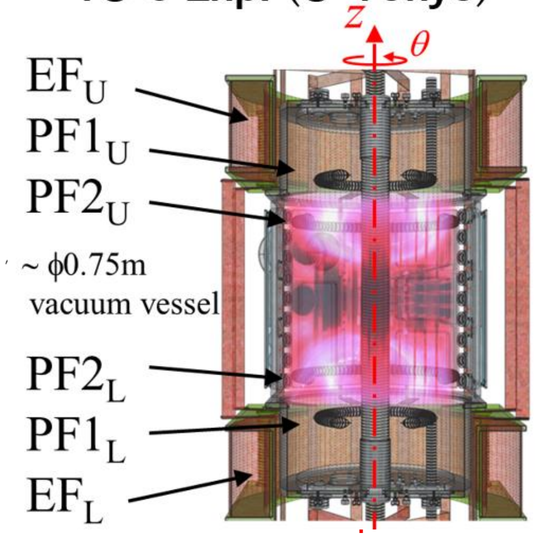
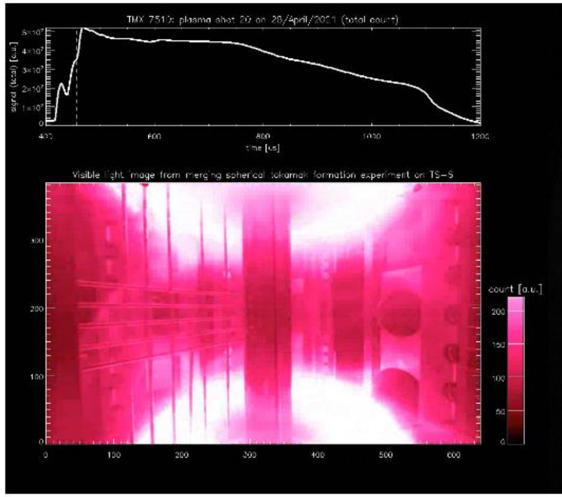
Workshop on the Interrelationship between Plasma Experiments in the Laboratory and in Space (IPELS-16)
Plenary 6, 79, 11:15-11:45, 5/Aug.

Particle acceleration/heating of high guide field reconnection in merging spherical tokamak formation experiments

TS-6 Exp. (U-Tokyo)

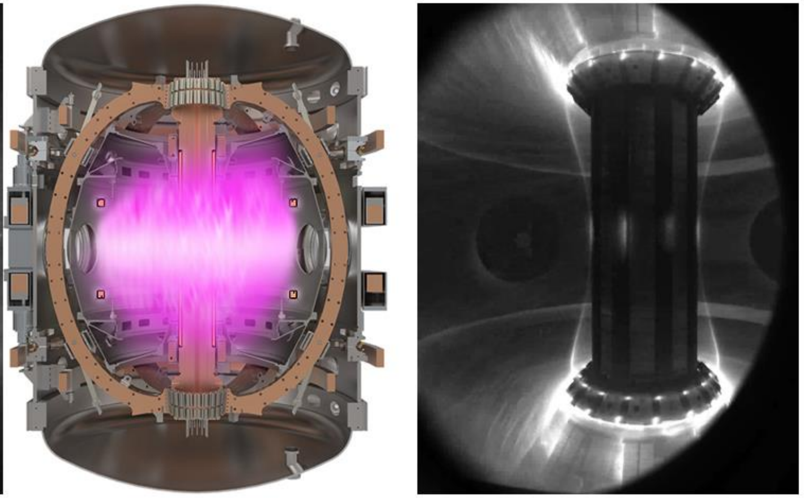


Plasma scenario (full)



Merging phase

ST40 Exp. (Tokamak Energy Ltd.)



Hiroshi Tanabe[1] (University of Tokyo)

H. Tanabe[1], R. Someya[1], T. Ahmadi[1], M. Gryaznevich[2], D. Osin[2], H. Willet[2], H. Lowe[2], M. Inomoto[1] and Y. Ono[1]
1) University of Tokyo, 2) Tokamak Energy Ltd.

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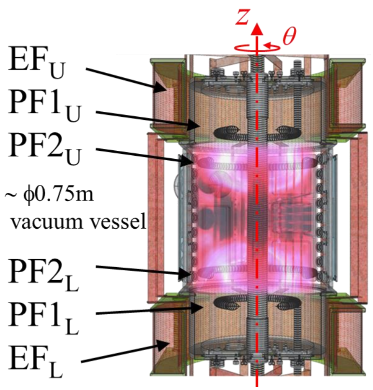
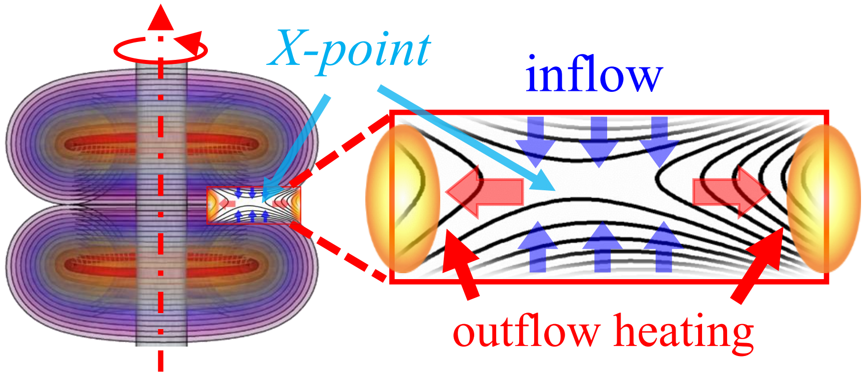
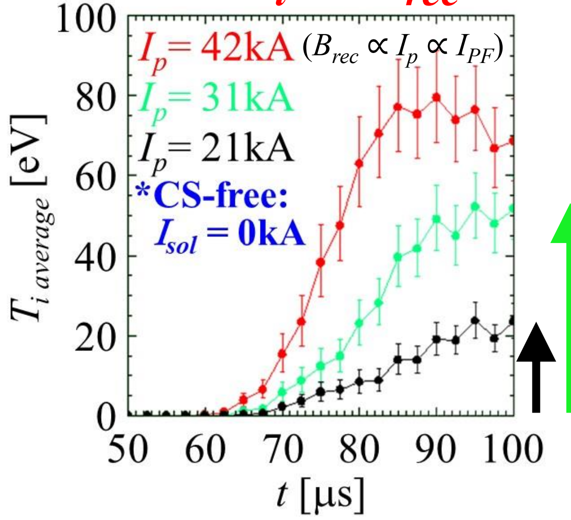
Highlight of this talk:
Rec. heating and its application for fusion plasma scenarios

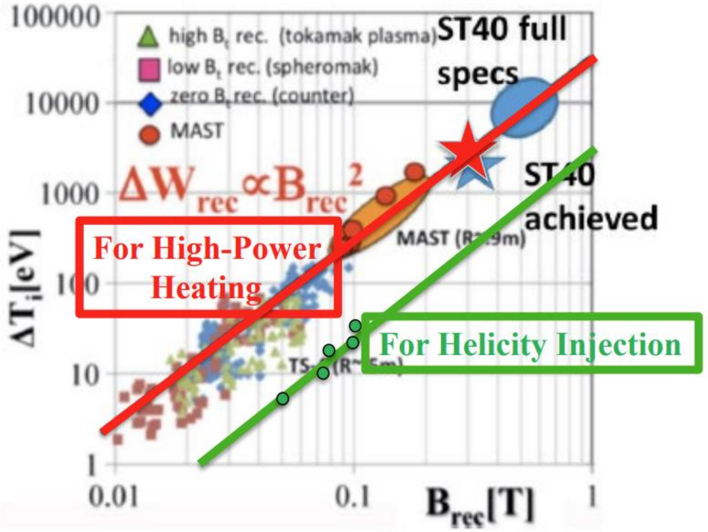
①TS-6 experiment (U-Tokyo)





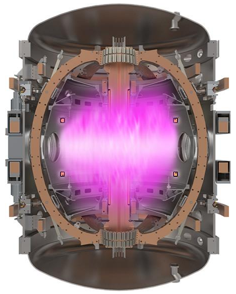
$\Delta T_i \propto B_{rec}{}^2$

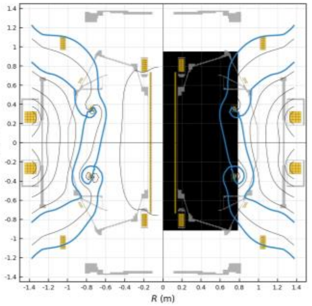




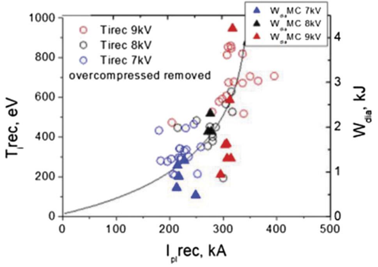
Y. Ono's talk on Monday

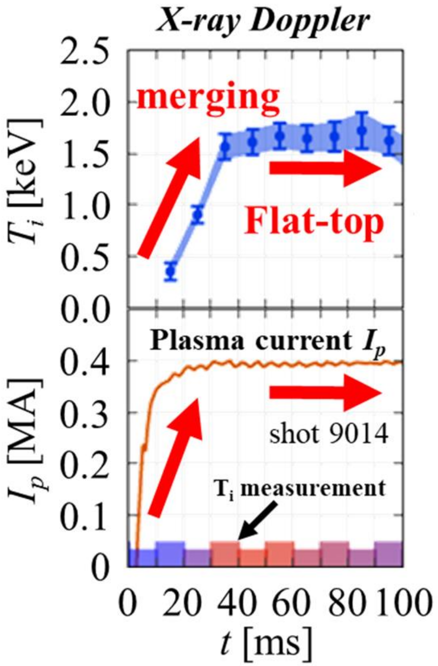
②ST40 experiment (Tokamak Energy)

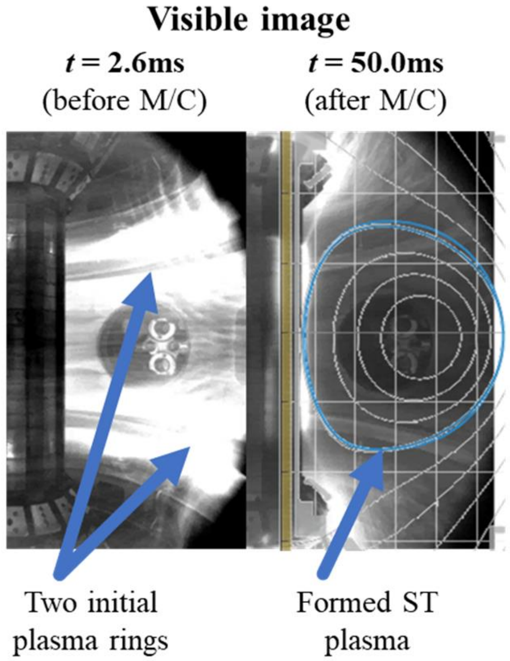




M. Gryaznevich et al., Nucl. Fusion 62 042008 (2022)







Outline

①TS-6 experiment (U-Tokyo)

- Ion heating/transport in flux tube merging configuration
- Sustainment/confinement of ion heating inside the closed flux surface after merging

Detailed investigation of reconnection process **with in-situ probe diagnostics**

- ➢ 2D magnetic diagnostics is available
- ➢ 2D 96CH/320CH Doppler tomography

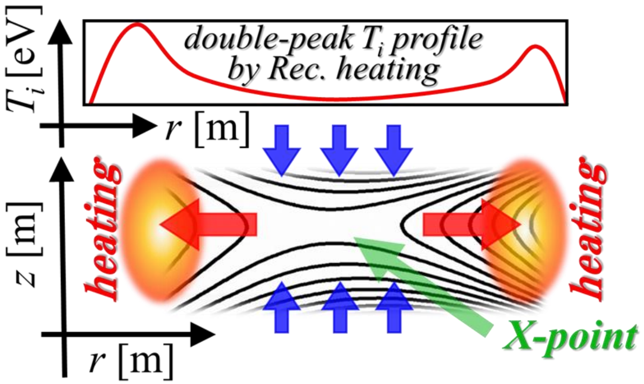
②ST40 experiment (Tokamak Energy)

- Quick review of high field application in ST40
- First measurement of both ion and electron temperature profile during *Rec.* heating

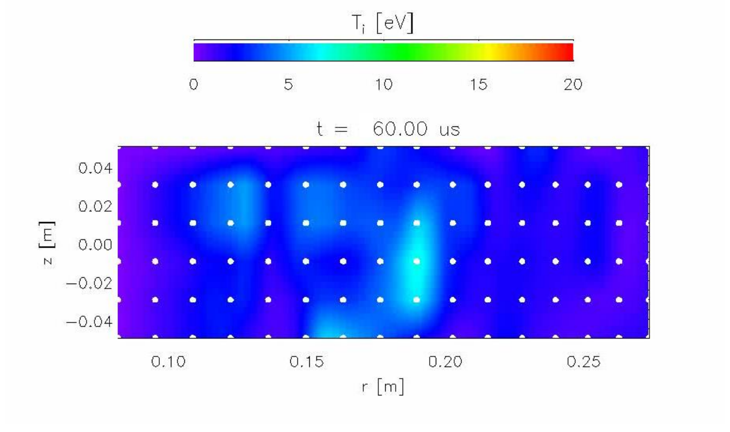
Application of reconnection heating in the **keV range** (in-situ probes are not available)

- ➢ 30CH Thomson scattering
- ➢ 32CH/96CH Doppler tomography

Typical feature of ion heating during magnetic reconnection in TS-6
~ ions are heated in the downstream region of outflow jet ~

