# High Power Heating of Magnetic Reconnection in ST Merging Experiments

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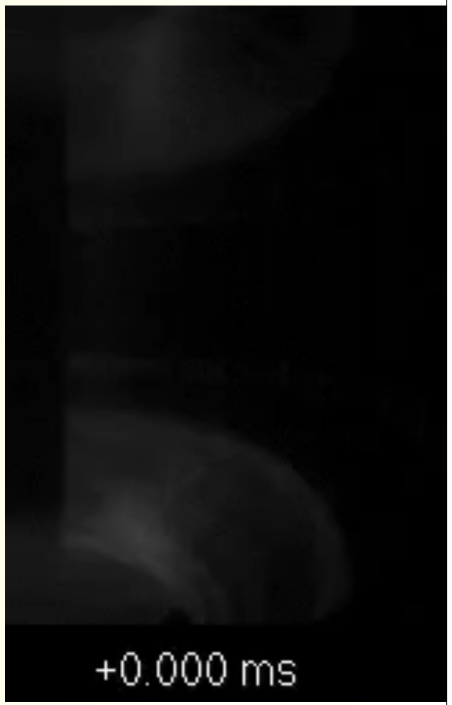


● **How much does reconnection heat ions and electrons? How is it useful?**

TS-3, UTST, MAST, based on UK-J collaborations

Significant rec. heating of ions MAST **$T_i$ > 1keV**

1) Closed field exp. vs Open field exp.

2) Downstream heating of ions MAST,TS-3, PIC, Solar

3) X-point heating of electrons MAST, TS-3, PIC

4) Effect of $B_t$ on reconnection heating MAST, TS-3, PIC

5) Upgrade of TS merging exp. for high B rec. heating

High guide field (high-q tokamak) reconnetion heating :

Ono et al. PPCF'12, PRL'11, POP'15, POP'93, Tanabe et al. PRL'15

Low guide field (low-q tokamak and spheroamk) reconnection heating:

Ono, Kawamori et al. PRL'05, PRL'96, PPCF'92, PFR'86

# 2D Steady-State Physics of Magnetic Reconnection
## -The Sweet-Parker 2-D Model for Magnetic Reconnection-

Assumptions: ・2D ・Steady-state

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$$

$$\begin{cases} V_{in} B = \eta_{Spitz} j_t \\ 4LB = 4L\delta \mu_0 j_t \end{cases}$$

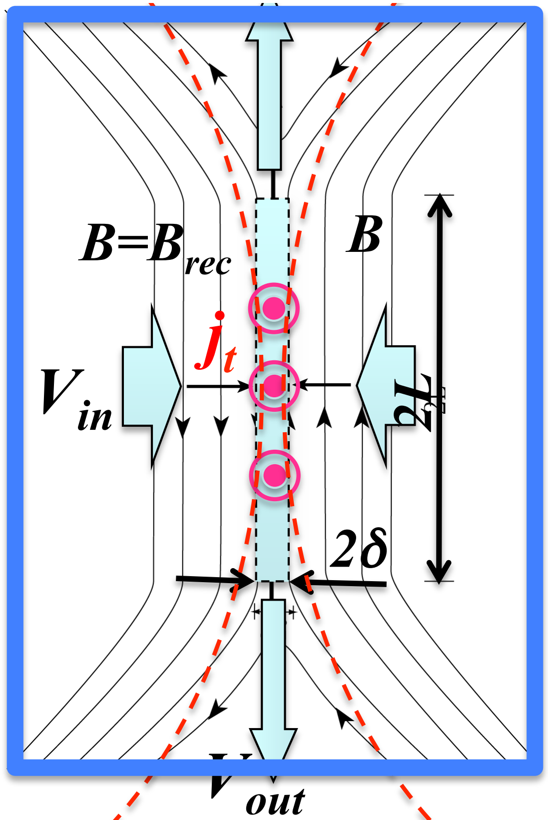
$$\Rightarrow V_{in} B = \frac{\eta_{Spitz}}{\mu_0} \frac{B}{\delta}$$

**Closed flux experiment**

$$\frac{V_{in}}{V_A} = \frac{1}{\sqrt{S}}$$

$$S = \frac{\mu_0 L V_A}{\eta_{Spitz}}$$

**Open flux experiment**



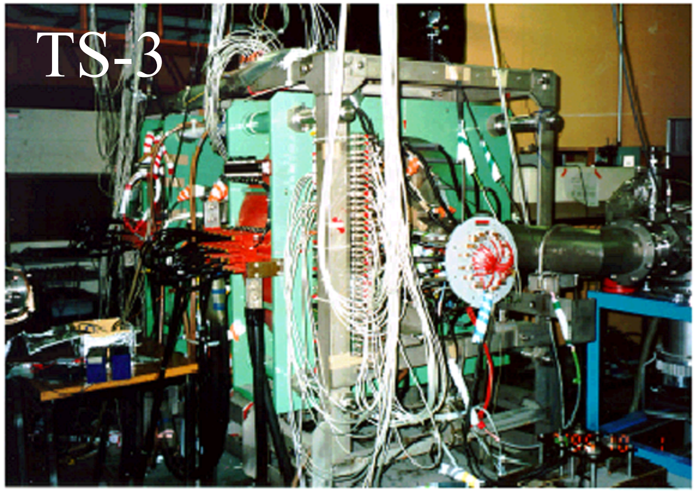

B is resistively annihilated in the sheet

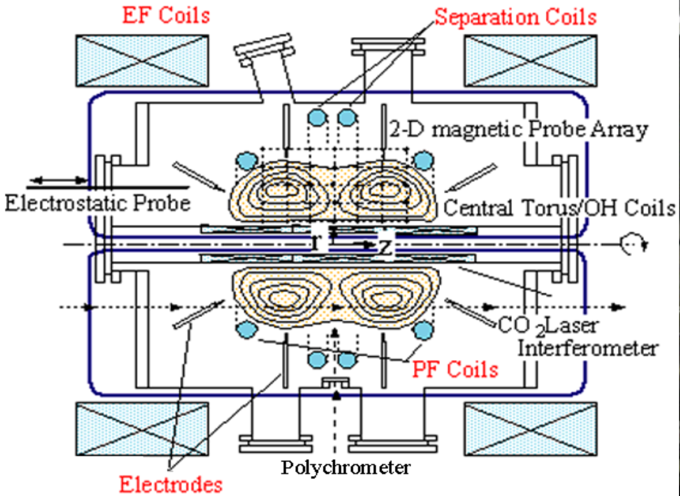
Mass conservation: $V_{in} L \approx V_{out} \delta$

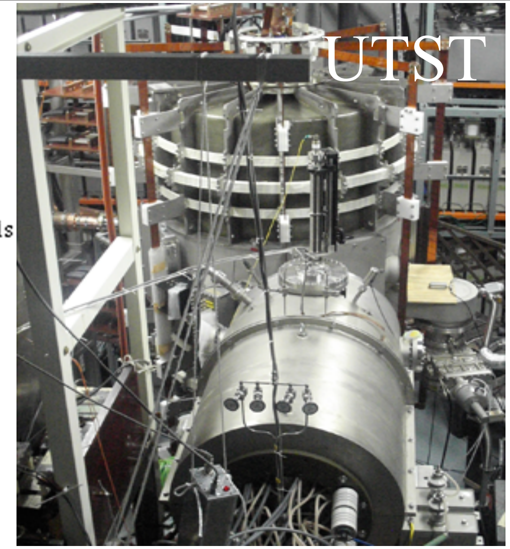
Pressure balance: $\frac{1}{2} \rho V_{out}^2 \approx \frac{B^2}{2\mu_0} \Rightarrow V_{out} \approx V_A$

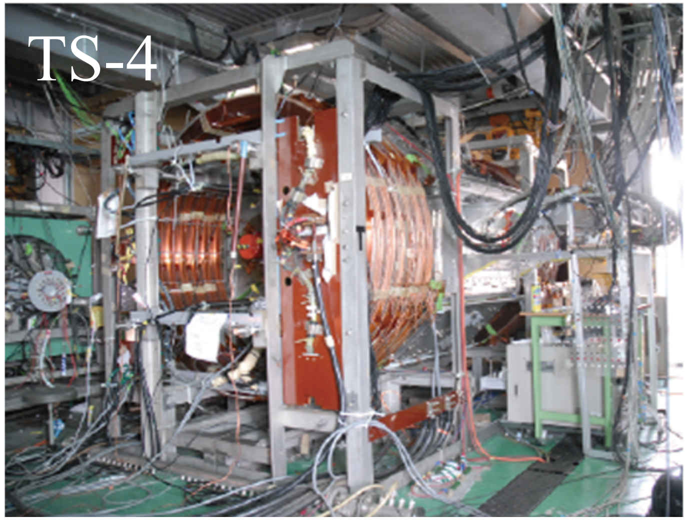
S=Lundquist number

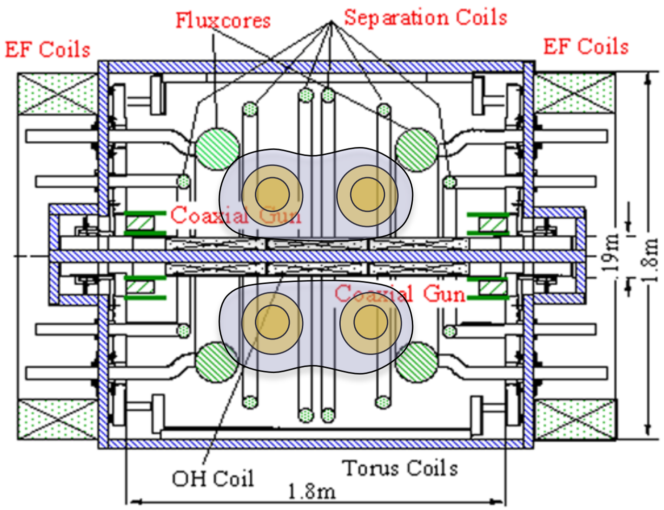
# Univ. Tokyo Merging/ Reconnection Experiments
# 1985～ TS-3 (R=0.2m)  2000～ TS-4 (R=0.5m)
# 2006～UTST (R=0.45m)
# for physics and application of reconnection heating

