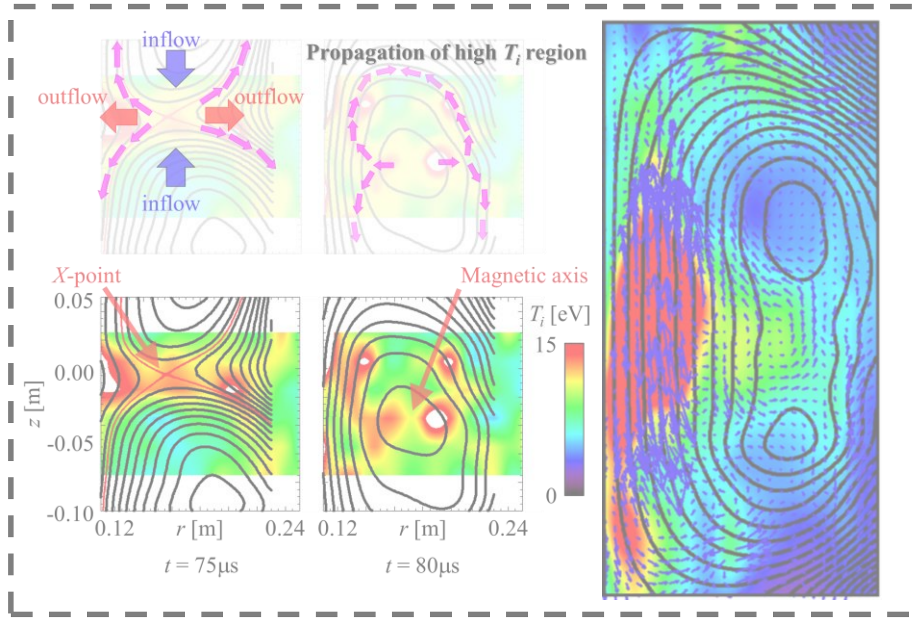
Comparison of 2D profile in MAST and TS-6

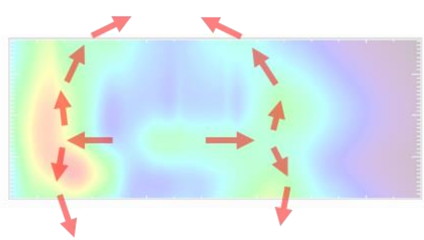
~ the characteristic profile formation mechanism has been clearly solved ~