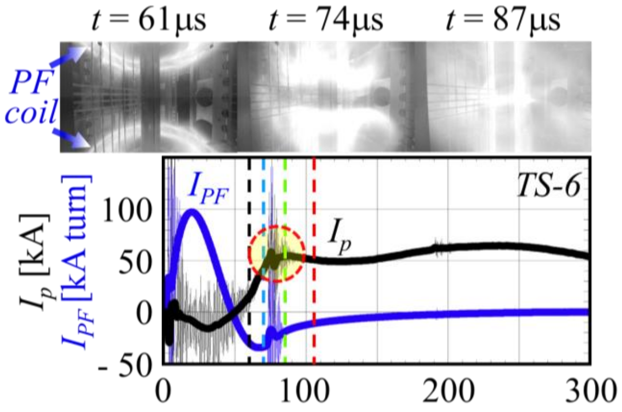


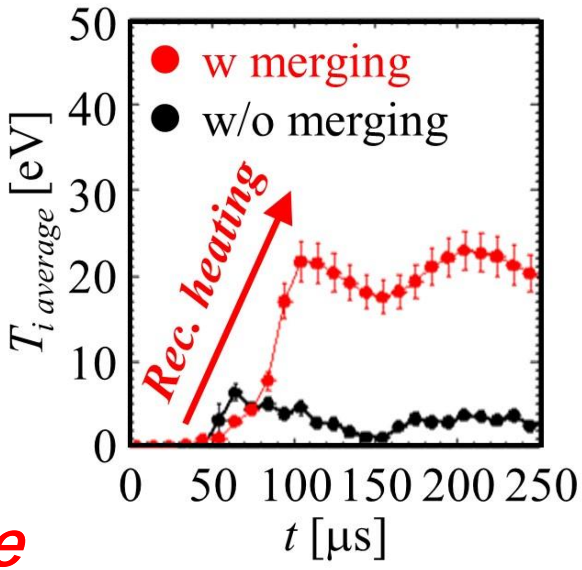
(a) Geometry of magnetic reconnection

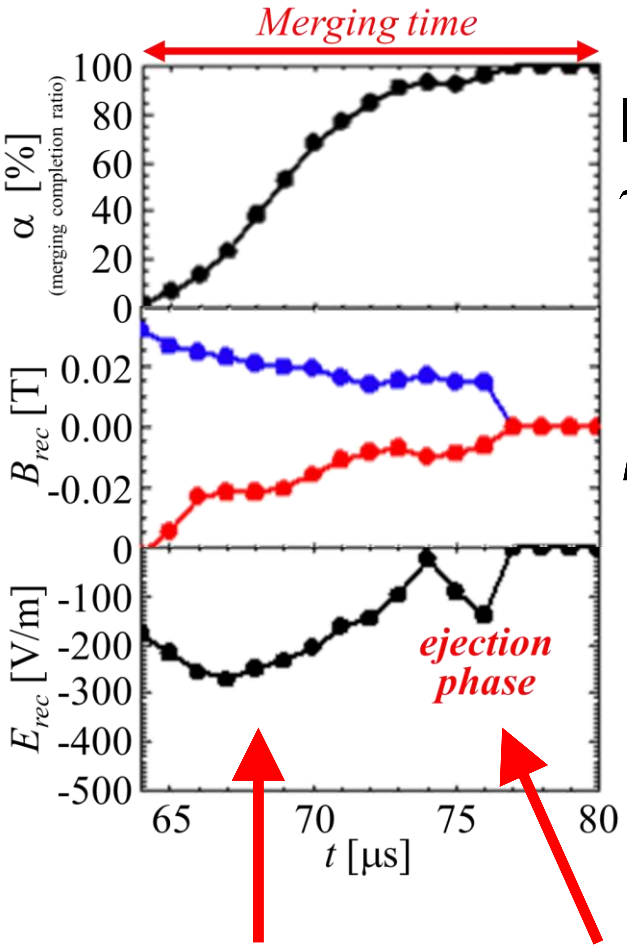


(b) Time evolution of T_i profile (movie)

Double-peak T_i structure







Merging time:
$\tau_{rec} \sim$ 10-20μs

Dissipation of *Rec.* field B_{rec}

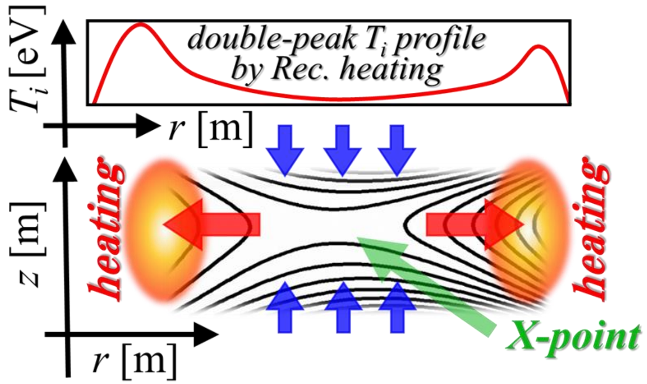
Rec. rate:
Two stages
of fast *Rec.*

driven phase

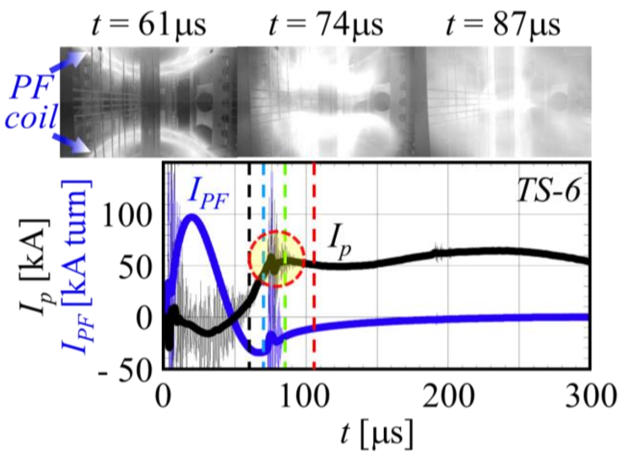
Spontaneous phase

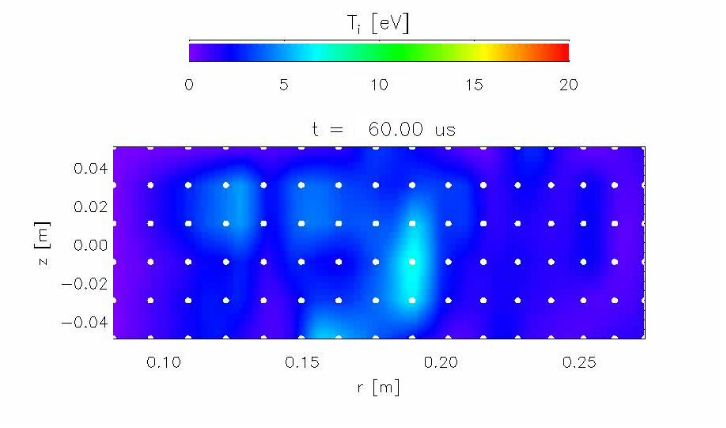
Typical feature of ion heating during magnetic reconnection in TS-6

~ ions are heated in the downstream region of outflow jet ~

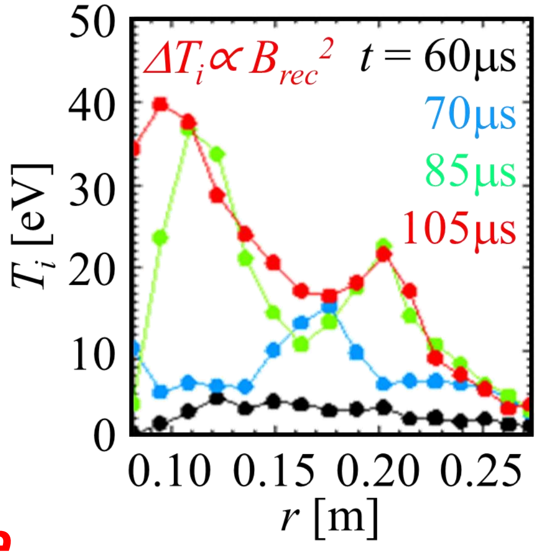


(a) Geometry of magnetic reconnection



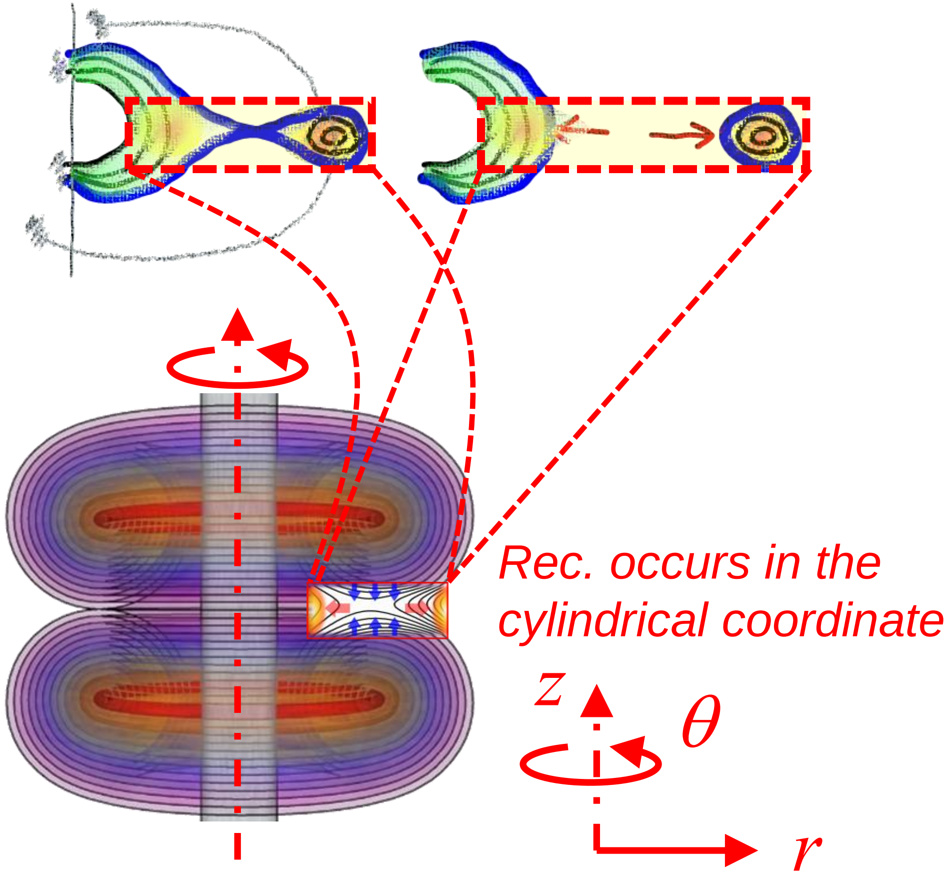


(b) Time evolution of T_i profile (movie)



Double-peak T_i structure

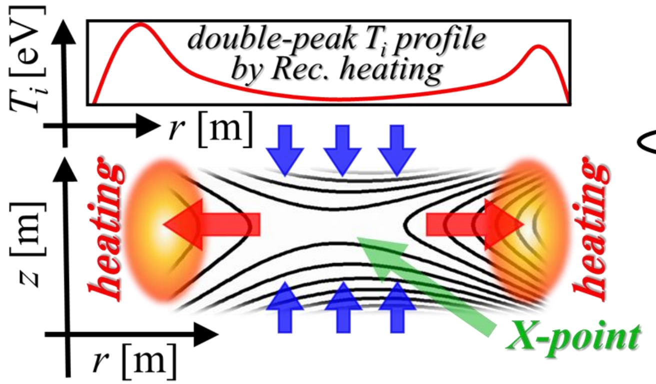
Comparison with solar flare



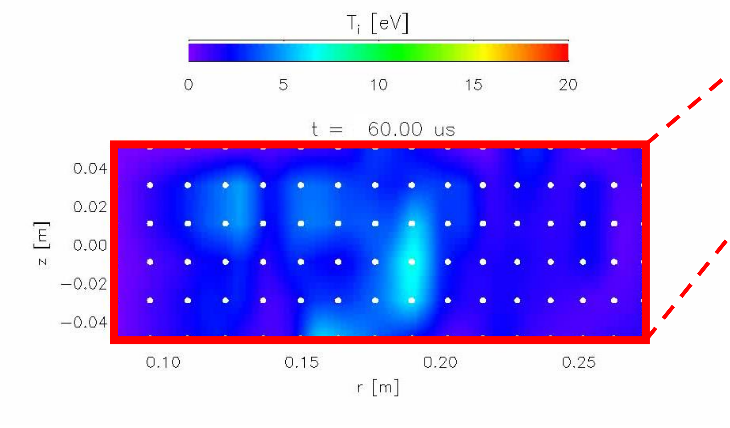
Rec. occurs in the cylindrical coordinate

Confinement of reconnection heating in the downstream region

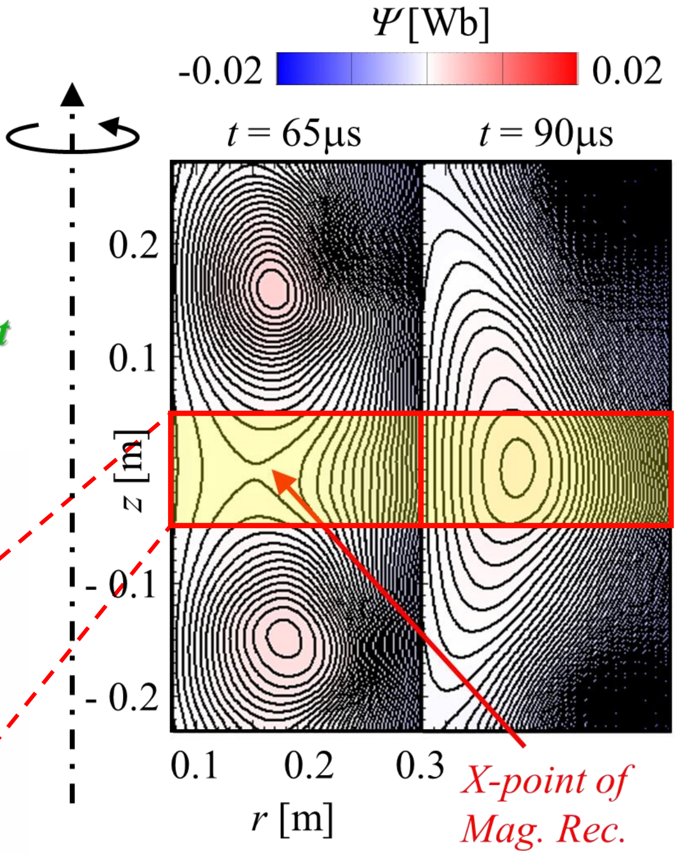
~ Reconnected fields lines form closed flux surface after merging ~



(a) Geometry of magnetic reconnection

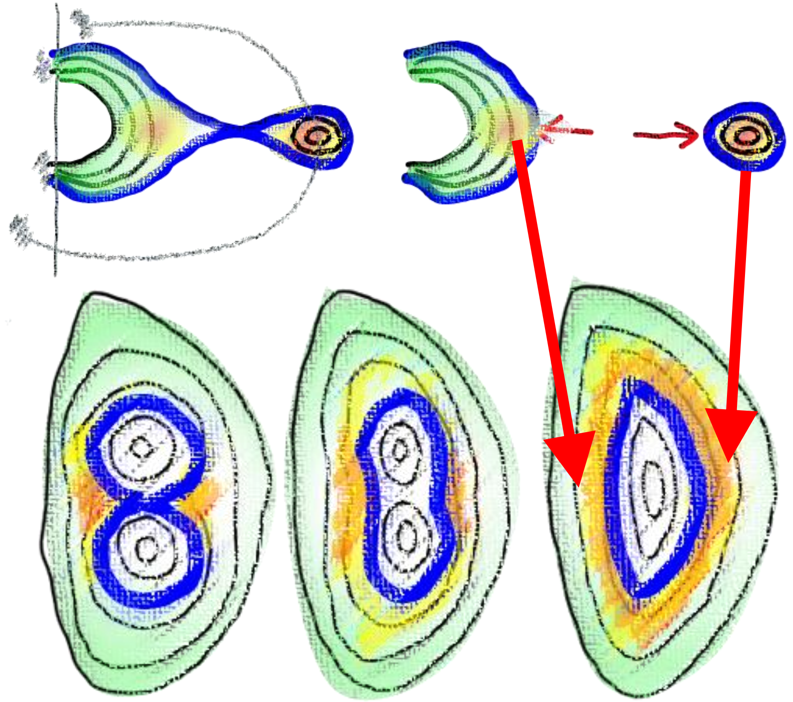


(b) Time evolution of T_i profile (movie)