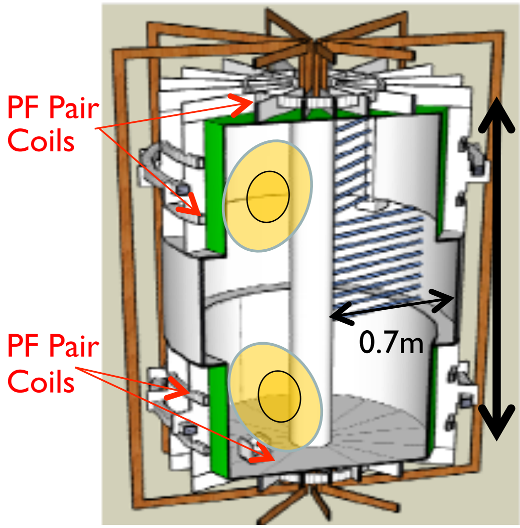


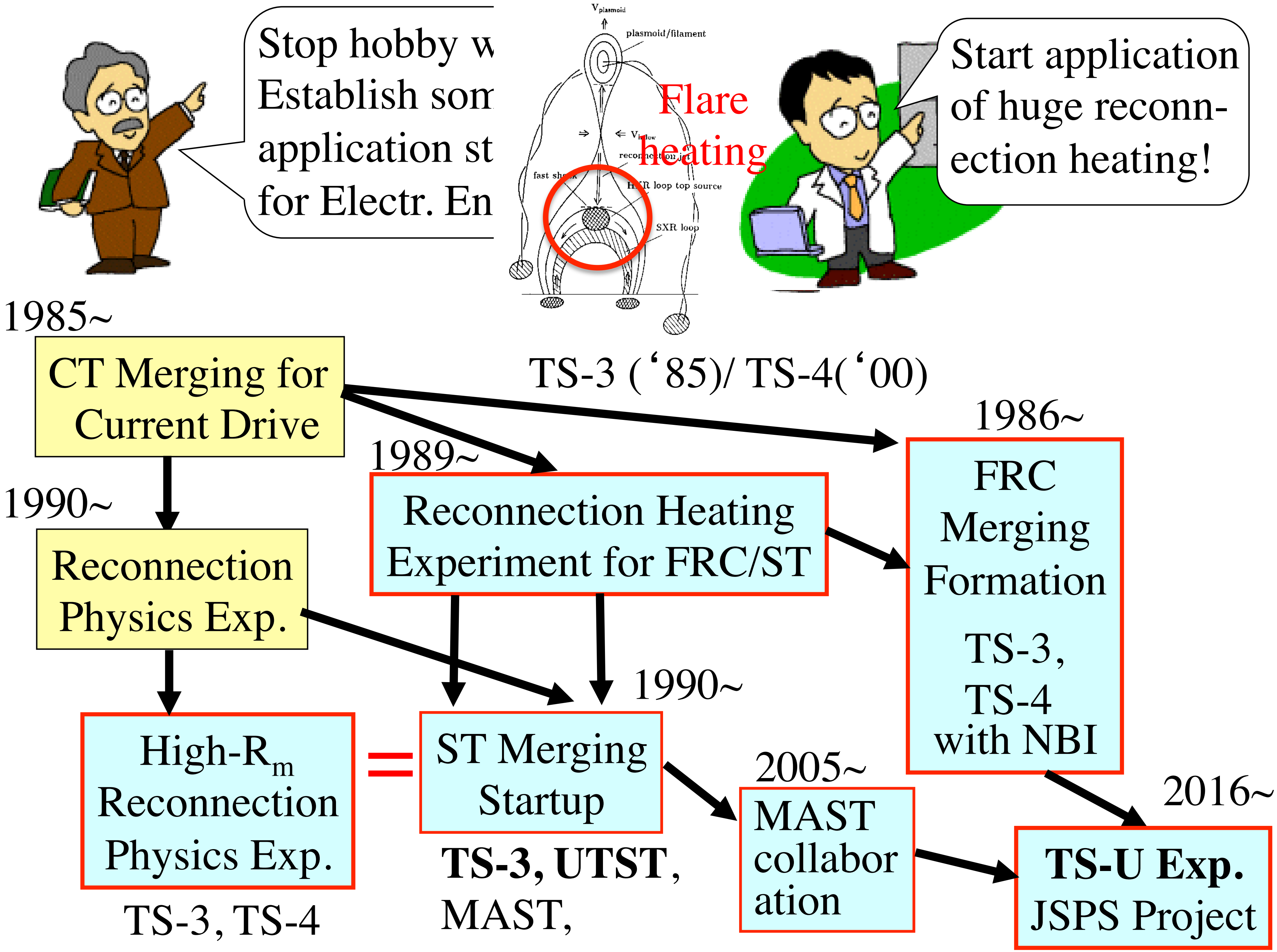



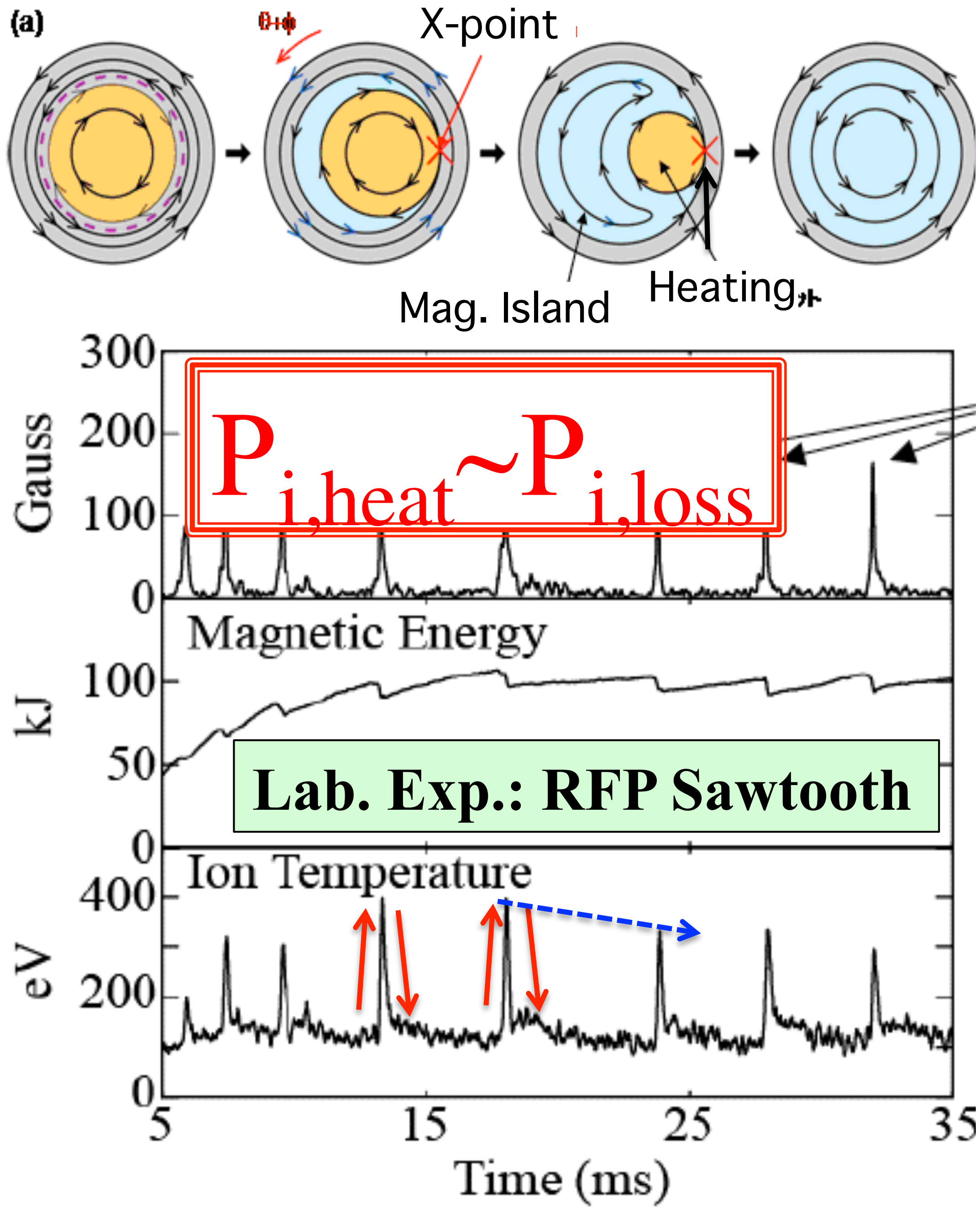



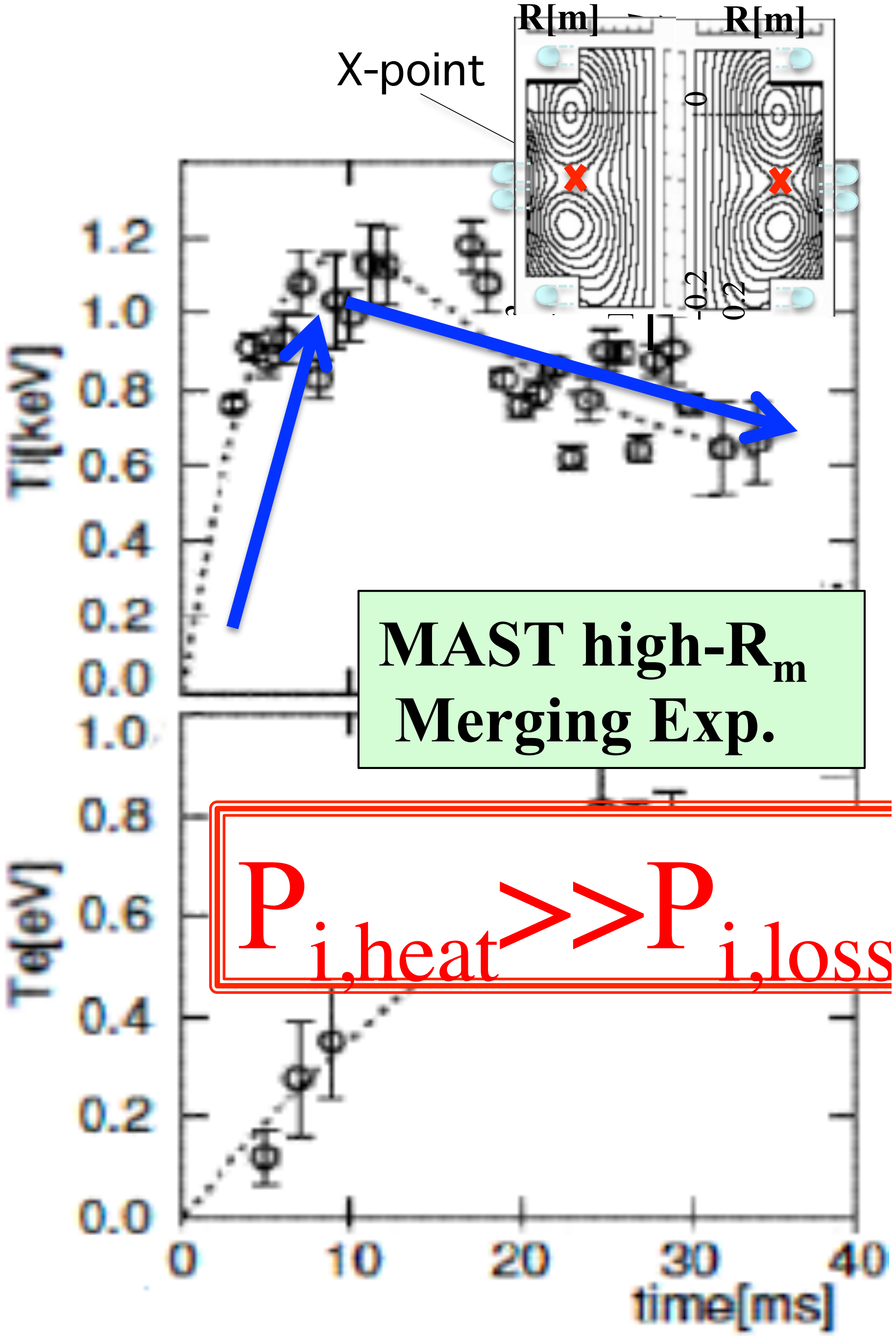



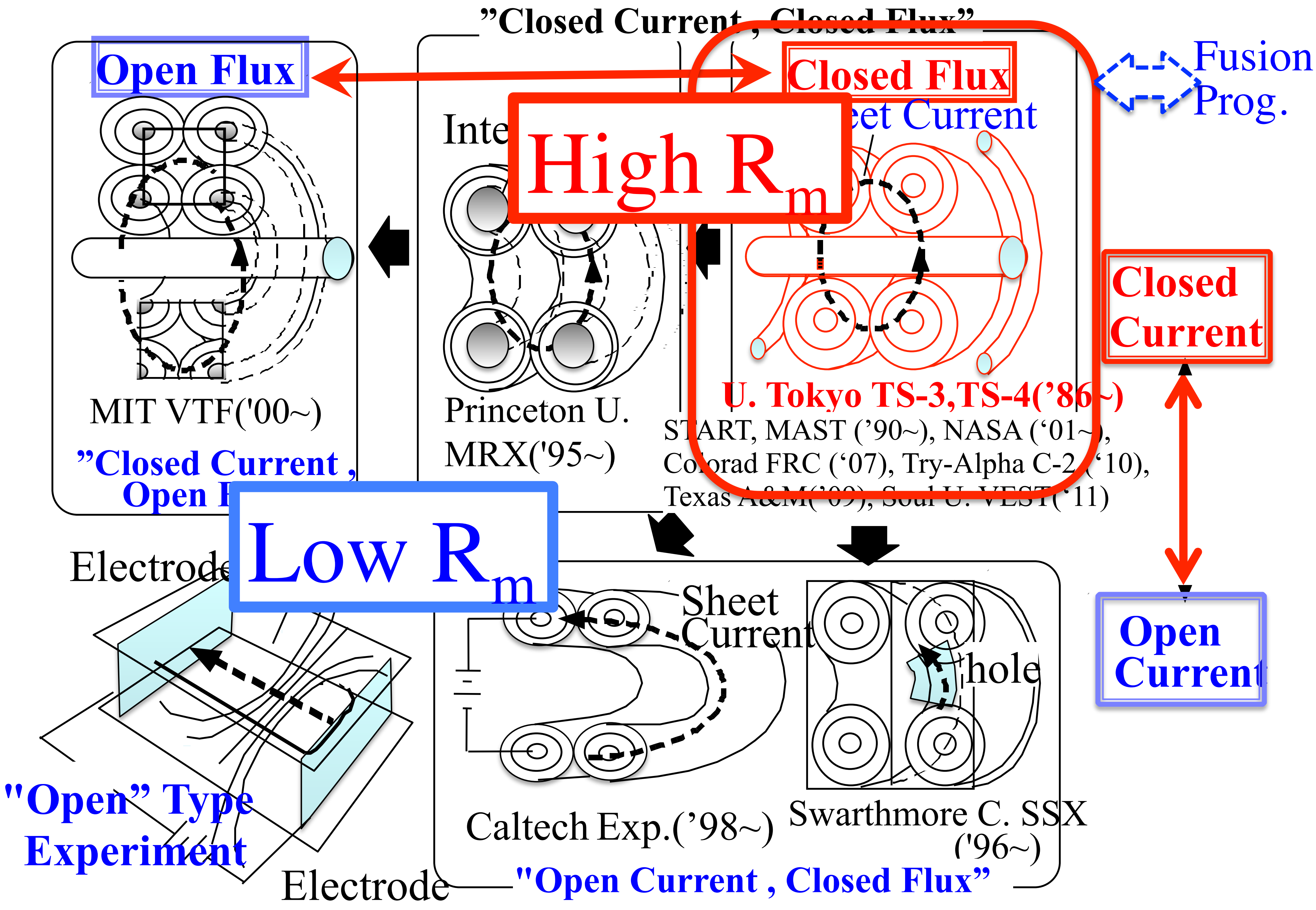

Stop hobby w
Establish son
application st
for Electr. En
plasmoid/filament
Flare
heating
SXR loop
Start application
of huge reconn-
ection heating!
TS-3 ('85)/ TS-4('00)
1985~
CT Merging for
Current Drive
1986~
1989~
1990~
Reconnection Heating
Experiment for FRC/ST
FRC
Merging
Formation
TS-3,
TS-4
with NBI
Reconnection
Physics Exp.
1990~
High-R$_m$
Reconnection
Physics Exp.
TS-3, TS-4
=
ST Merging
Startup
TS-3, UTST,
MAST,
2005~
MAST
collabor
ation
2016~
TS-U Exp.
JSPS Project

Closed fluxes surrounding X-point can confine rec. heating energy.



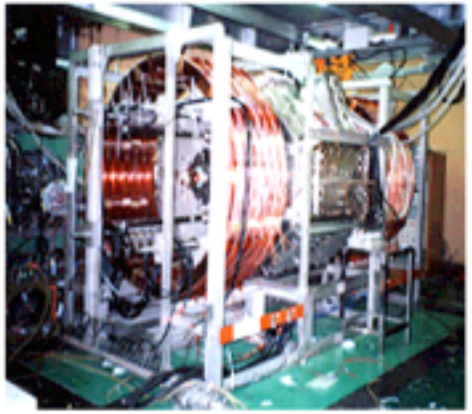



Number of merging/ reconnection experiments is over 10 now.