2D profile in MAST



Reference structure in TS-6



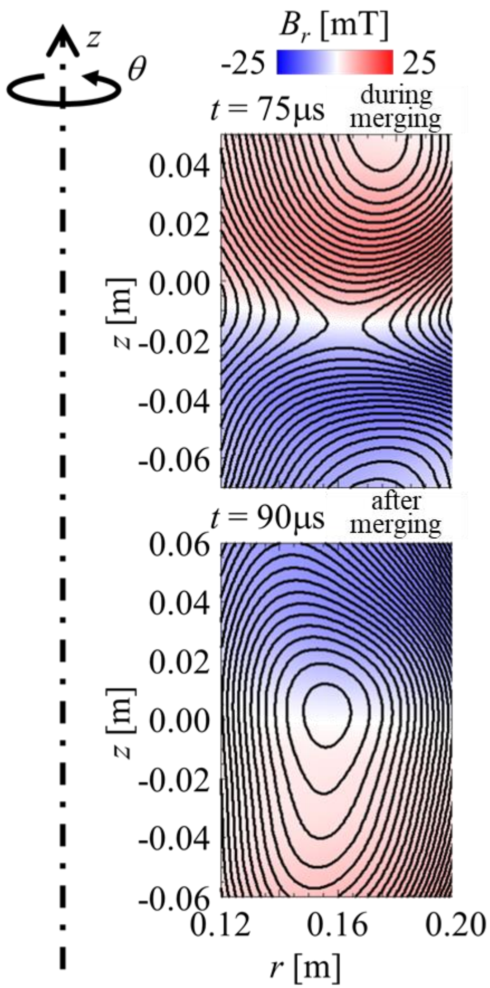


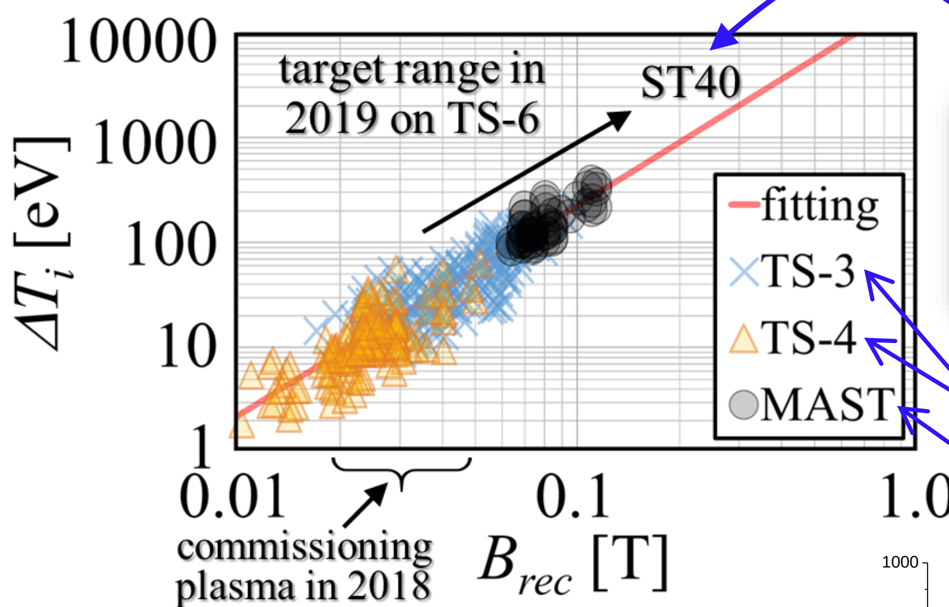
Better downstream transport property:

$$\chi^i_{//}/\chi^i_{\perp} \sim 2(\omega_{ci}\tau_{ii})^2 >> 100 \text{ satisfied}$$

(negligible heat loss by collision/transport)

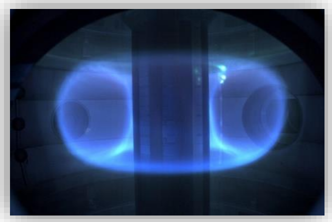
Achieved reconnection heating mostly depends on B_{rec}^2 ($\propto B_p^2 \propto I_p^2$) and negligible dependence on toroidal field:





ST40 target:

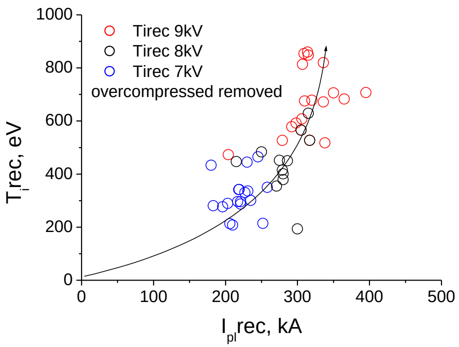
- B_{rec}: 0.1 - 0.5T
- B_t = 0.5 - 3.0T



Guide field:

- B_t = 0 ~ 0.2T
- B_t = 0.3 ~ 0.8T

Tokamak Energy Ltd. and U-Tokyo recently have more weight on high field tokamak merging for future upgrade scenario because higher $\chi^i_{//}/\chi^i_{\perp}$ is necessary required to confine reconnection heating.



Ref. from M. Gryaznvich in ST40 high field M/C

Summary and conclusion

Recent progress of the experimental study of merging/reconnection heating for the application to spherical tokamak was briefly reviewed

- **Magnetic reconnection heats ions by conversion of flow energy (kinetic energy) of outflow jet to ion thermal energy downstream**
- **Ultra-high resolution 2D imaging measurement revealed two types of fine structures both around X-point and downstream**

  1. Around X-point:

     > *Ion temperature increment around diffusion region is observed*

     > *Impulsive ejection event produces clear two hot spots downstream*

     After merging (transport/confinement phase):

     > *Hot spots formed by outflow heating is transported on field line direction*

     > *Poloidally double-ring structure formation by toroidal confinement*

- **Promising transport feature after merging has successfully been demonstrated when high B_t/B_{rec} condition ($B_t/B_{rec} > 3$) is satisfied**