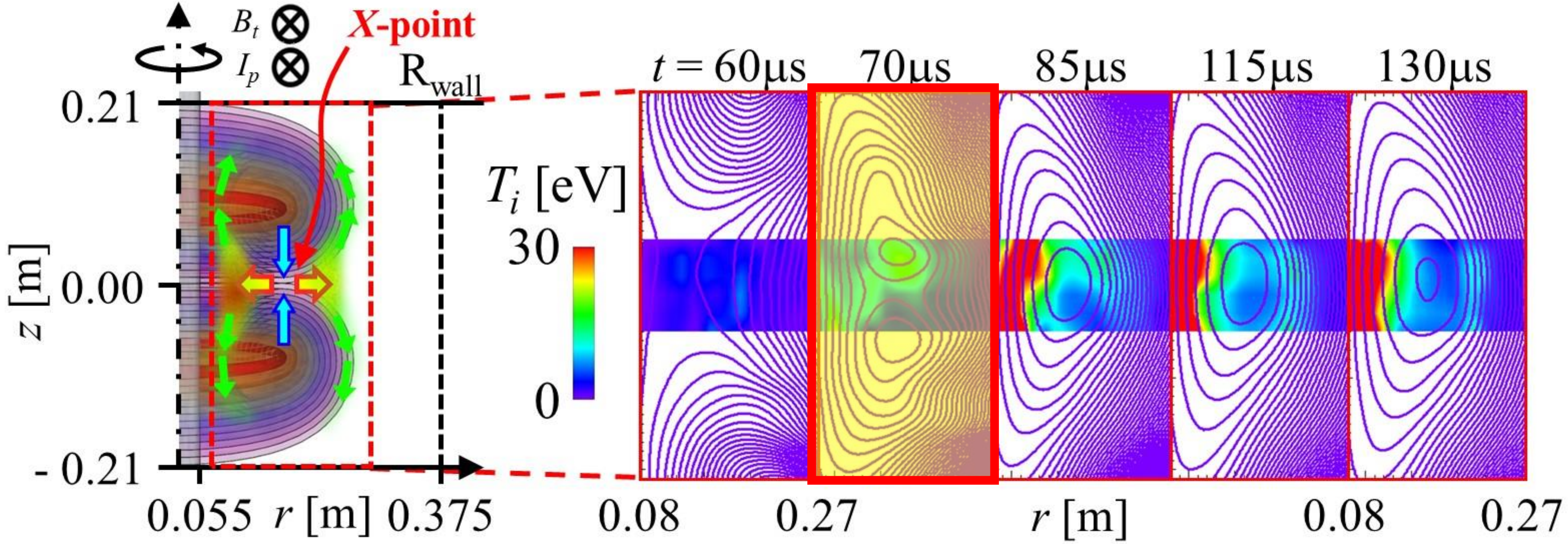
(c) Poloidal flux profile ($B_t/B_{rec} \sim 5$)

Comparison with solar flare



Downstream reconnection heating is confined inside the closed flux surface

After the end of merging, the heated ions are sustained/confined inside the closed flux surface



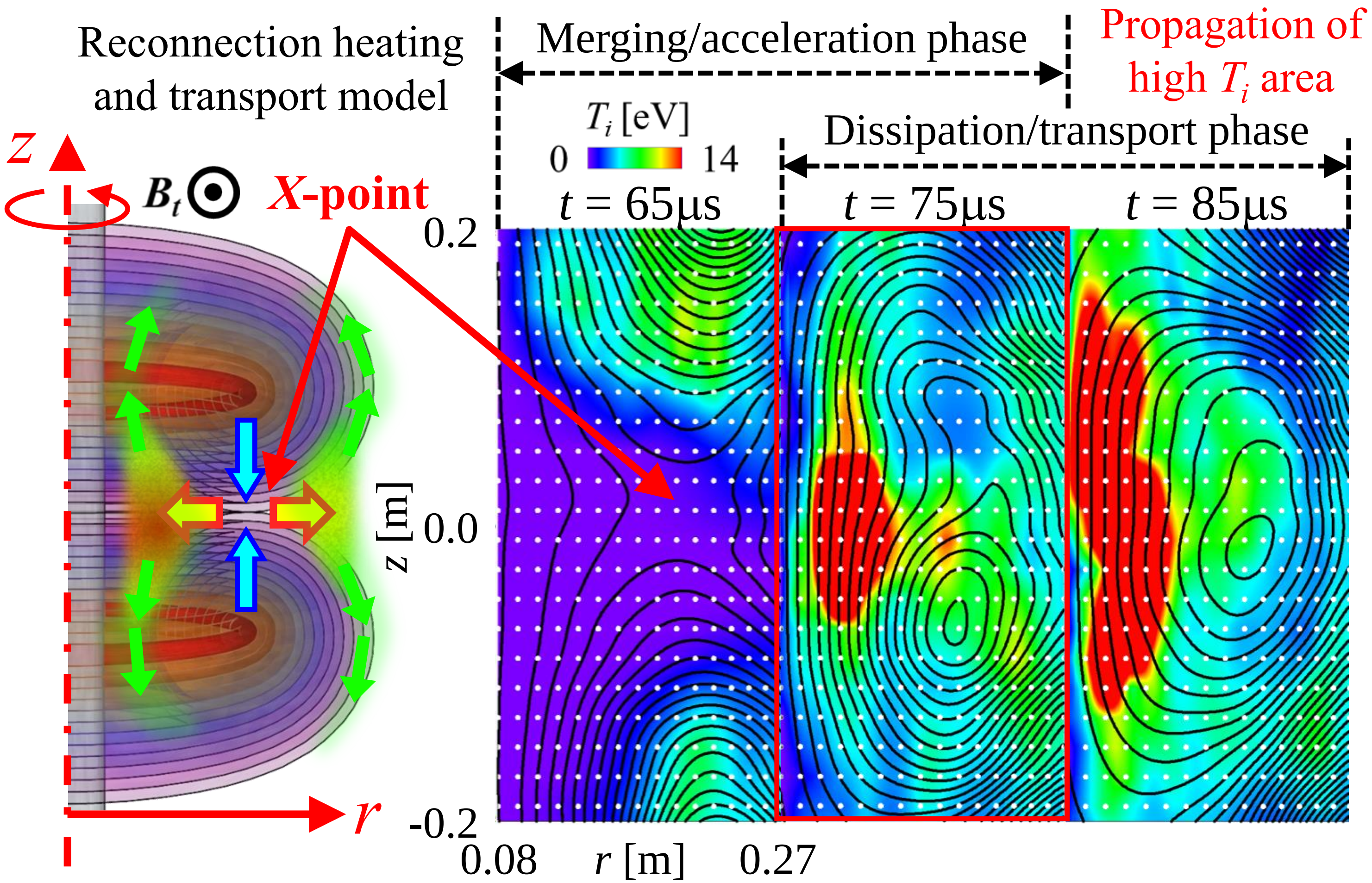
$B_t \sim 0.15$T, $B_{rec} \sim 0.03$T, $\omega_{ci}\tau_{ii} >> 1$
(guide field ratio $B_t/B_{rec} \sim 5$)

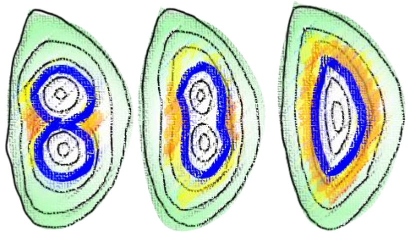
➡

Perpendicular heat conduction is strongly suppressed: $\kappa^i_{//}/\kappa^i_{\perp} \sim 2(\omega_{ci}\tau_{ii})^2 >> 1$

The structure is clearer with full-2D T_i imaging measurement

~ Rec. originated high T_i area propagates globally in the poloidal direction ~

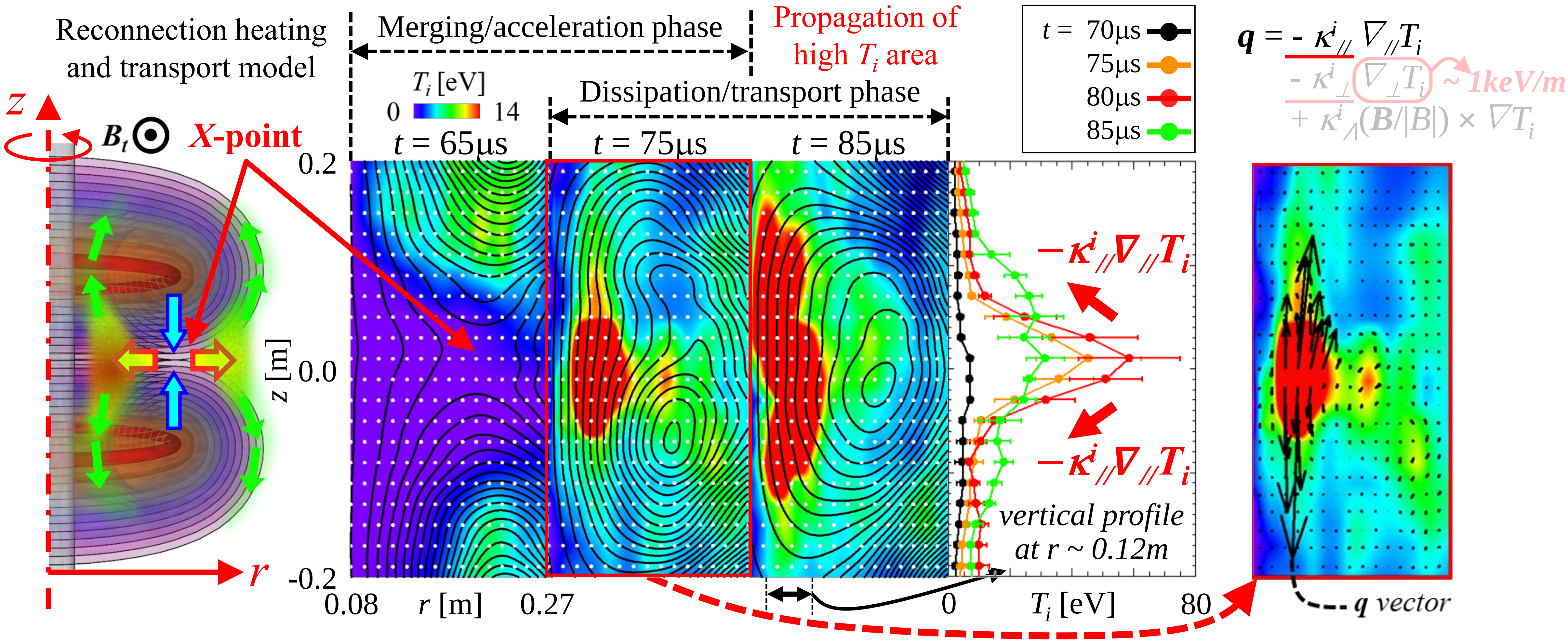




- Reconnection heating initially forms localized hot spot in the downstream
- High T_i area propagates poloidally after merging
- Poloidally ring-like hollow T_i profile is formed

The structure is clearer with full-2D T_i imaging measurement

~ Rec. originated high T_i area propagates globally in the poloidal direction ~



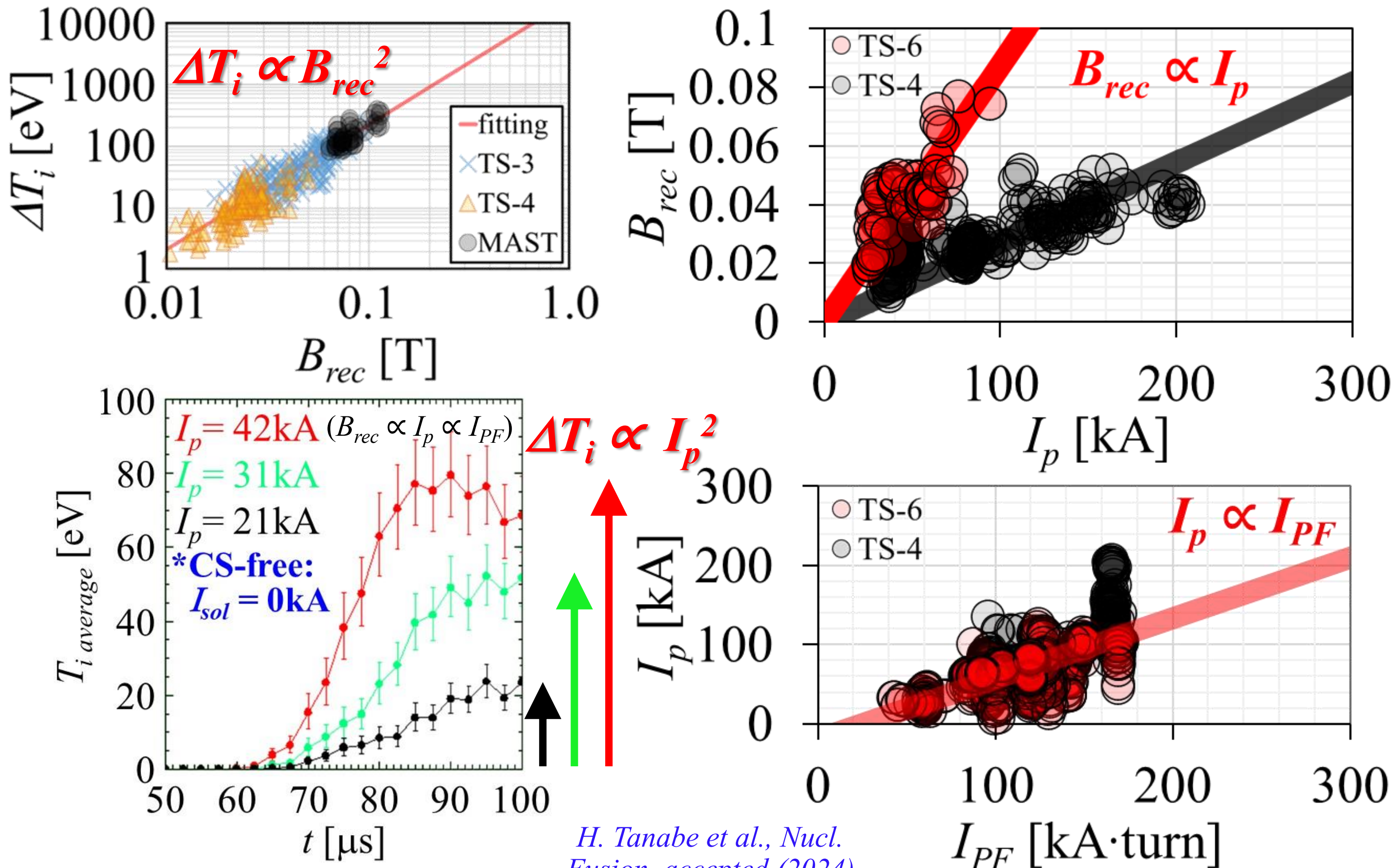
H. Tanabe et al., Nucl. Fusion 61, 106027 (2021)

Cross-field transport is strongly suppressed: $\kappa^i_{//}/\kappa^i_{\perp} \sim 2(\omega_{ci}\tau_{ii})^2 >> 1$

Revisit of heating scaling: $\Delta T_i \propto B_{rec}^2 \propto B_p^2 \propto I_p^2 \propto I_{PF}^2$