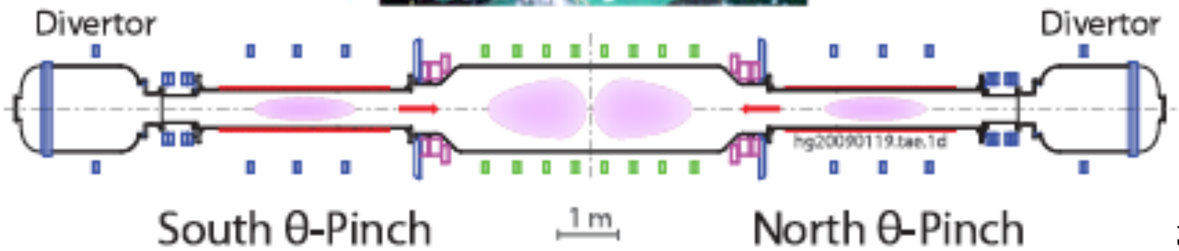


# Just the closed-current+closed flux experiments have high T & $R_m$.

**1985~ TS-3,4 (U.Tokyo)**



**2010~C-2 (Tri Alpha)**

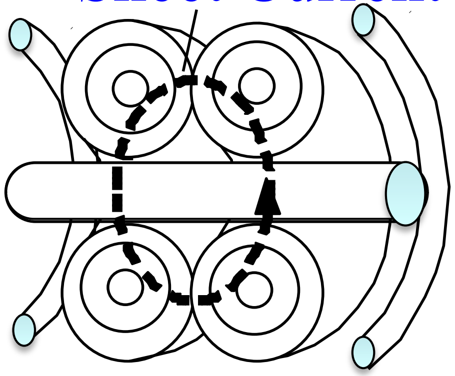



**"Closed Current , Closed Flux"**

**High $R_m$**

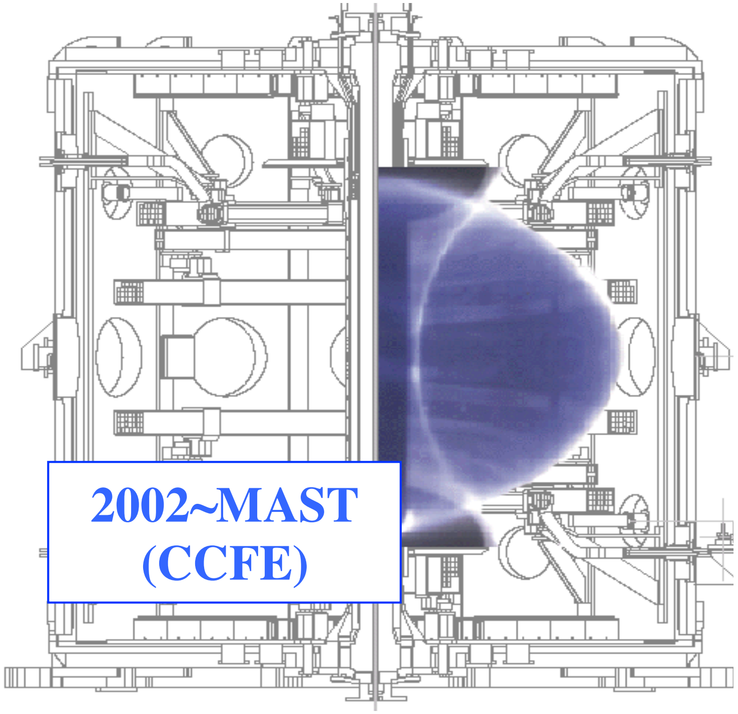
**Closed Flux**

Sheet Current

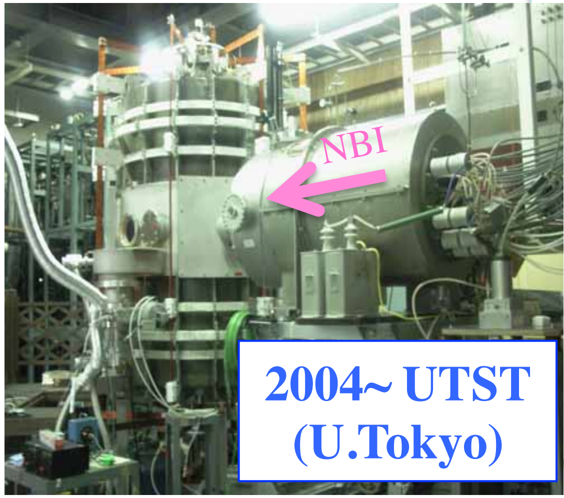


**U. Tokyo TS-3,TS-4('86~)**

START, MAST ('90~), NASA ('01~), Colorad FRC ('07), Try-Alpha C-2 ('10), Texas A



**2002~MAST (CCFE)**



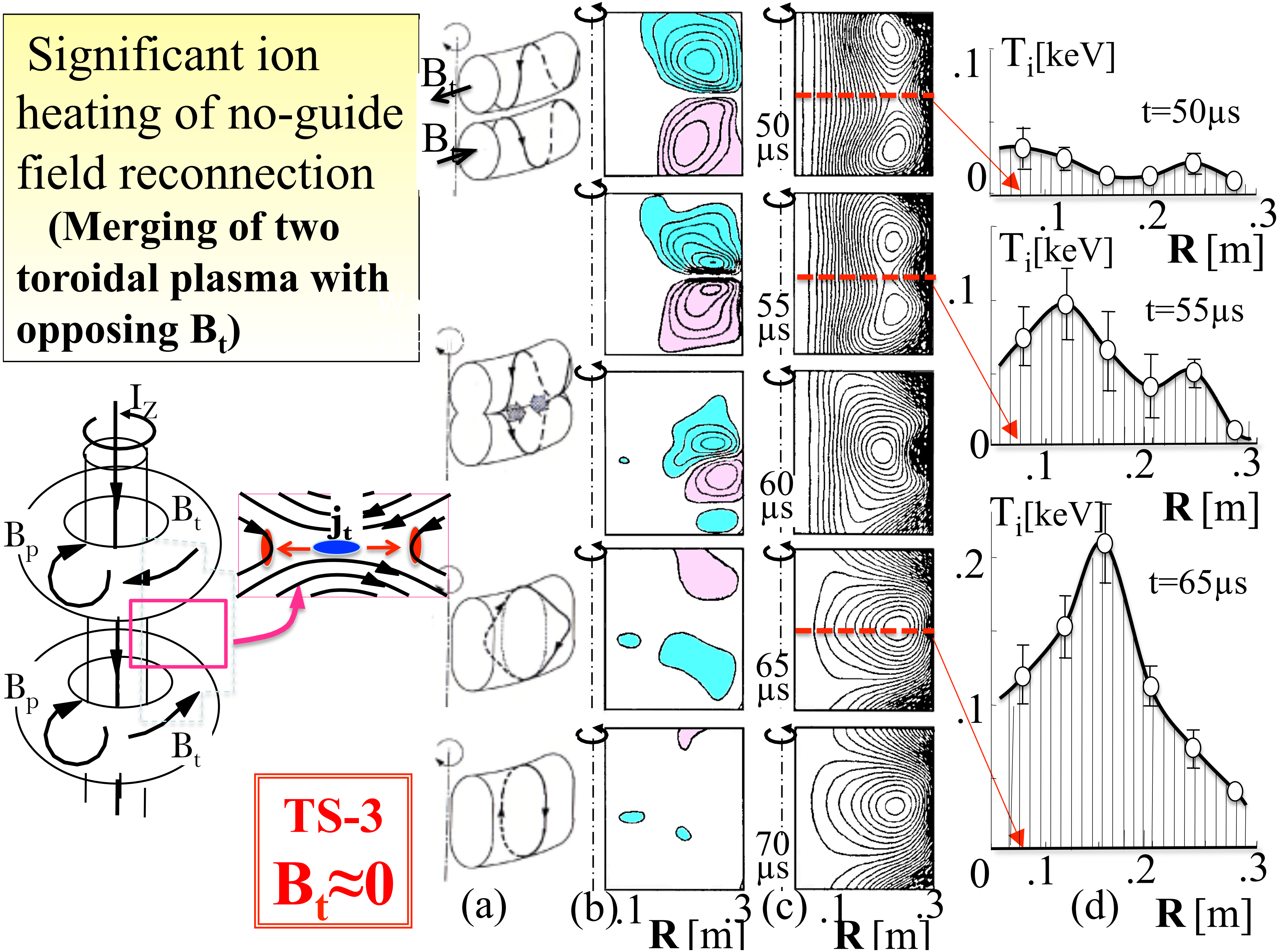

**2004~ UTST (U.Tokyo)**

**TS-U Exp 2016~**

**ST-40 2016~**

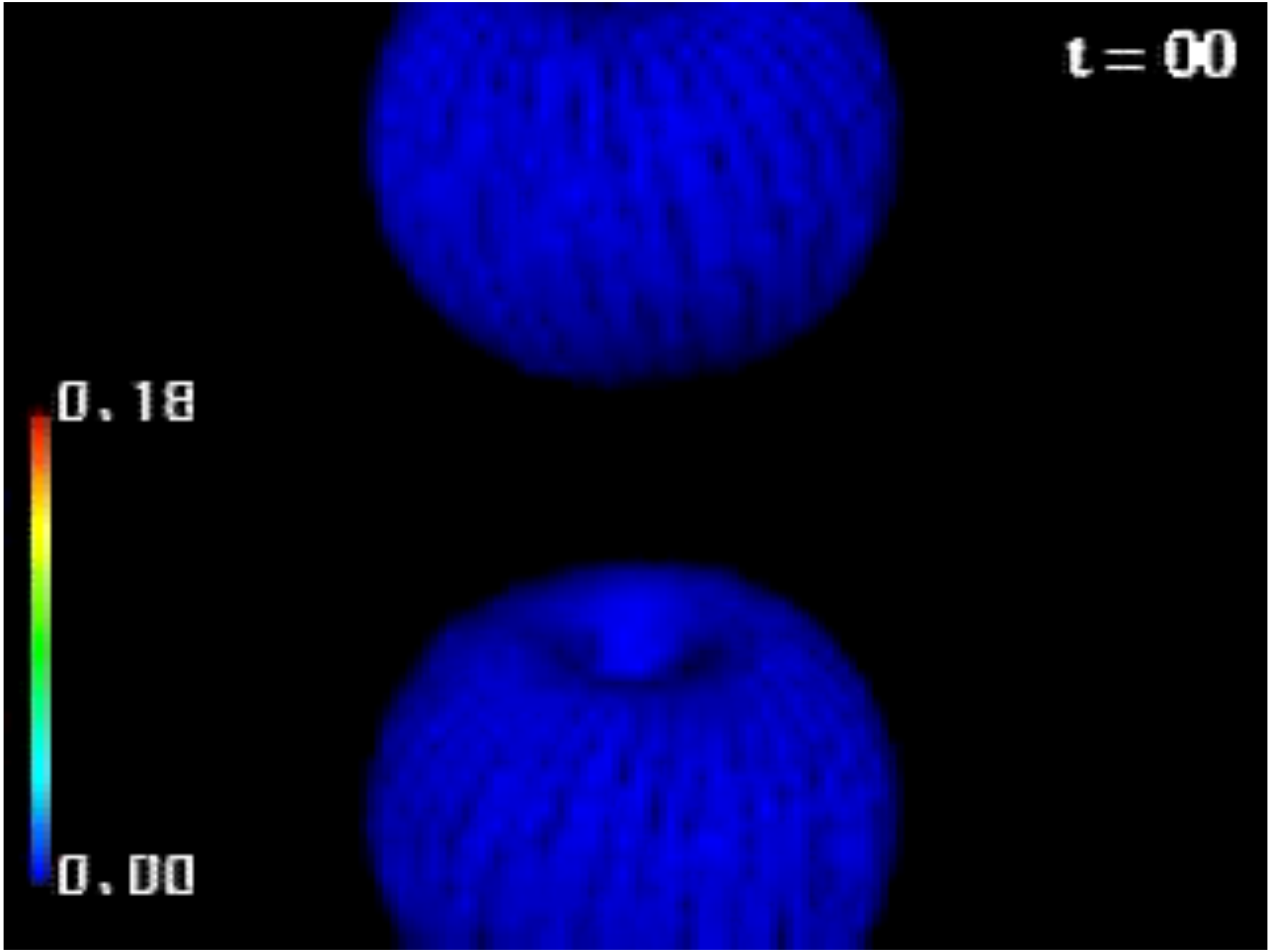
# Significant ion heating of no-guide field reconnection

**(Merging of two toroidal plasma with opposing $B_t$)**




**TS-3**
**$B_t \approx 0$**

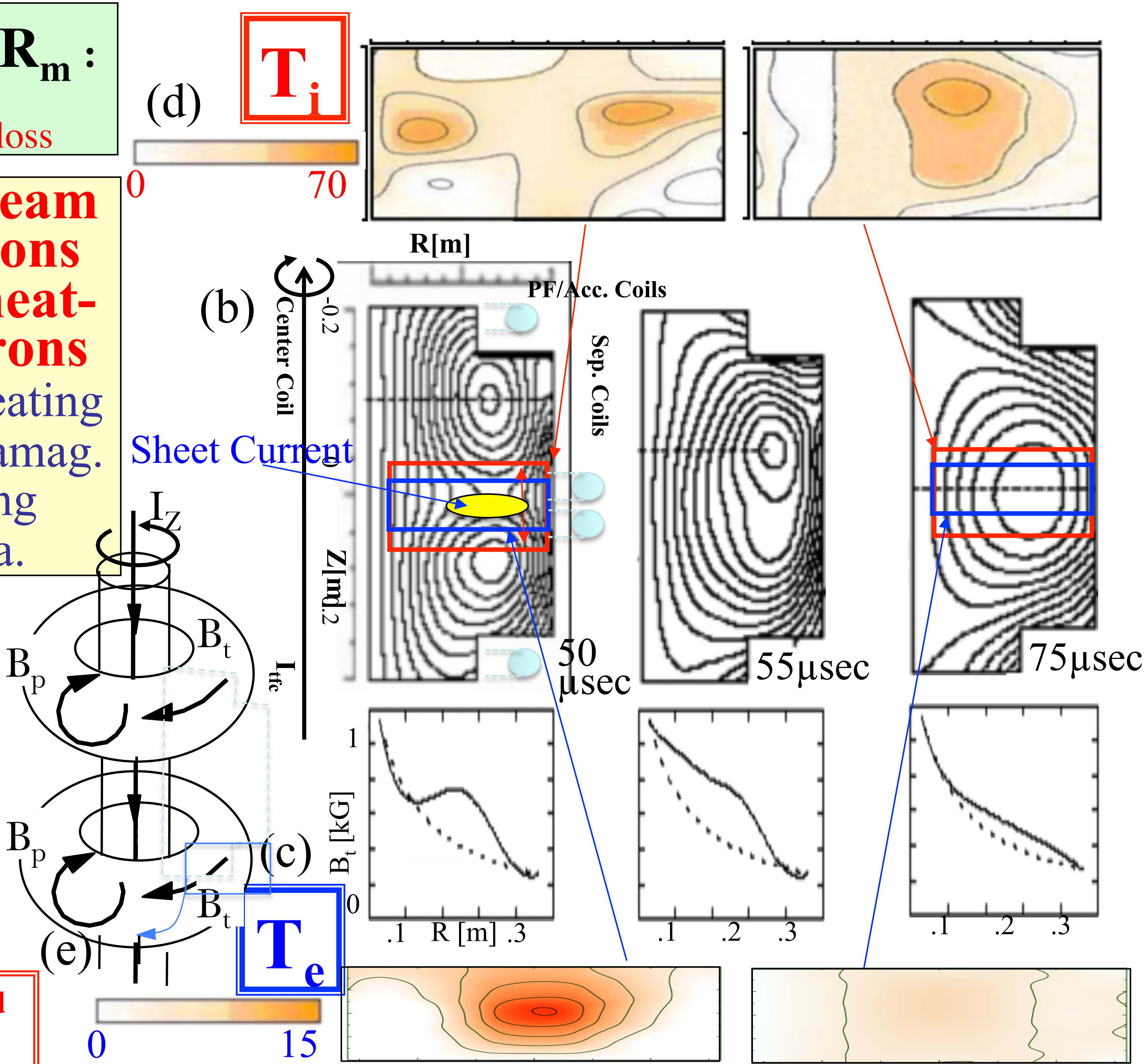
**Watanabe (NIFS) PFR00 made the global MHD simulation of couterhelicity reconnection, including its heating effect.**

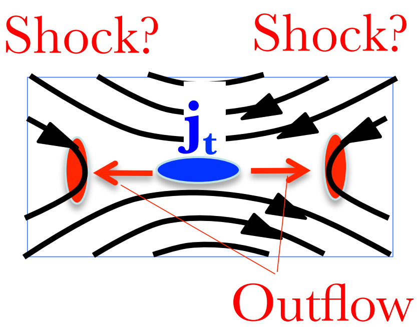


# TS-3: High-$R_m$ : $P_{i,heat} >> P_{i,loss}$

**1) Down-stream heating of ions**
**2) X-point heating of electrons**

High power heating suppresses paramag. $B_t$, increasing plasma beta.