~ Reconnection heating power can be upgraded by increasing I_{PF}! ~

Reconnection heating ΔT_i increases in proportion to B_{rec}^2 and I_p^2



H. Tanabe et al., Nucl. Fusion, accepted (2024)

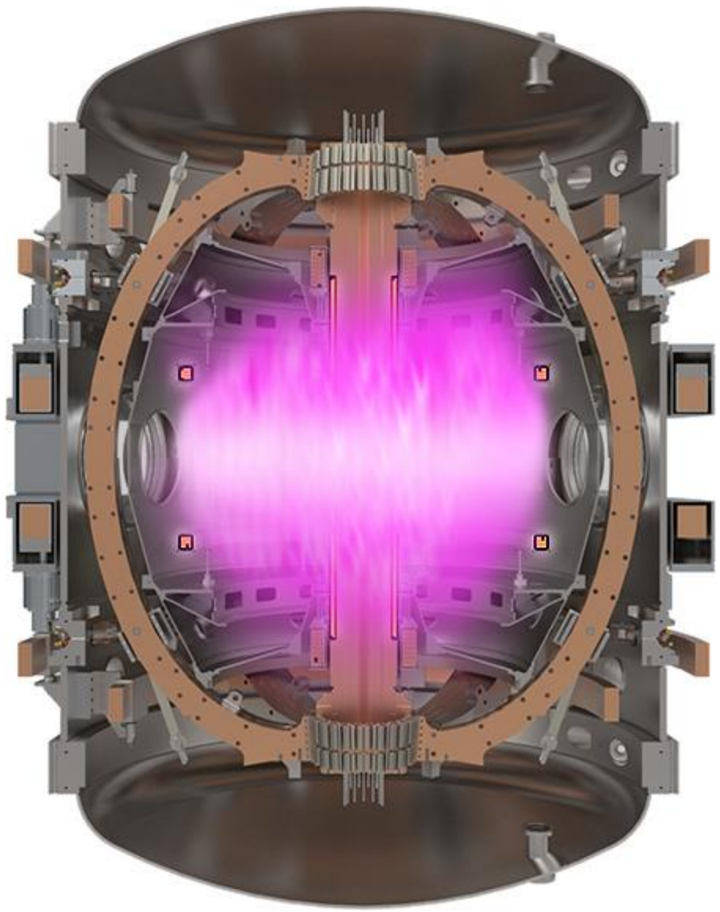
- The origin of B_{rec} is poloidal field B_p and plasma current I_p
(it is higher in a smaller device)
- Plasma current I_p *can be amplified by the driving coil current* I_{PF}

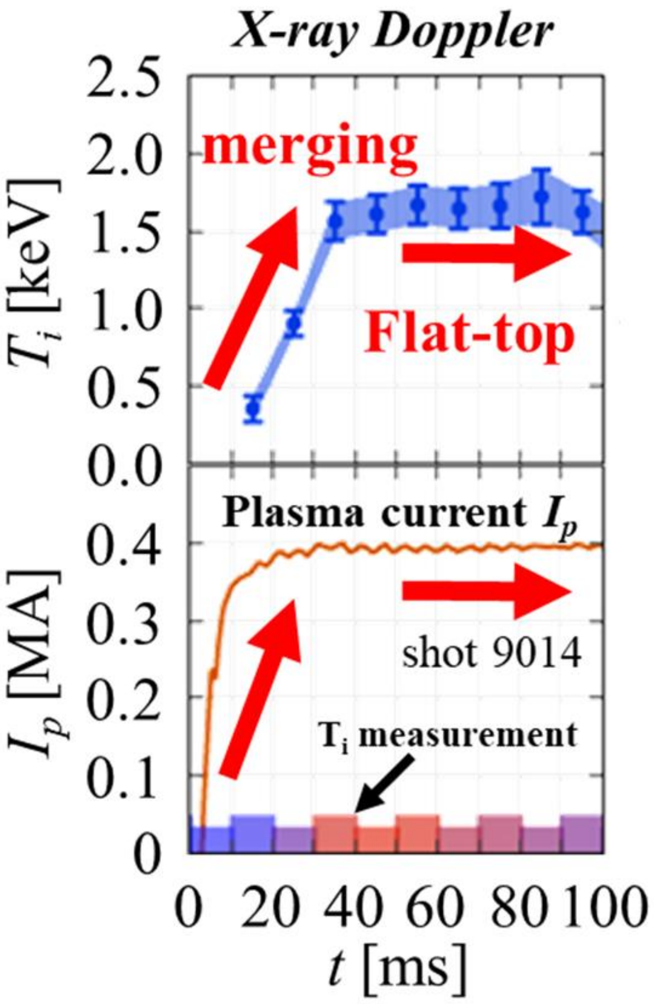
From the engineering point of view, driving current I_{PF} can be simply increased by upgrading power supply (capacitor bank)

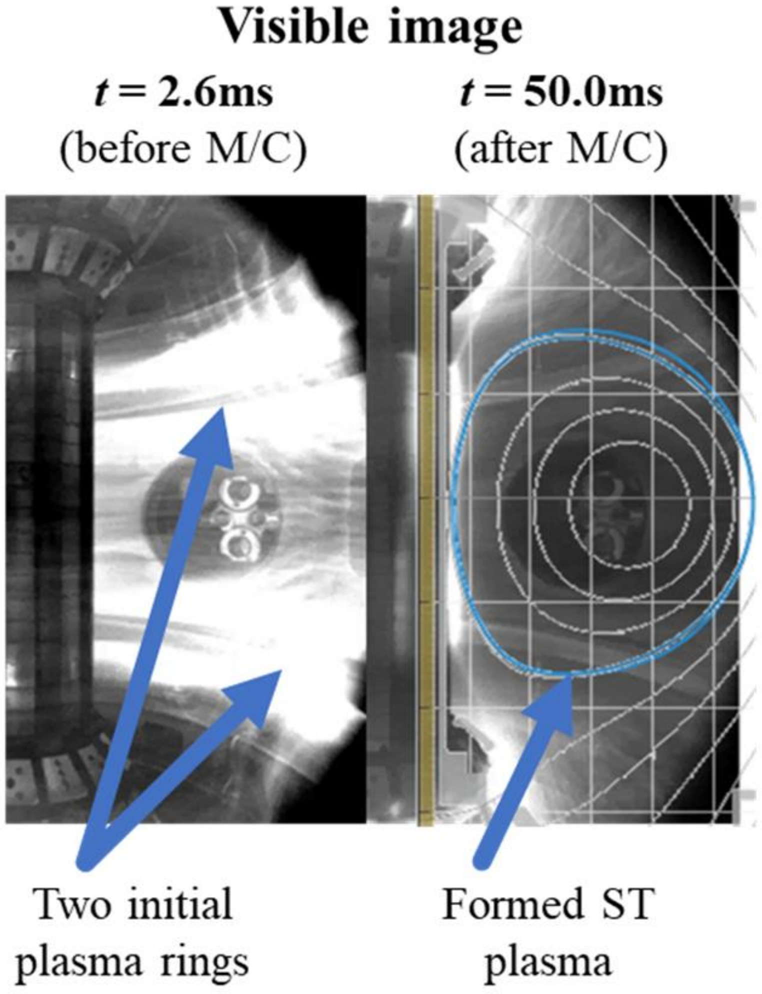
High Field application of Rec. heating in ST40

~ Rec. heating is routinely used to form high temperature plasma ~

ST40 device（R_0 ~ 40cm）







High Field application of Rec. heating in ST40

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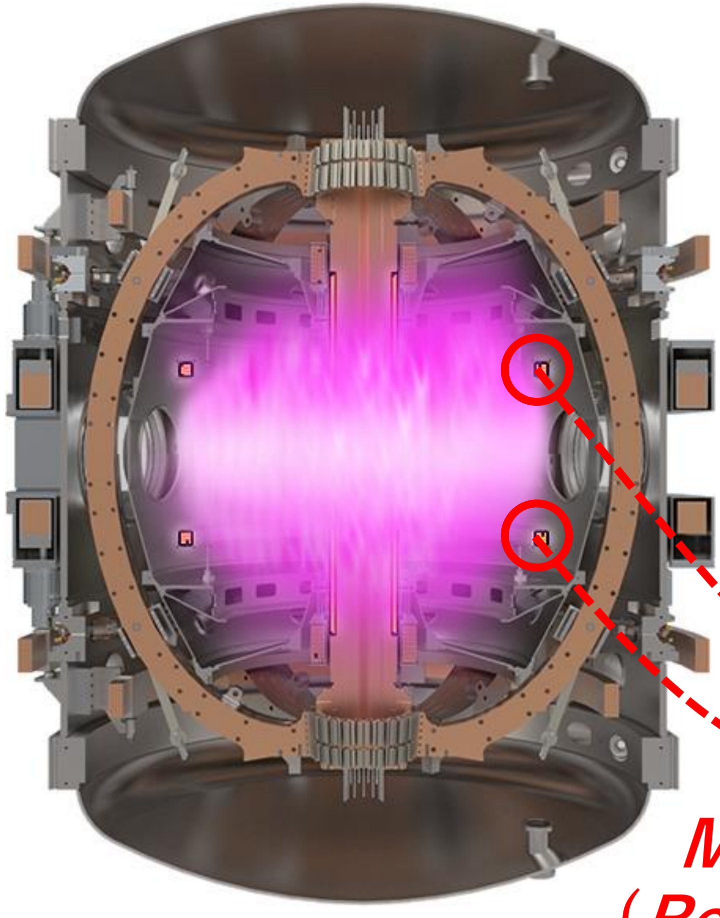
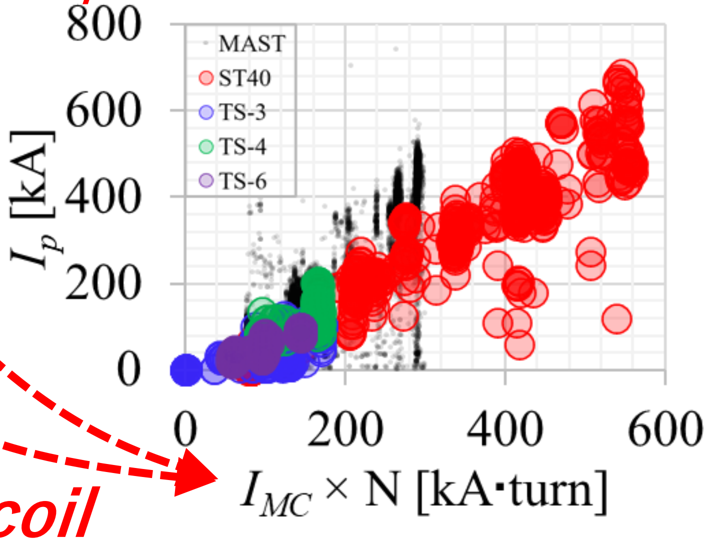


MC coil
（*Rec. drive*）

<u>Standard plasma scenario in ST40:</u>

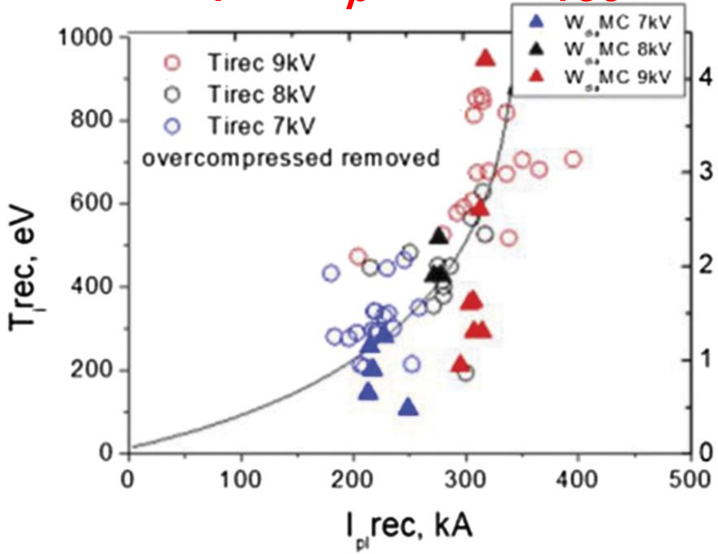
- High I_p startup by merging: I_p ~ 0.5MA
- T_i ~1keV plasma startup by *Rec.* heating
- Auxiliary heating to 10keV by NBI

$I_p \propto I_{MC}$ (I_{PF} in TS-6)



to be published in a future publication

$\Delta T_i \propto I_p^2 \propto B_{rec}^2$



M. Gryaznevich et al., Nucl. Fusion 62 042008 (2022)

High Field application of Rec. heating in ST40

~ Rec. heating is routinely used to form high temperature plasma ~

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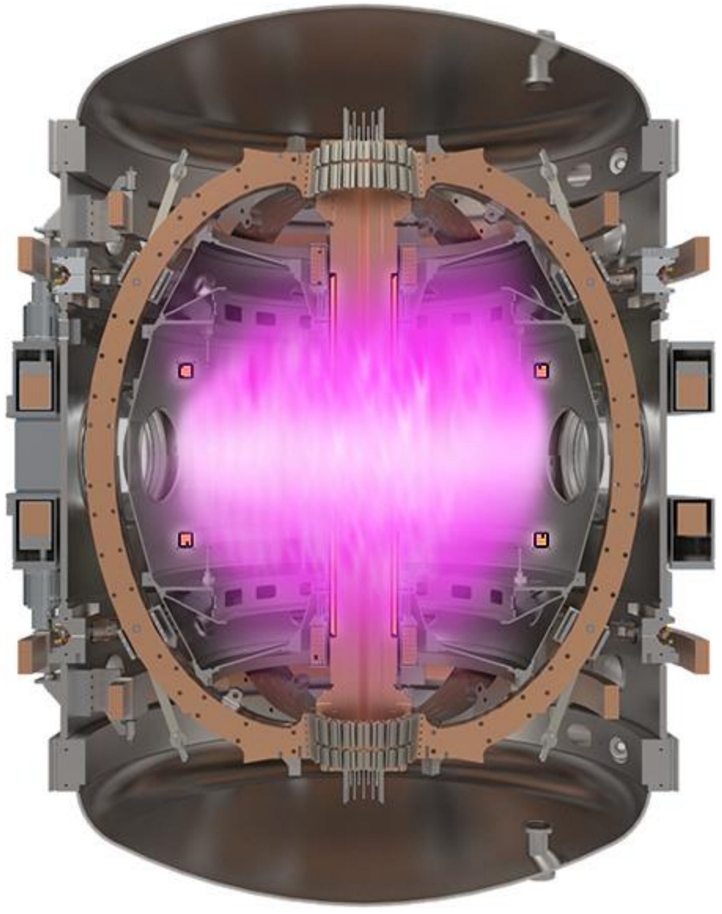

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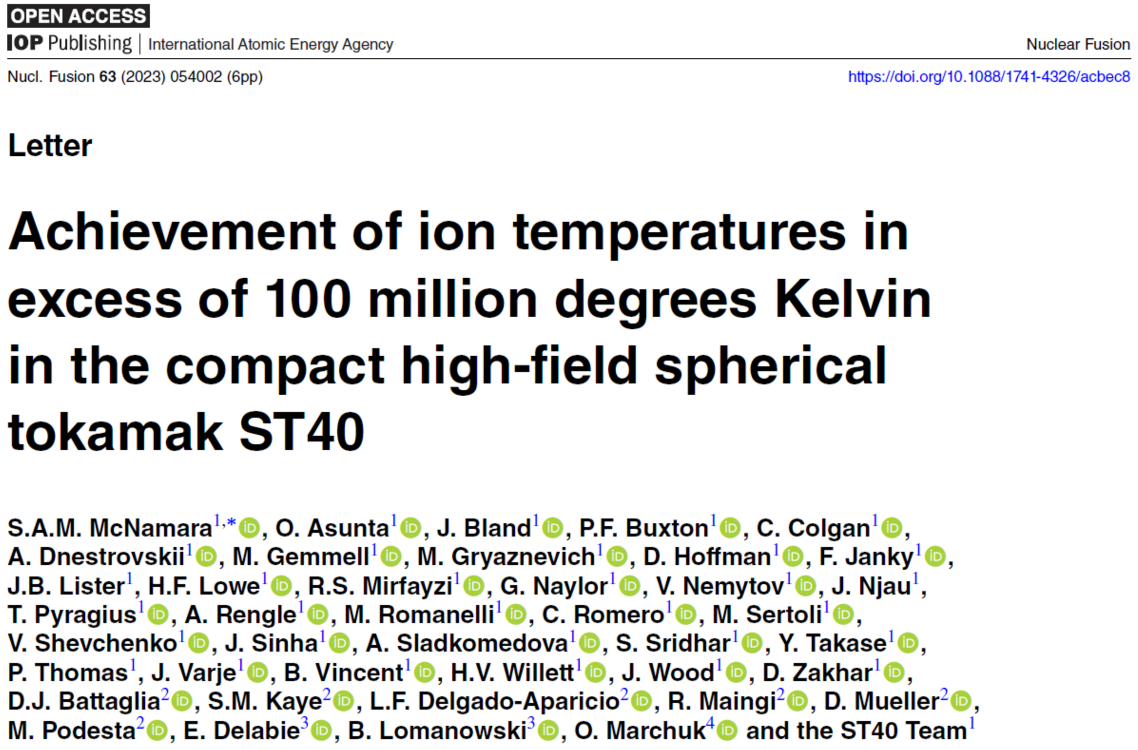

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Letter

Achievement of ion temperatures in excess of 100 million degrees Kelvin in the compact high-field spherical tokamak ST40

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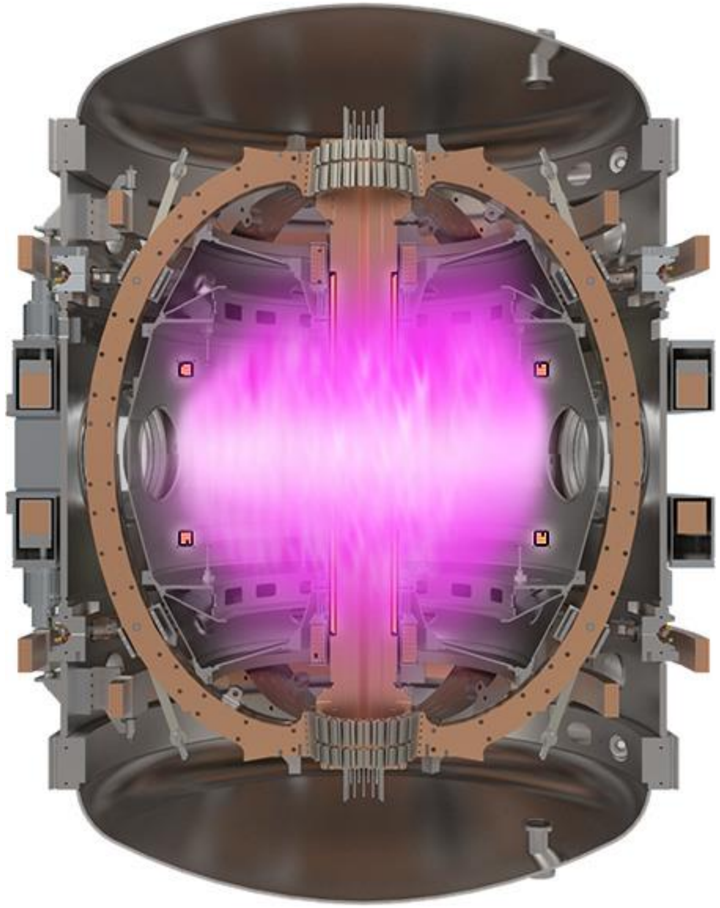
High Field application of Rec. heating in ST40

~ Rec. heating is routinely used to form high temperature plasma ~

ST40 device（R_0 ~ 40cm）



Before 2023 during COVID-19

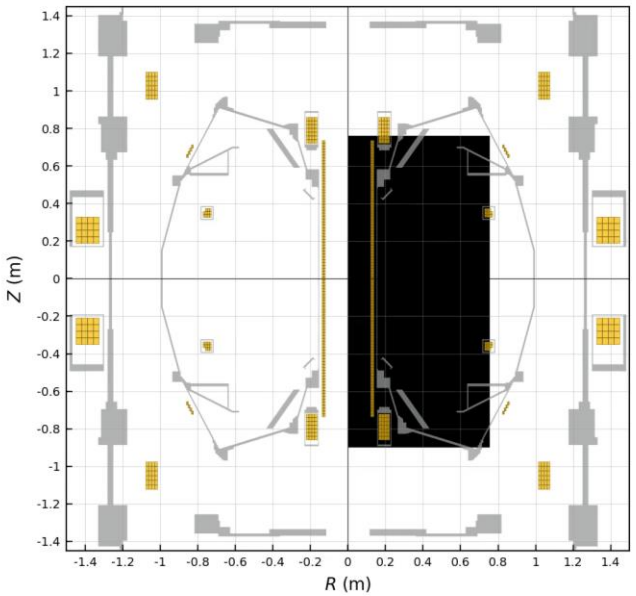
- First plasma in 2018 and 2.3keV achievement of T_i by *Rec.* heating
- 10keV achievement of T_i in 2022
- Profile measurement was not available

From 2023 after MR2023 meeting

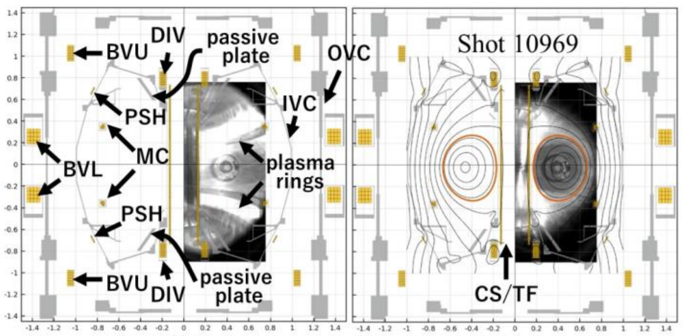
- Thomson scattering measurement of T_e and n_e was installed in 2023
- U-Tokyo Doppler tomography restarted the measurement of T_i profile

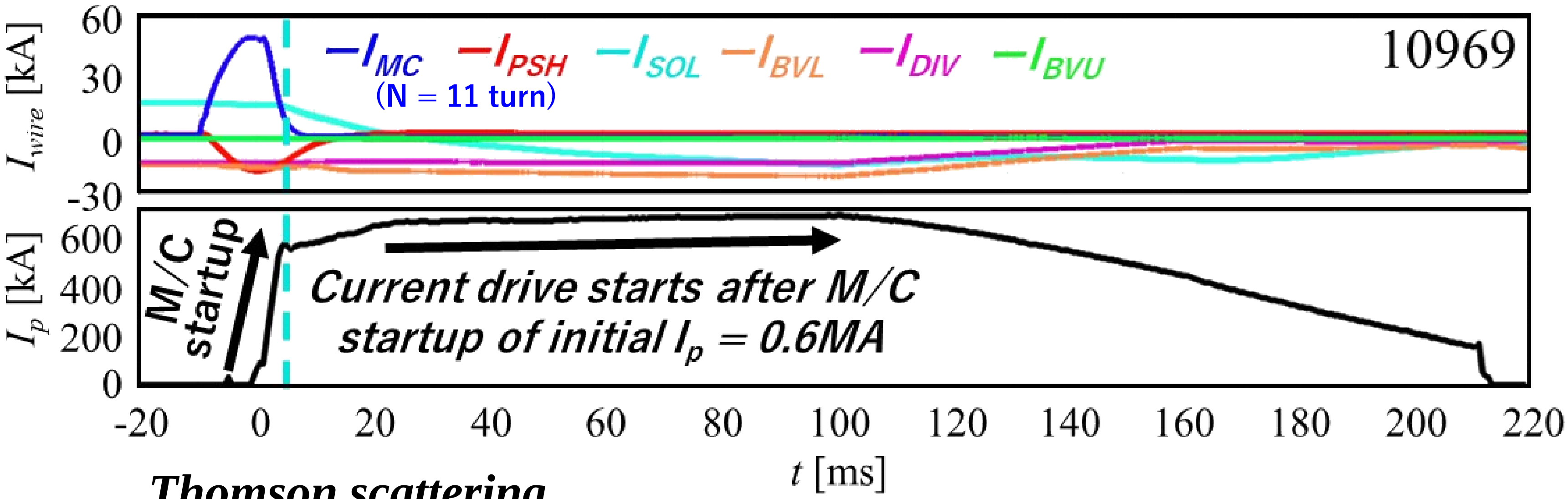
Thomson Scattering measurement started from 2023

~ 1keV plasma formation by *Rec.* heating is now confirmed by ***TS*** ~

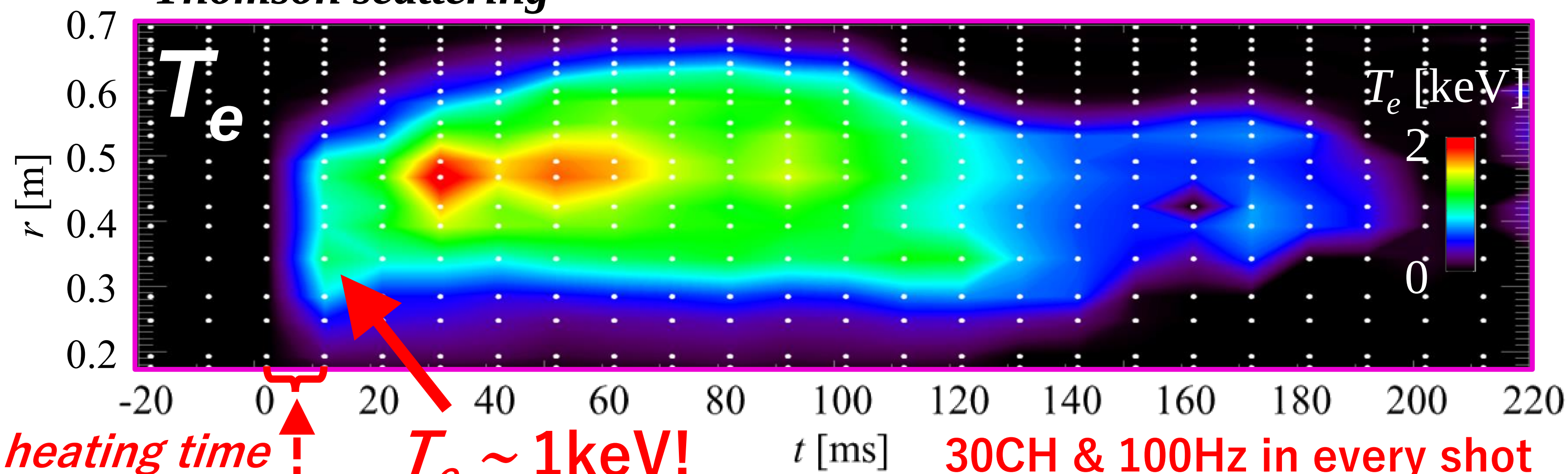


t = 0ms **t = 10ms**





Thomson scattering

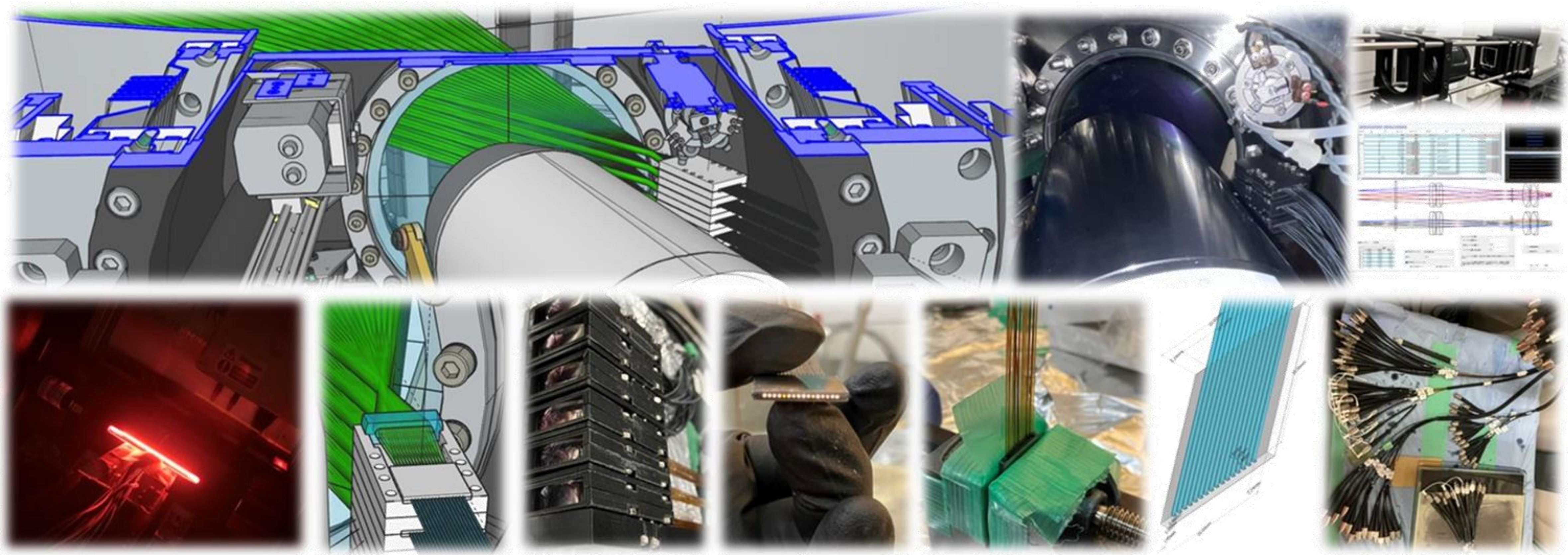


Merging/Rec. heating time

T_e ~ 1keV!