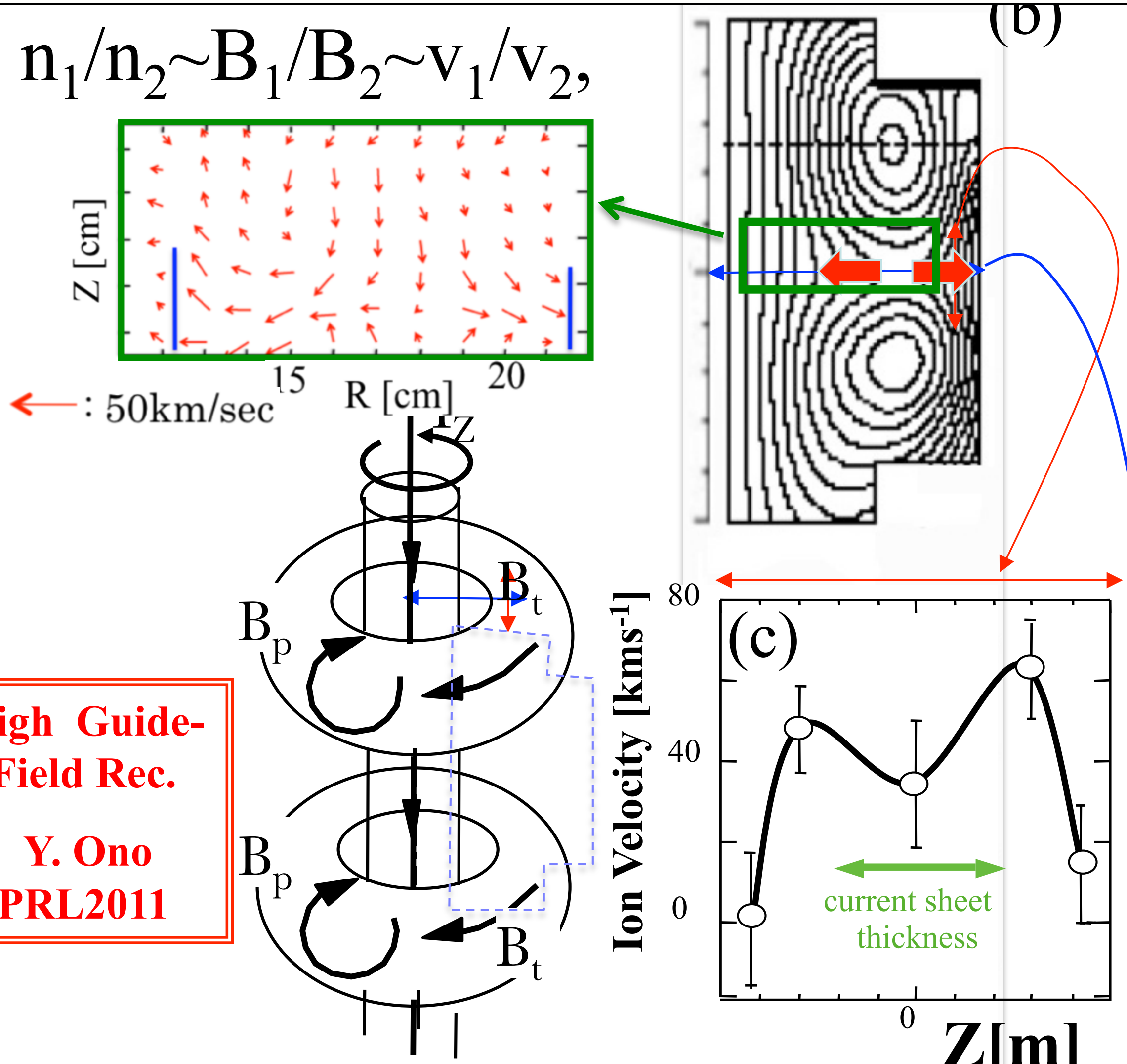

**High Guide-Field**

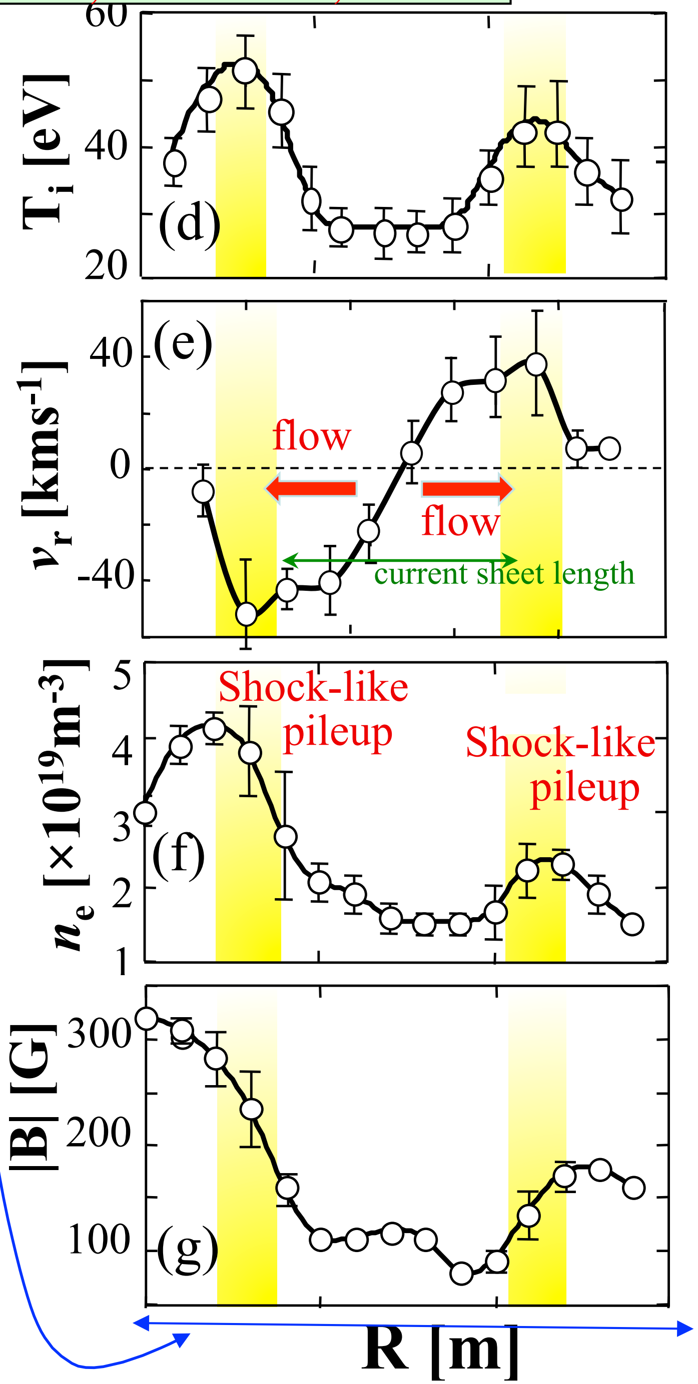
**Y. Ono PRL2011**

# TS-3: Mechanism for rec. heating : $P_{i,heat} >> P_{i,loss}$

In the downstream, hot $T_i$ spot, steep increase in $n_e$ B and dumping of flow appear, indicating fast shock form.

$n_1/n_2 \sim B_1/B_2 \sim v_1/v_2$,




**High Guide-Field Rec.**

**Y. Ono PRL2011**

# Energy Flow during Reconnection with high $B_t$

**TS-3 High Guide field $B_t \approx 5B_{rec}$, $B_t \approx 0$** (cf. No-Guide field: Ono PRL96)

Magnetic Energy Dissipation ≈ **1, 1**

**Ion Acceleration** $v_{ion} \approx v_{pol.Alf.}$

**Outflow Energy**

**Shock-like (pile-up) & viscosity damping mechanisms?**

**Ion heating Energy ≈ 0.88, 0.85**

**»**

**Current Sheet Heating**

$\int\int E \bullet J dV dt$ **≈0.09, 0.10**

**Small localized electron heating**

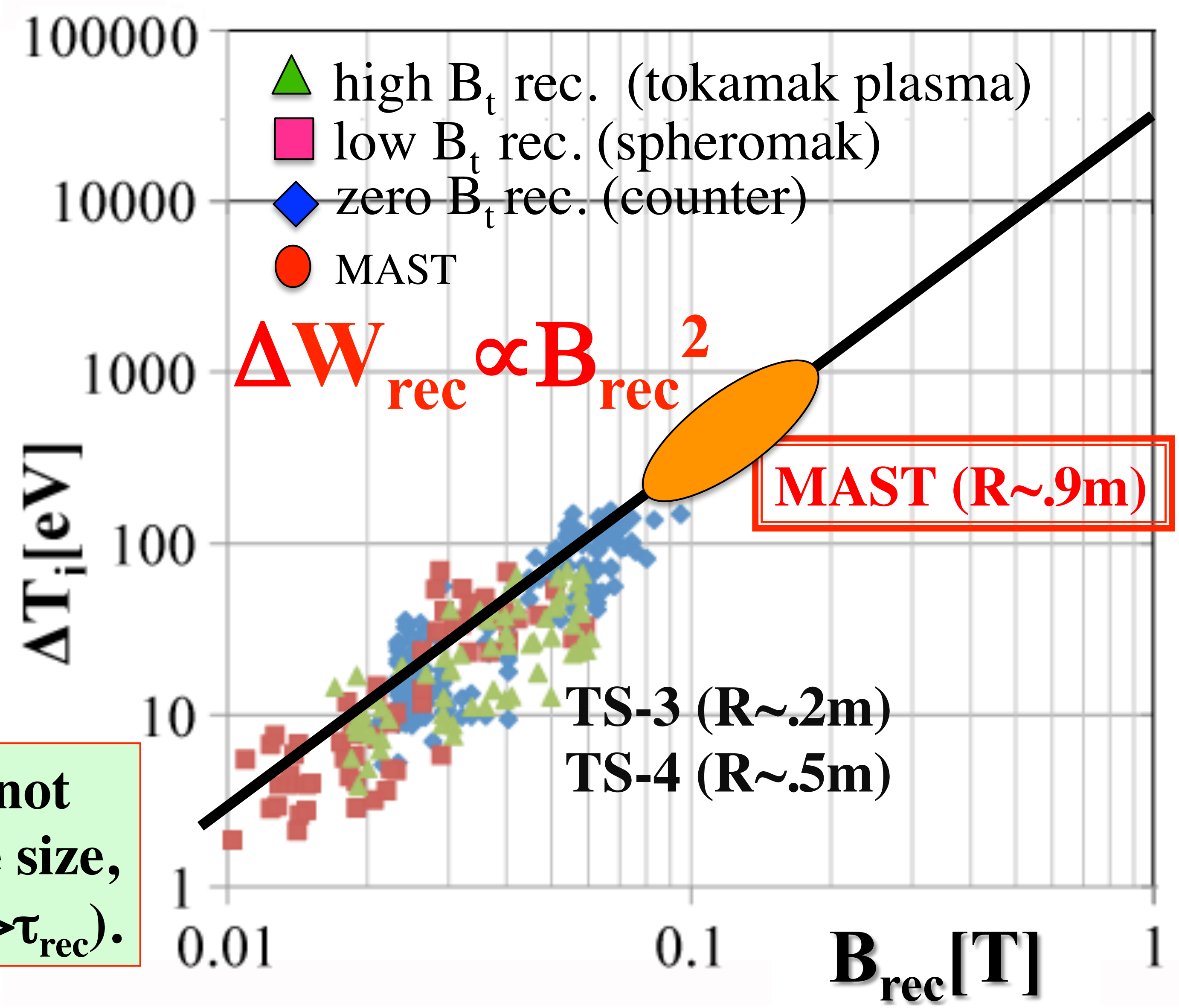
**Electron heating Energy ≈ 0.07, 0.07**

Using MAST exp., we extended the $B_{rec}^2$-scaling to 1.2keV (1.5kG).