30CH & 100Hz in every shot

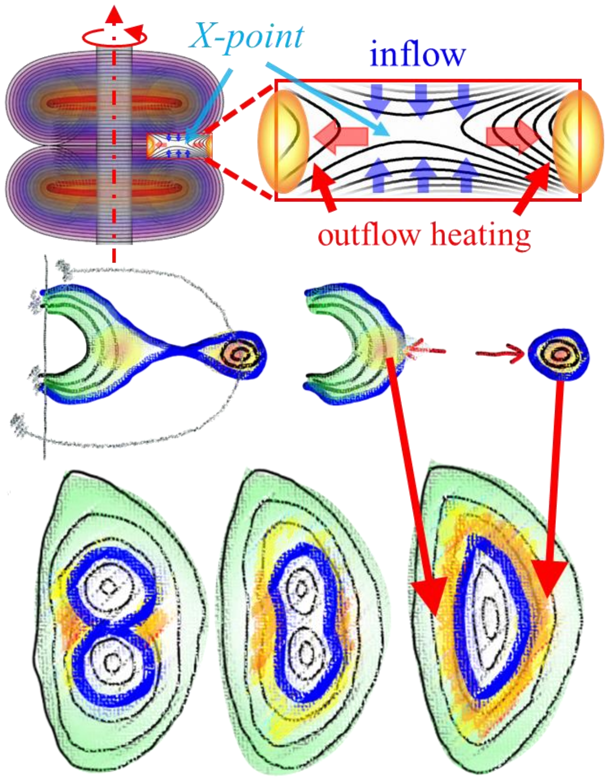
Diagnostics collaboration in ST40 (2D Doppler tomography is shipped from U-Tokyo to ST40): 32CH in 2023 → 96CH in 2024



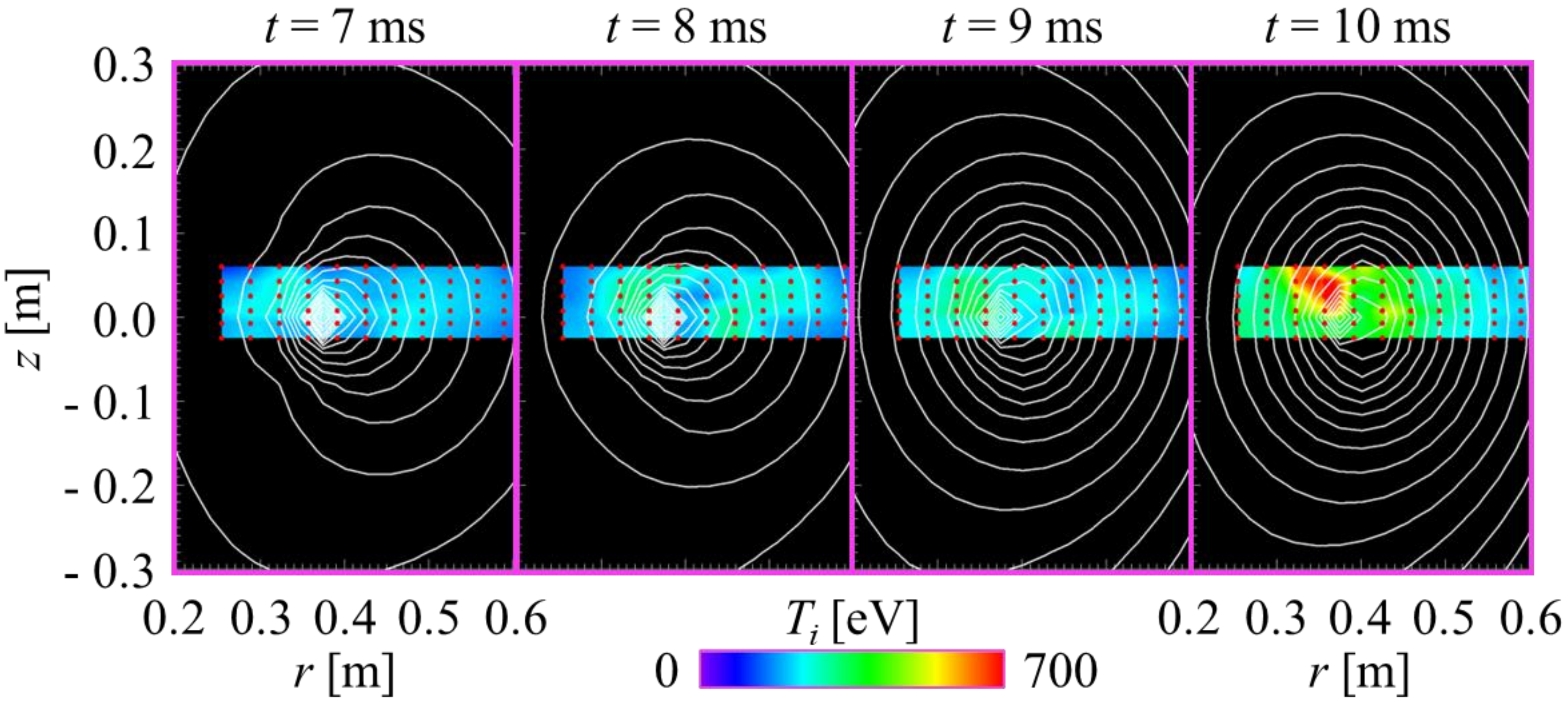
- Now we can use profile measurement of T_i, T_e and n_e
- Upgrade of Doppler tomography has been completed (32CH → 96CH: 2D imaging of T_i is now available in ST40)

First 2D imaging measurement of T_i in ST40

Reference model



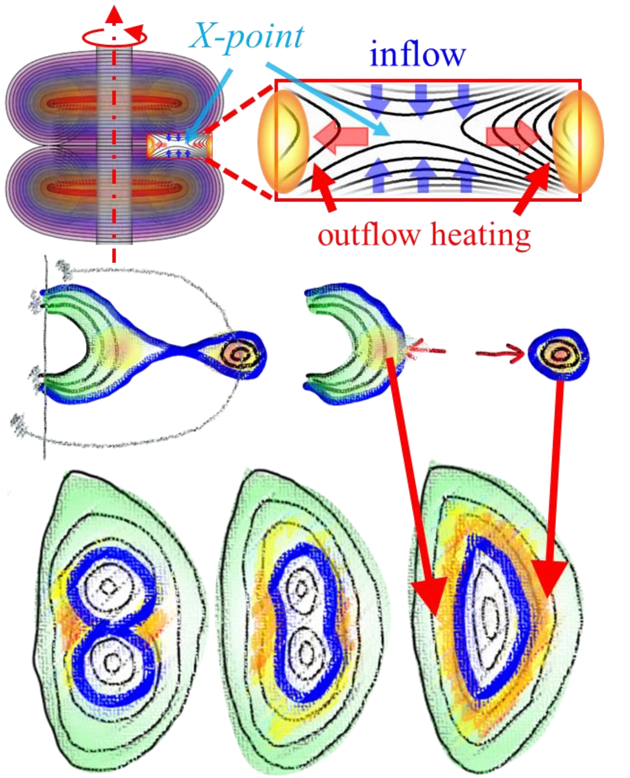
Time evolution of 2D T_i profile with EFIT



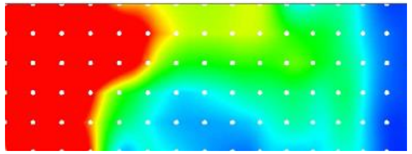
Note: magnetic diagnostics just assumes single-axis and don't trust too much.
(Reconnection might be still continuing. We can't use in-situ measurement)

Reconnection heating structure becomes clearer by adjusting the color bar range (700eV → 250eV)

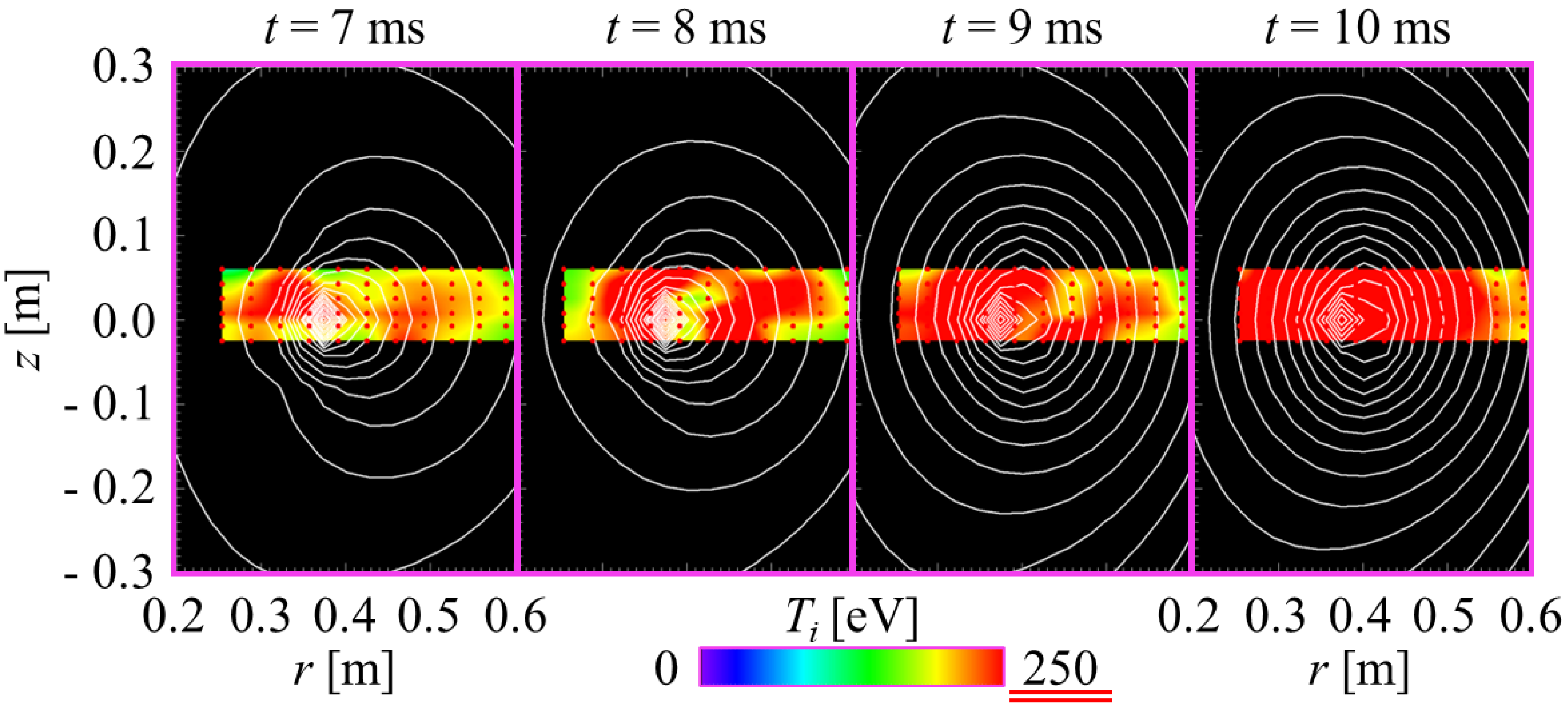
Reference model



Ref.
TS-6



Time evolution of 2D T_i profile with EFIT

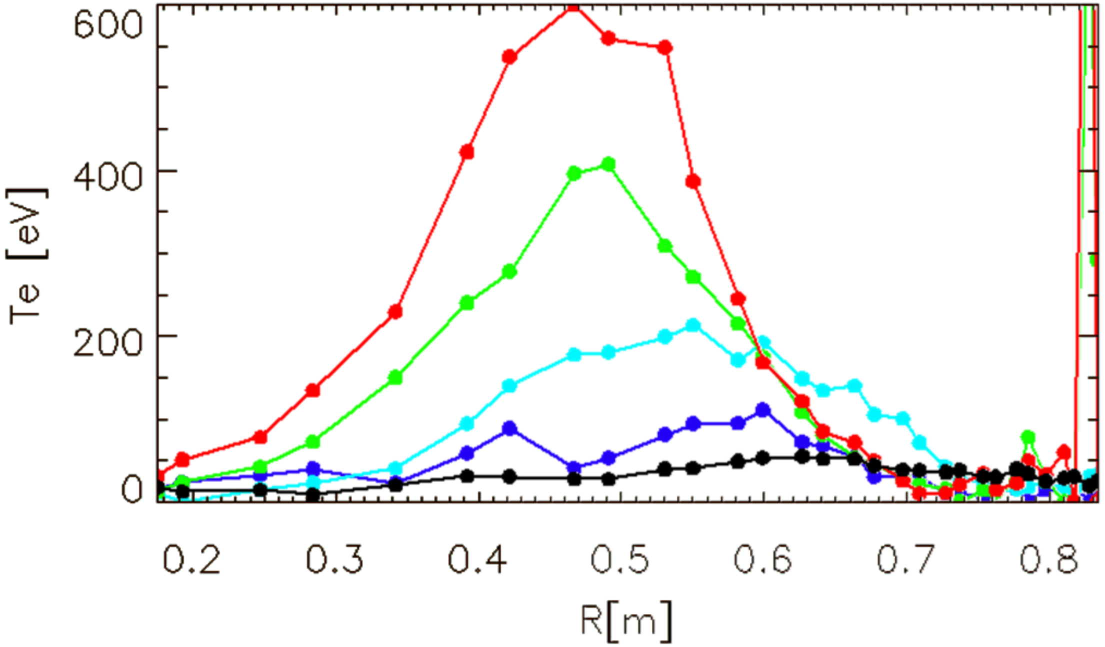


As in TS-6 experiment, outflow-like heating structure has been detected

At the similar timings, electron heating is also observed
~ 1D 30CH Thomson scattering measurement of T_e and n_e ~

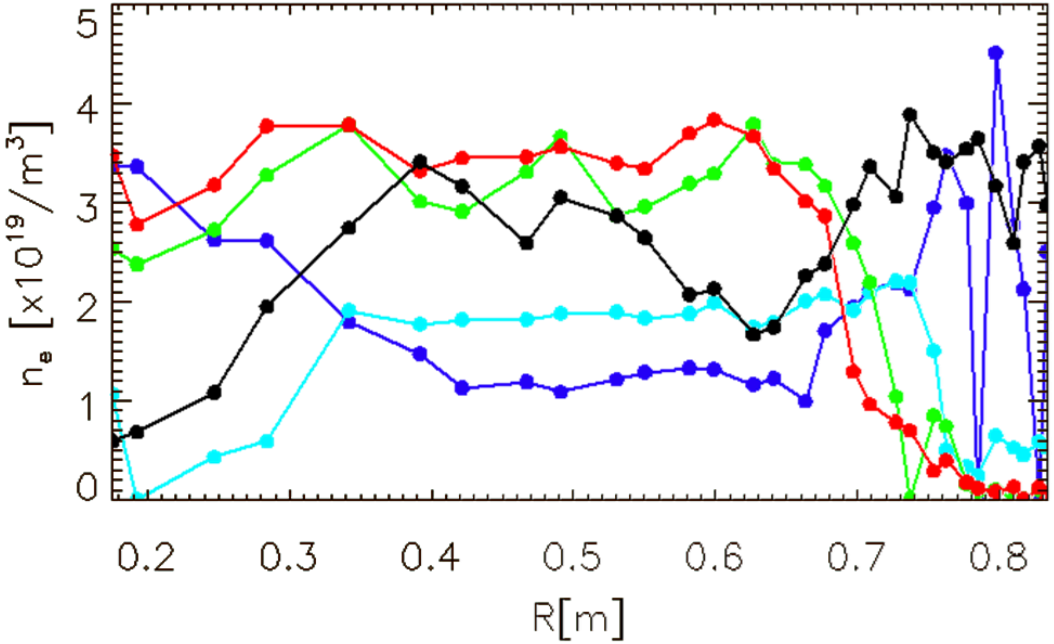
T_e increases around the X-point (or magnetic axis)

$t =$ 5ms, 6ms, 7ms, 8ms, 9ms



n_e profile shows radial motion at $t =$ 5ms and 6ms

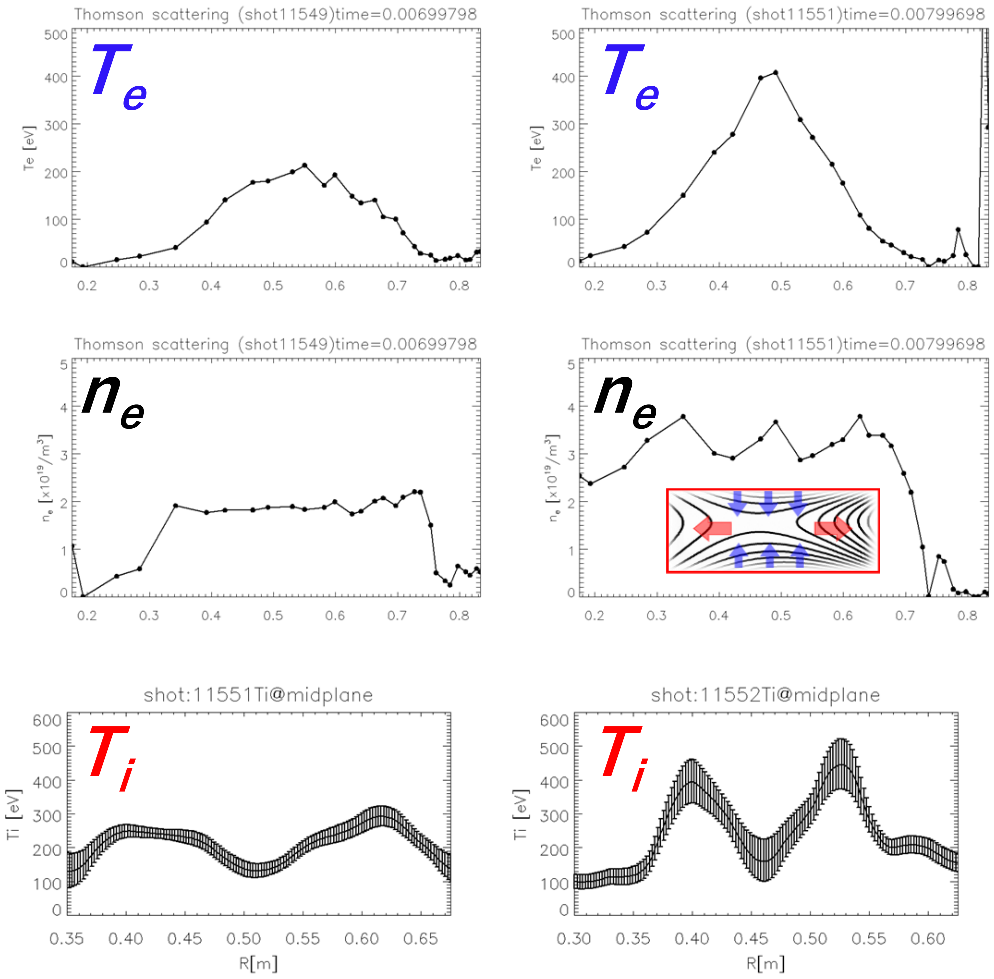
$t =$ 5ms, 6ms, 7ms, 8ms, 9ms



Synchronized measurement with ion Doppler tomography

~ Full pressure profile measurement of ions and electrons has started! ~

$t = 7$ ms $t = 8$ ms

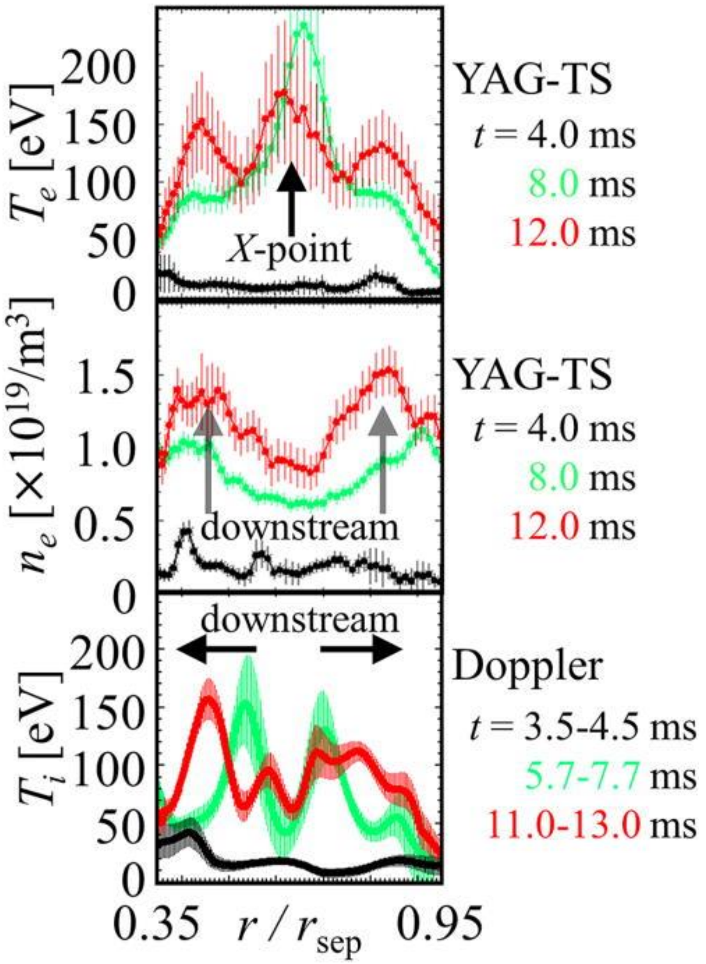


T_e increase around the X-point

n_e increase in the downstream (and the X-point?)

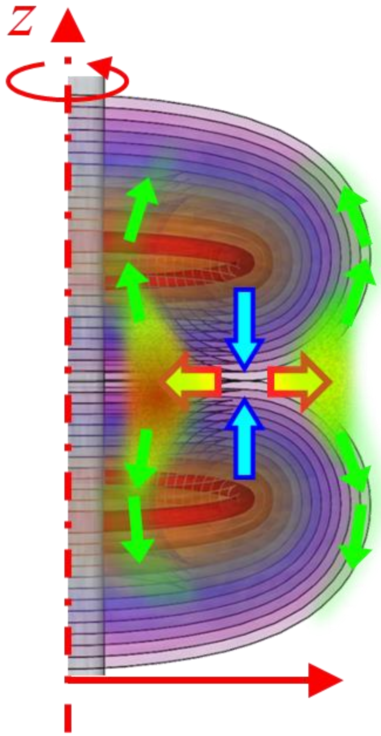
T_i also increases in the downstream (double-peak)

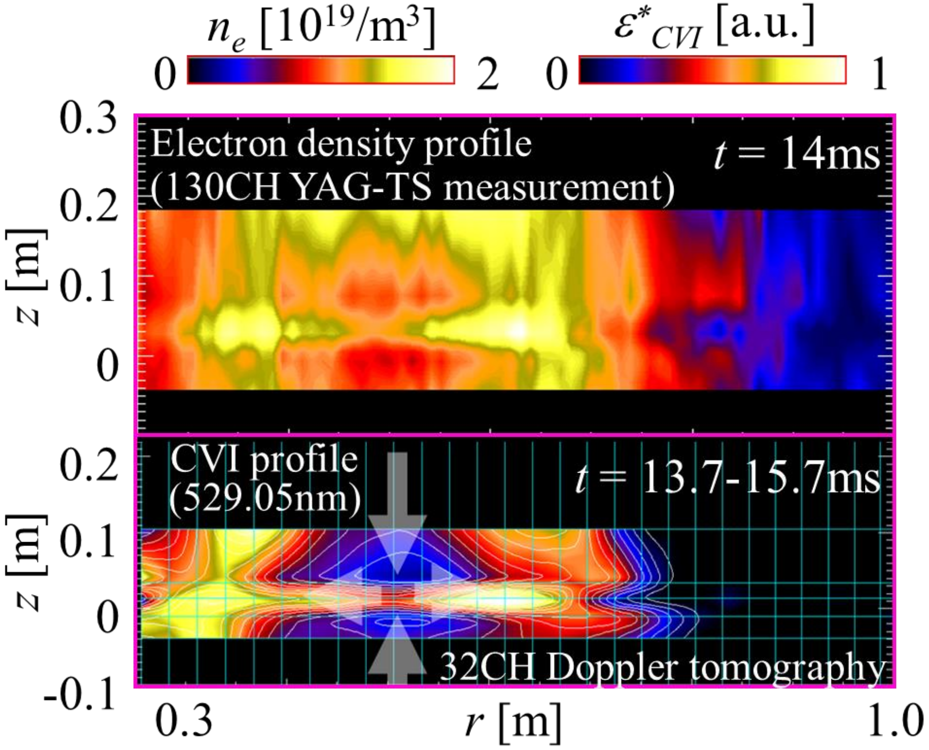
Reference from MAST



Triple-peak n_e might be *on-axis* of acceleration path

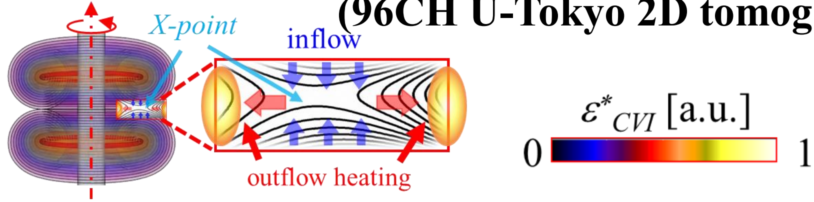
In MAST, 2D n_e profile shows similar structure with CVI emission profile $\varepsilon_{\mathrm{CVI}}$

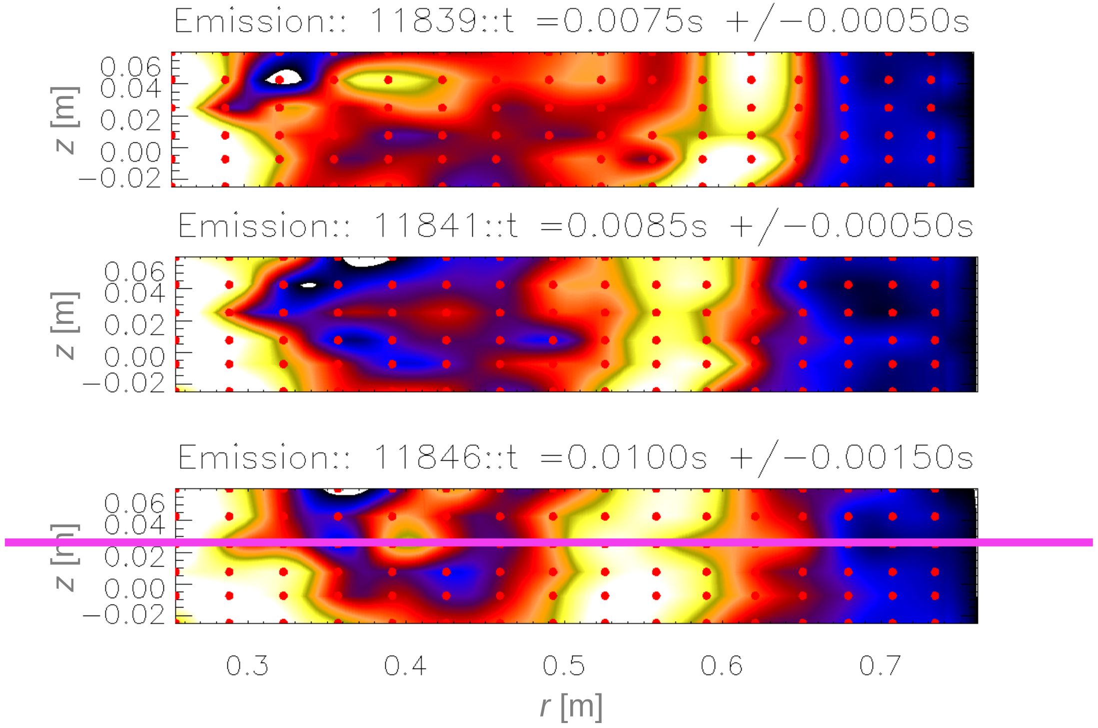




2D CVI emission profile in ST40

(96CH U-Tokyo 2D tomography)

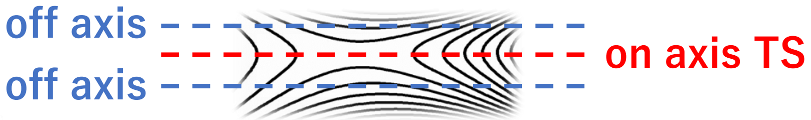


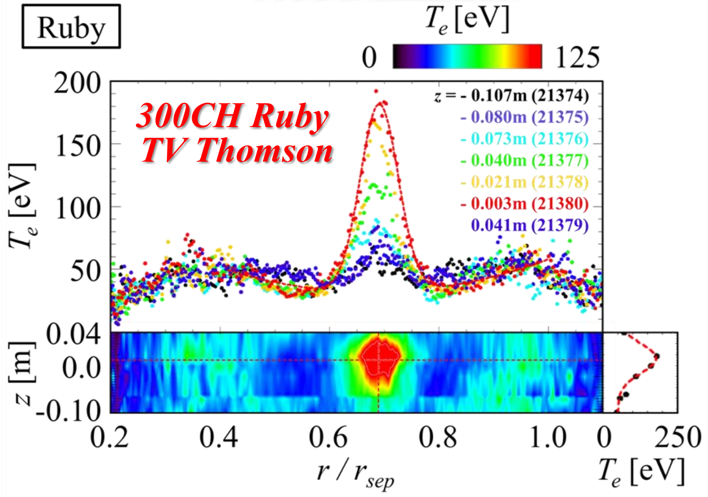


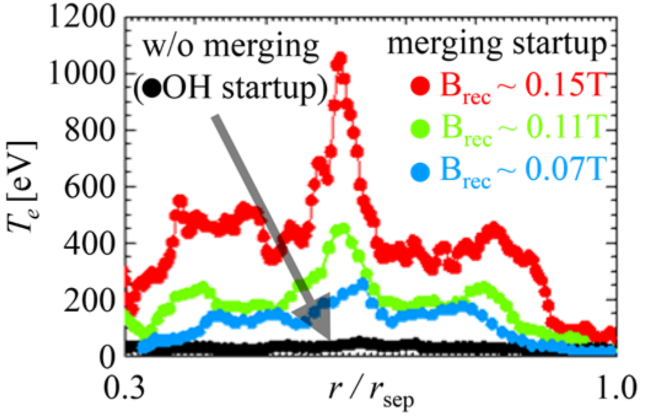
If T_e measurement is well aligned on-axis, X-point heating would be also clearer

Detection of the MAST-like localized electron heating around the X-point in ST40

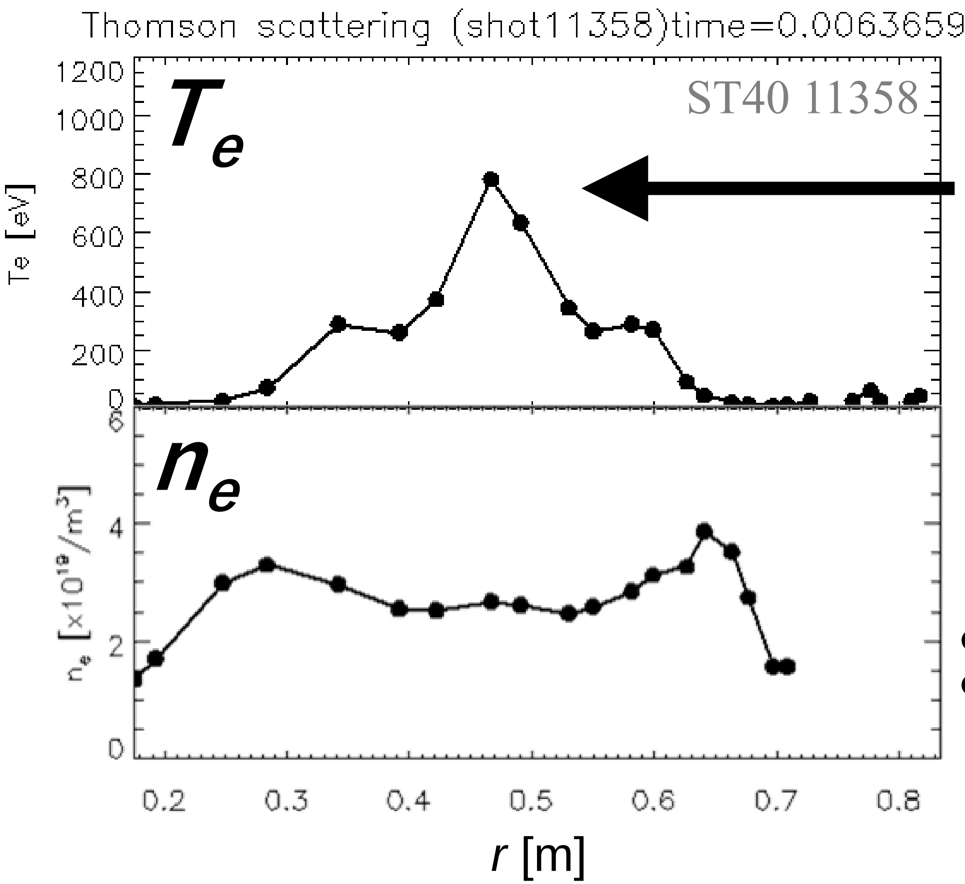
Reference from MAST







MAST-like clear peak structure of T_e has successfully been reproduced in ST40!