# $B_{rec}^2$-scaling for direct ion heating of reconnection

$\Delta W_{th} \sim \Delta W_{ion}$
$\propto \Delta(nT_i)$
$\propto \Delta T_i$
(n~normalized)
$\propto B_{rec}^2 \propto B_p^2$

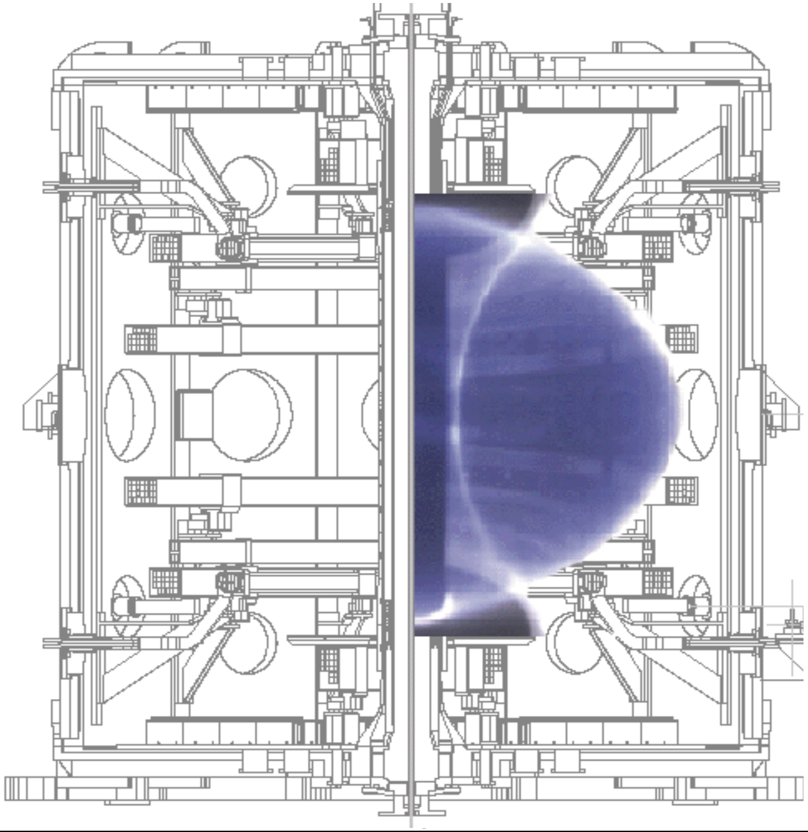
$V_{outflow} \sim$
$V_{pA} \propto B_p / n^{1/2}$




The scaling does not depend on machine size, if $P_{i,heat} >> P_{i,loss} (\tau_E >> \tau_{rec})$.

## $B_{rec}^2$ -Scaling of Rec. Heating → High-$B_{rec}$ Merging Exp.

# Up-scaled Reconnection Experiment in MAST



$>10^5$ ← $R_m$ — $>10^3$

| | MAST | TS-4 | TS-3 |
|---|---|---|---|
| R [m] | 0.9 | 0.5 | 0.2 |
| a [m] | 0.7 | 0.4 | 0.15 |
| $I_p$ [MA] | 2 | 0.1 | 0.07 |
| $B_t$ [T] | 0.4-0.7 | 0.1 | 0.2 |
| $B_p$ [T] | 0.1-0.2 | 0.03 | 0.05 |

1D measurements of $T_i$ and $T_e$ :
1) 130ch. Thomson scattering,
2') NPA
2) 32ch Ion Doppler from UTokyo

*The MAST plasma has higher reconnecting B field than TS-3.*

↓

*UK-Japan Joint Experiment supervised by M. Gryaznevich and MAST team*

# MAST: Ultra-High-$R_m$ :

$P_{i,heat} >> P_{i,loss}$ ,

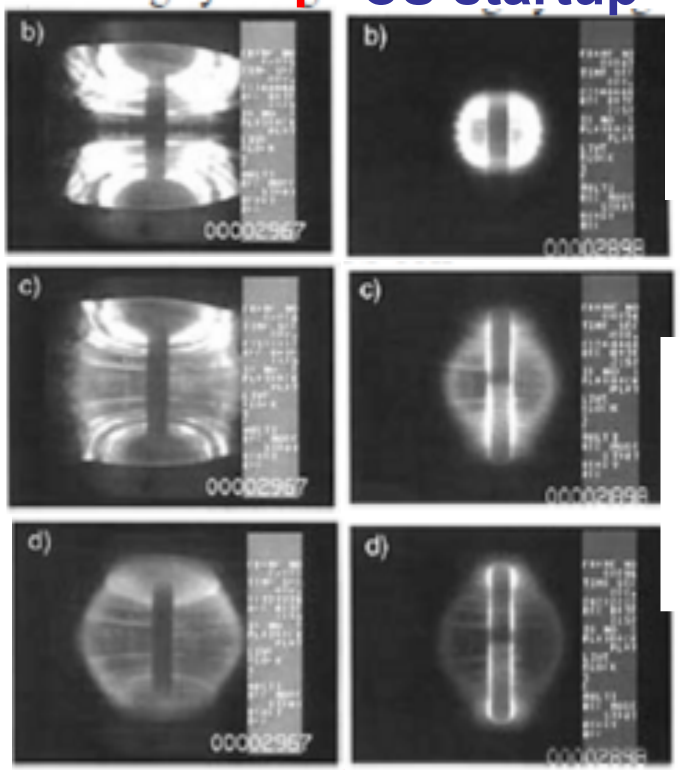
$P_{e,heat} >> P_{e,loss}$

## Significant Ion Heating in MAST Rec.

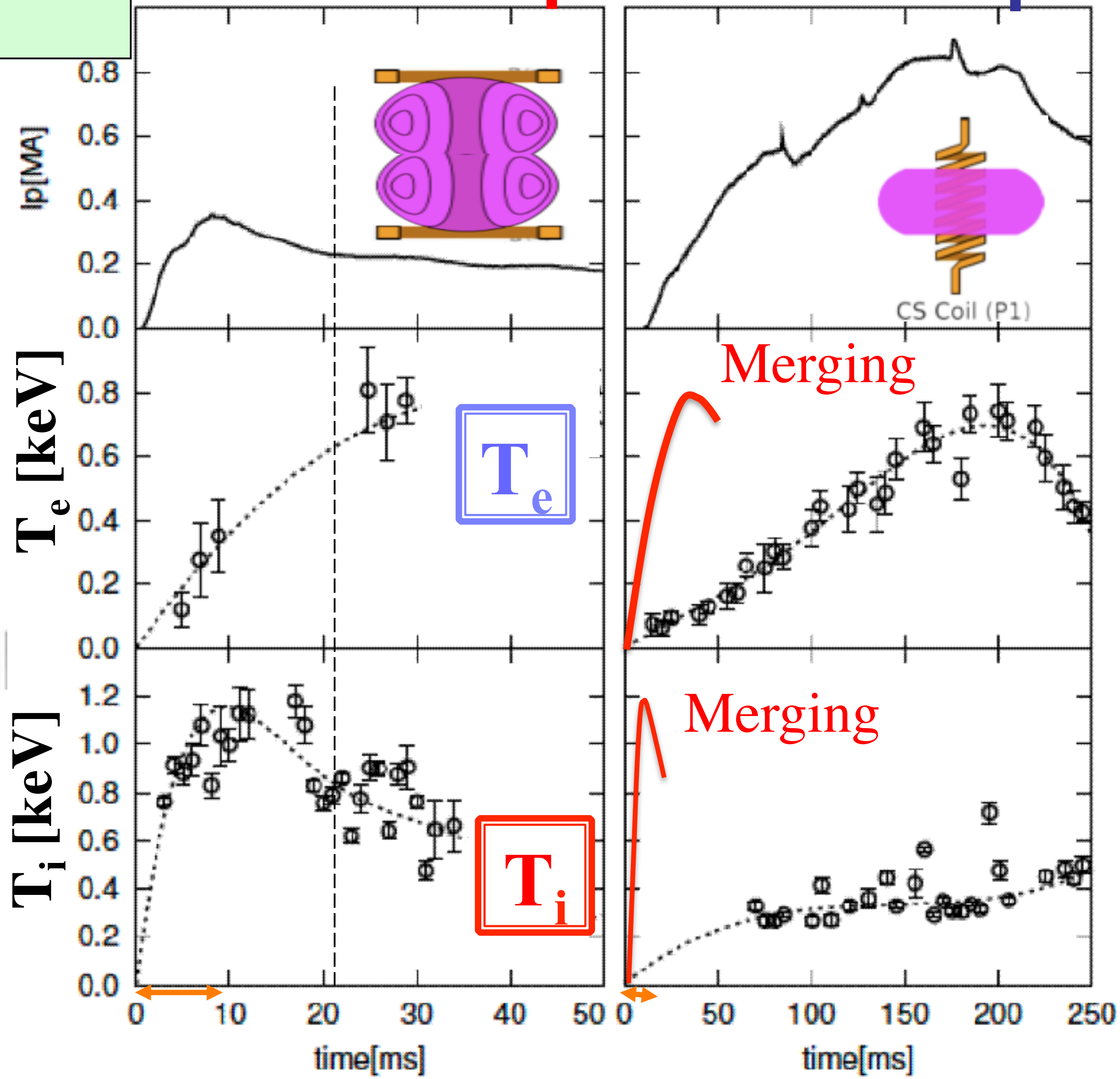
**MAST Reconnection Exp.**

The ST merging/reco-nnection heats ions to 1.2keV within 10 msec.