In ST40, there is quite strong guide field: B_t ~ 2T

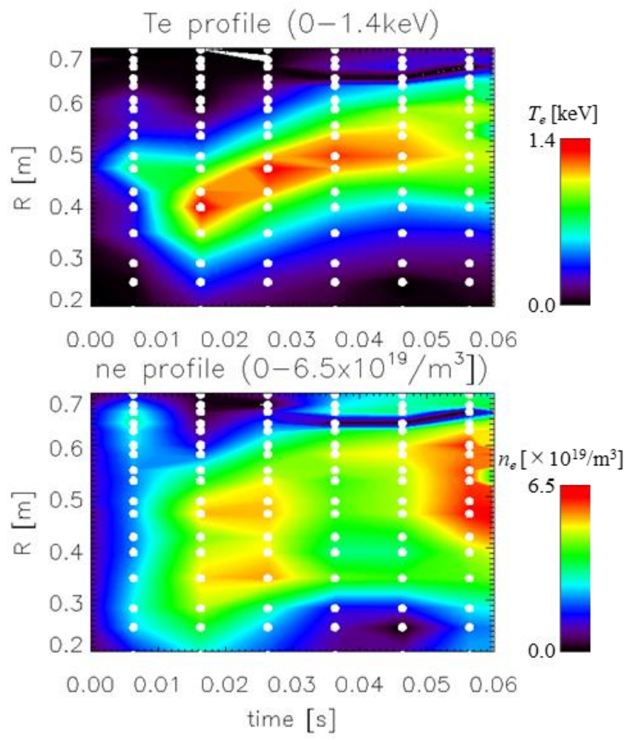
$E_{//} = E\cdot B/|B|$ should have strong deposition from $E_{rec} = E_t$ which is parallel to the guide field direction

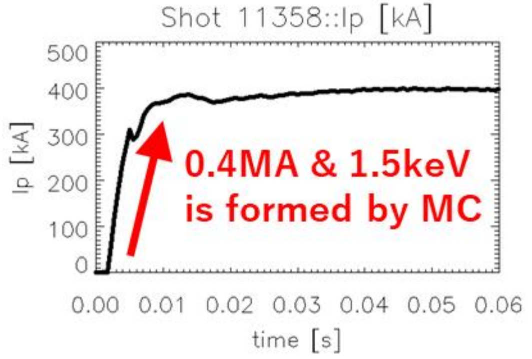
- MAST: T_e ~ 1keV & n_e ~ 1×10^{19}/m^3
- ST40: T_e ~ 1keV & n_e ~ 3×10^{19}/m^3

The record pressure is updated!

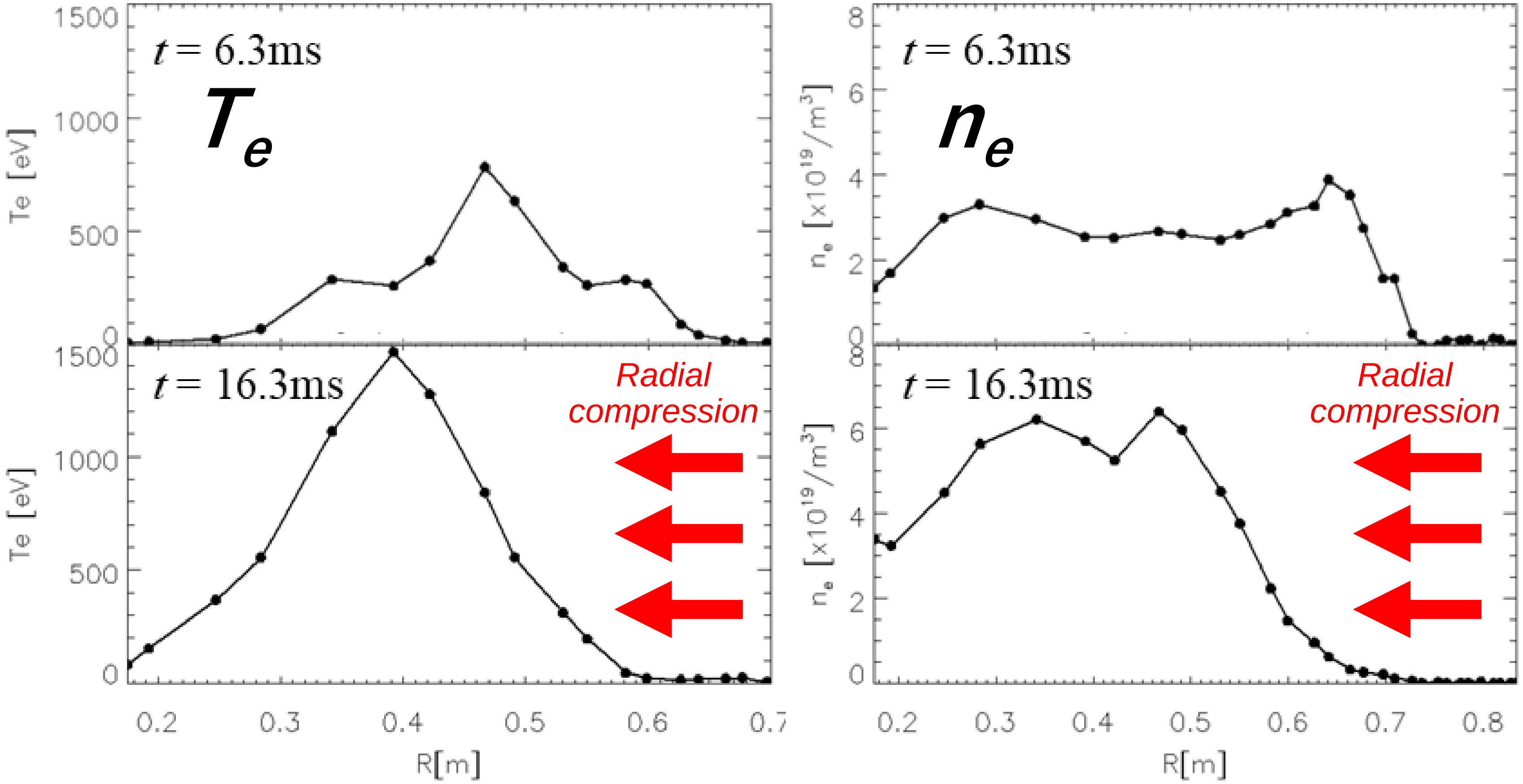
After merging, radial compression is also applied to enhance the pressure

~ The M/C electron heating record in MAST has been updated in ST40 ~



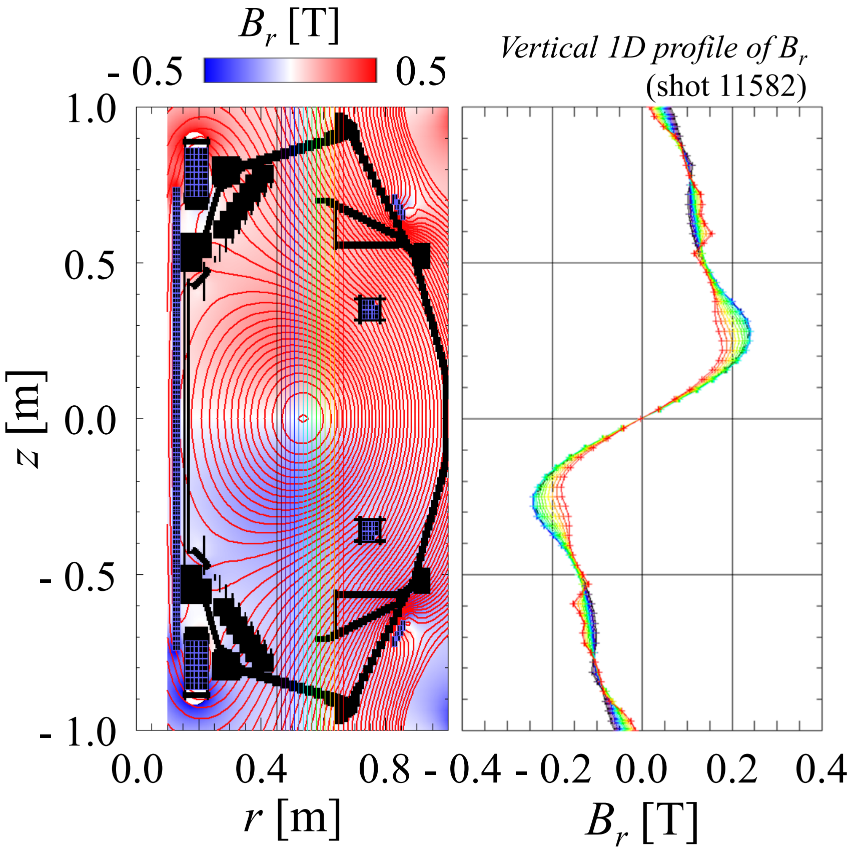


0.4MA & 1.5keV is formed by MC

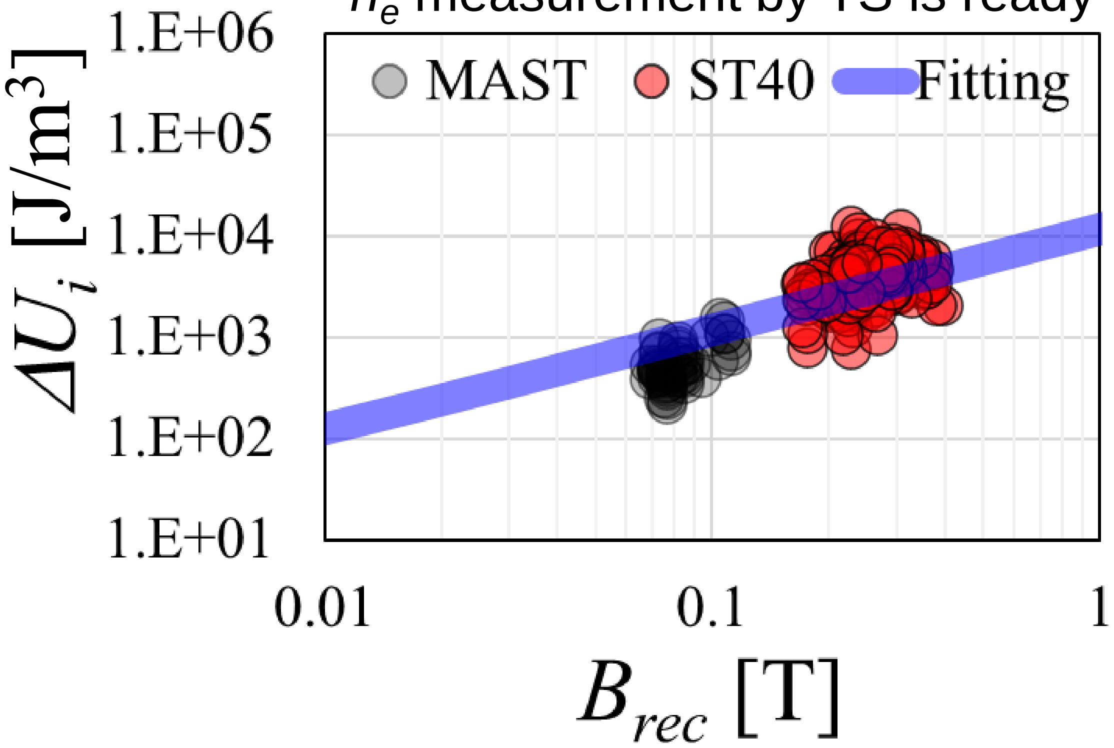


- **MAST:** $T_e \sim \underline{1}$**keV & $n_e \sim \underline{1} \times 10^{19}/\mathrm{m}^3$**
- **ST40:** $T_e \sim \underline{1.5}$**keV & $n_e \sim \underline{6} \times 10^{19}/\mathrm{m}^3$**

The reconnection heating scaling is now upgraded to the full pressure one: $\Delta T_i \propto B_{rec}^2 \propto B_p^2 \rightarrow \Delta U_i \propto B_{rec}^2 \propto B_p^2$



TS-6 will be also included when n_e measurement by TS is ready



- **MAST**：$B_{rec} \sim 0.1\mathrm{T}$ $\Delta U_i = \frac{3}{2} n \kappa_B T_i \sim 1kJ/m^3$
- **ST40**：$B_{rec} \sim 0.3\mathrm{T}$ $\Delta U_i = \frac{3}{2} n \kappa_B T_i \sim 10kJ/m^3$

~30% of $B_{rec}^2/2\mu_0$ is converted to $1.5 n\kappa_B T_i$

Summary and conclusion

The application experiments of reconnection heating for fusion in TS-6 and ST40 have been introduced

Physics *Exp.*:

1. **Magnetic reconnection heat ions in the downstream of outflow jet**
2. ***MAST-like peaked T_e was reproduced by reconnection heating in ST40***
3. **The heated plasmas are well confined inside the closed flux surface**

High field application:

1. ***Rec.* heating scenario is successfully connected to semi-steady operation**
2. **Application of reconnection heating is upscaled to the keV range in ST40**
3. **$\Delta T_i \propto B_{rec}^2$ scaling is upgraded to thermal energy one: $\Delta U_i \propto B_{rec}^2$**

(~ 30% of $B_{rec}^2 \rightarrow \Delta U_i$ in ST40)

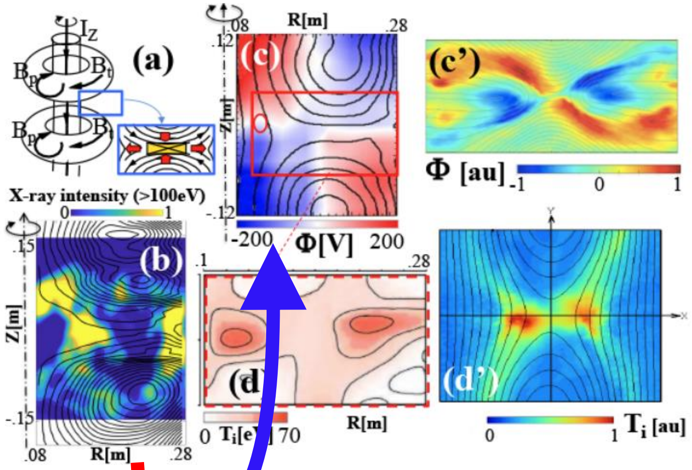
Related talks/posters from our group (*Merging Exp.*)

- **Yasushi Ono (16:40 ~ 17:00 Monday):**
  High power ion heating by magnetic reconnection in two merging toroidal plasmas with high guide field

- **Michiaki Inomoto (10:40 ~ 11:00 tomorrow):**
  Effects of spontaneously-generated and artificially-controlled electrostatic fields in high guide-field magnetic reconnection in laboratory experiment

- **S. Takeda (13:00 ~ 17:00 (poster) today/tomorrow):**
  Localized electron acceleration at X-point during magnetic reconnection of two merging tokamak plasmas

Y. Ono’s talk on Monday



Artificial control of potential profile

More details about the 2D SXR imaging of high energy electrons

Summary and conclusion

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(30% of B_{rec}^2 → ΔU_i in ST40)