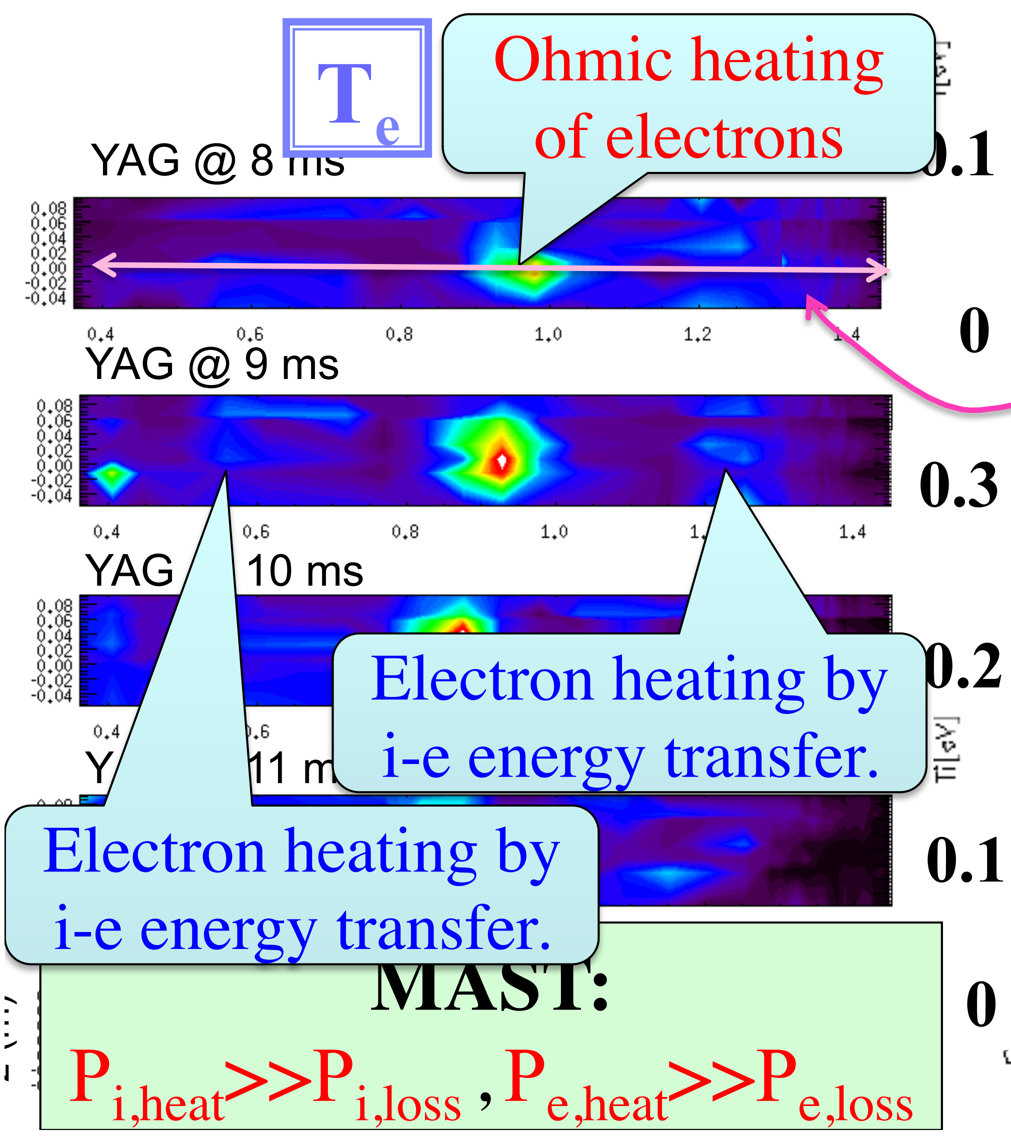
Rec. startup CS startup

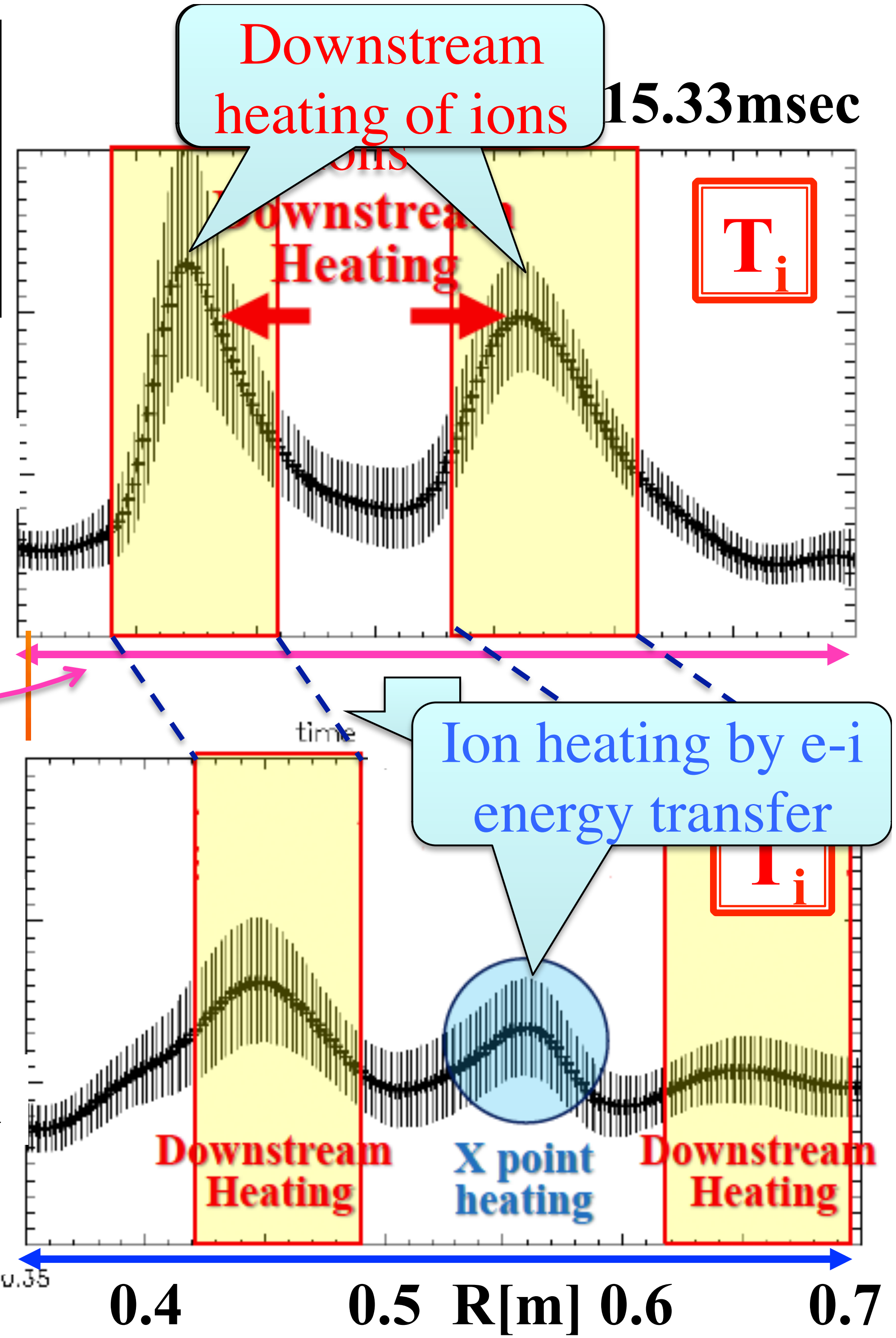


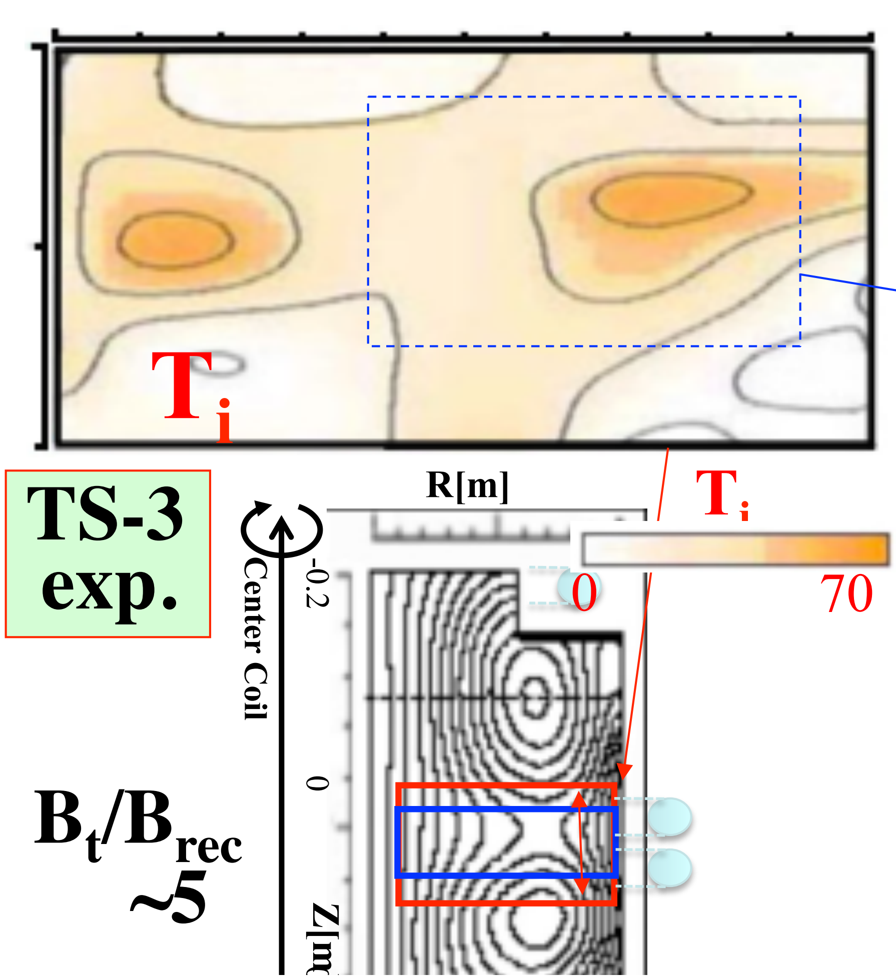

Rec. startup CS startup

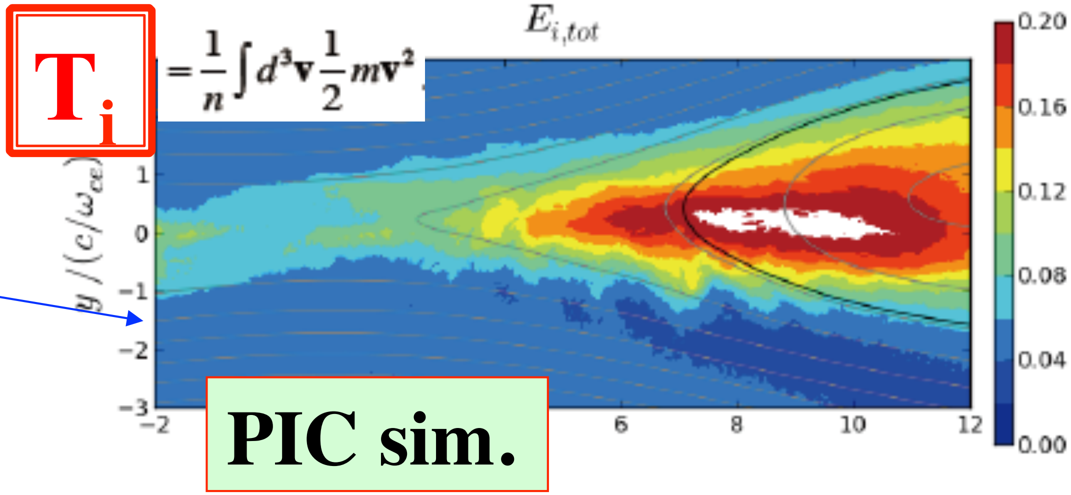


Initially, $T_i$ and $T_e$ profiles have a double and a single peaks, respectively but finally have triple peaks due to ion-electron relaxation.

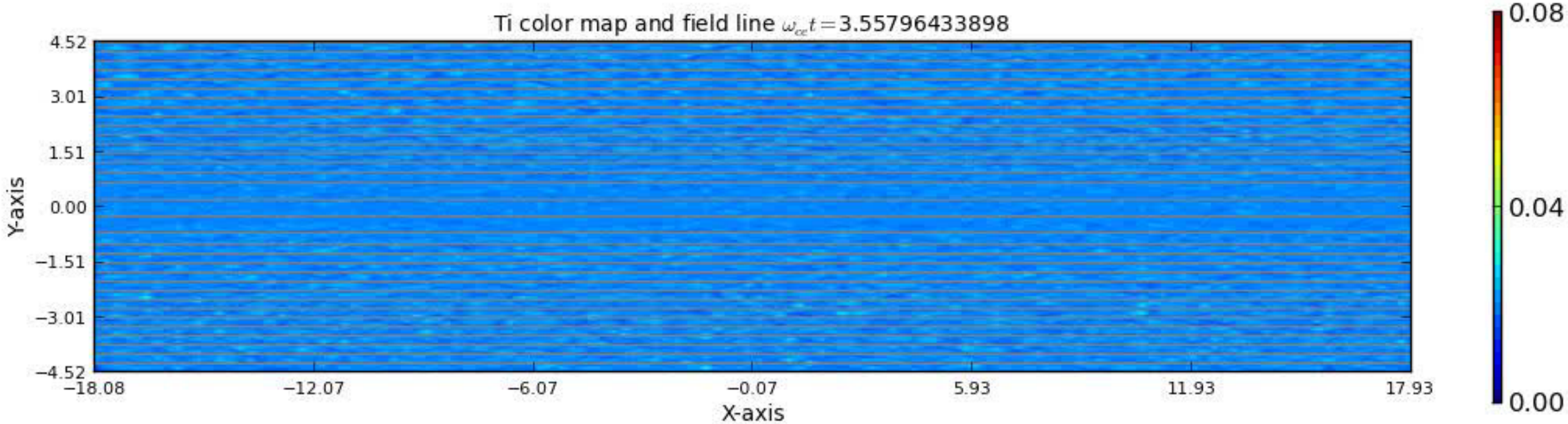




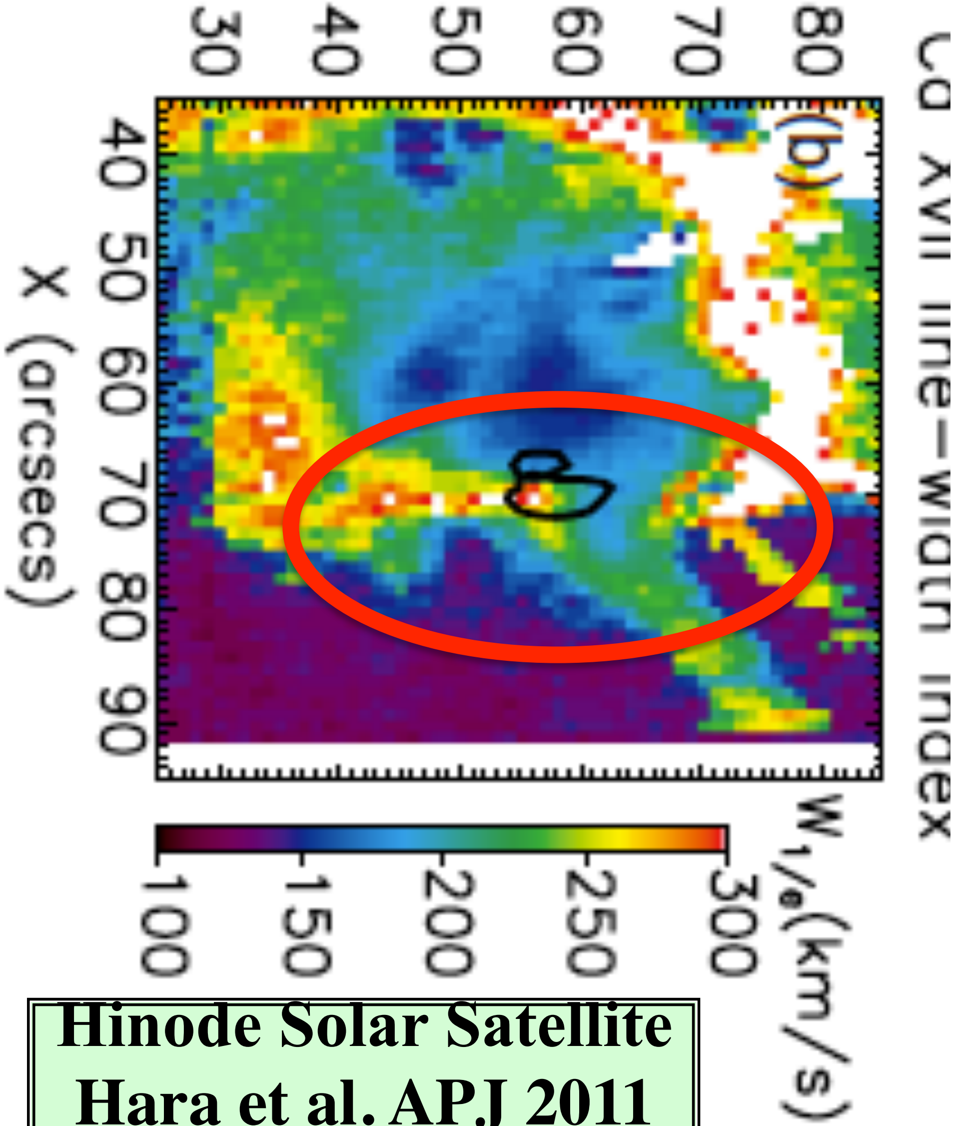




$T_i$ and $T_e$ profiles agree with recent particle (PIC) simulation results by Inoue & Horiuchi at NIFS.



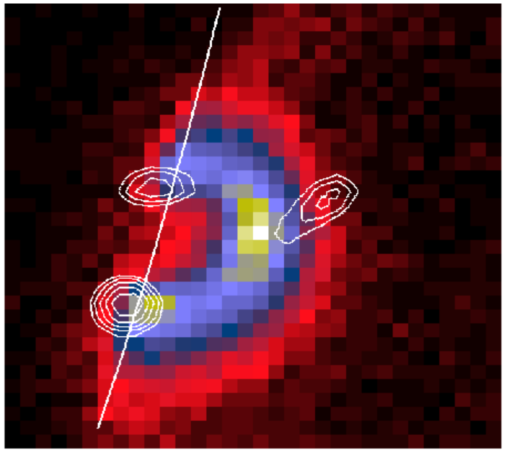
# First Hinode satellite measurement of $T_i$

Cross-validation of experiment and observation!

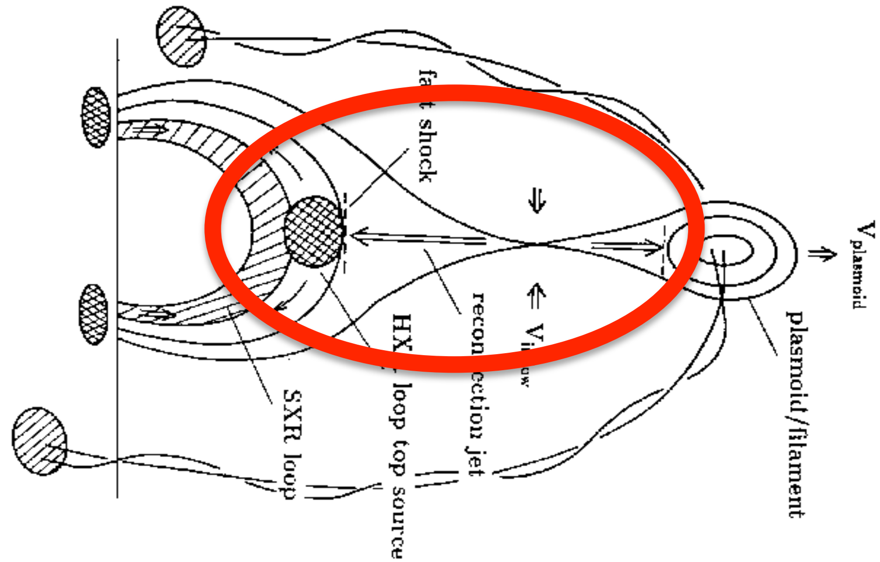



**Hinode Solar Satellite**
**Hara et al. APJ 2011**

Loop top hard X-ray sources



Masuda et al. 1994

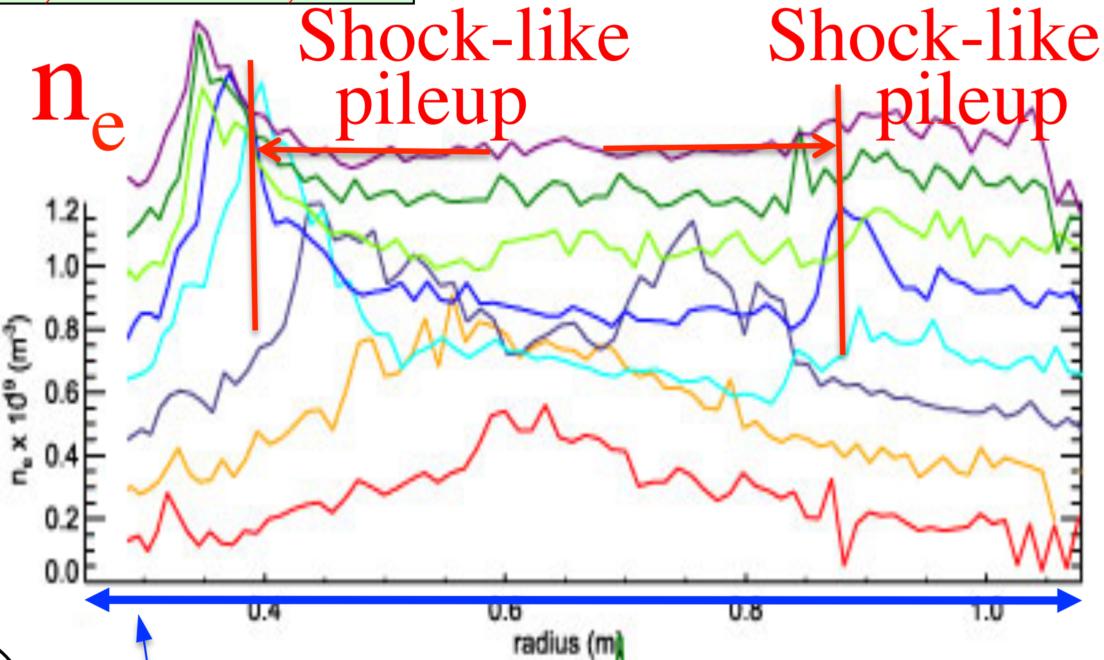



Shibata et al. 1995

# MAST: Ultra-High-$R_m$ : $P_{i,heat} >> P_{i,loss}$

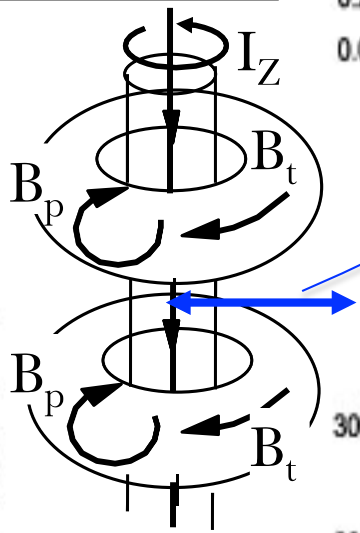
1) Electron heating localized at X-point

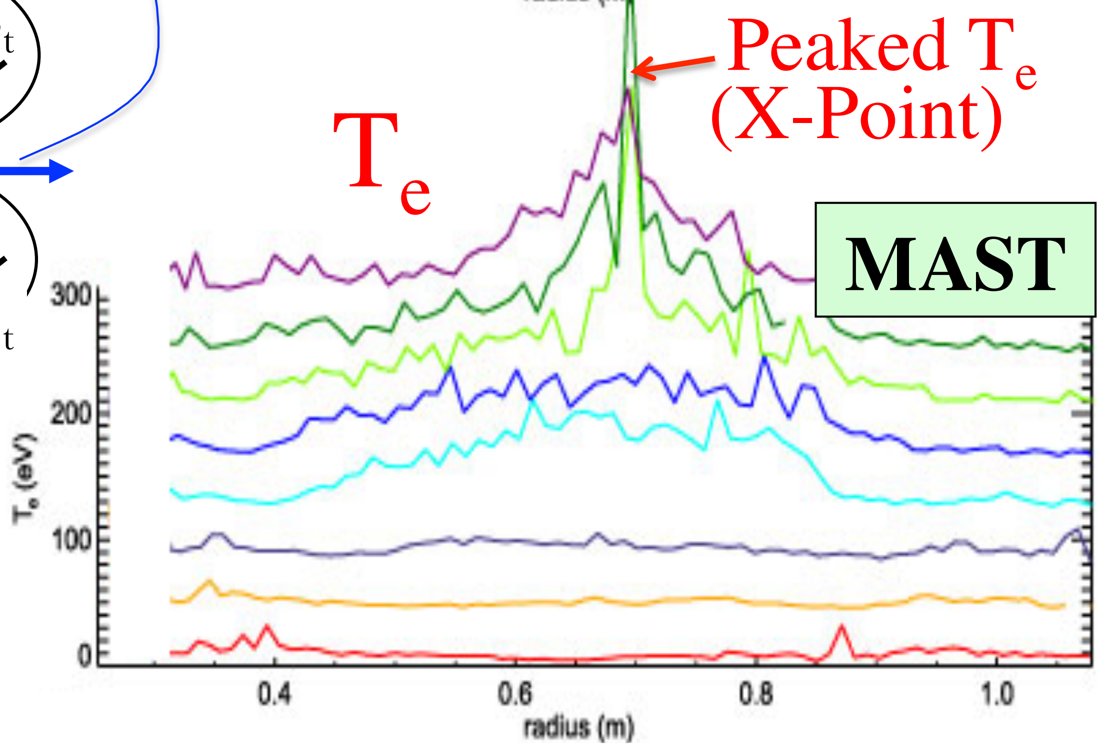
2) Shock-like pile-up in downstream.

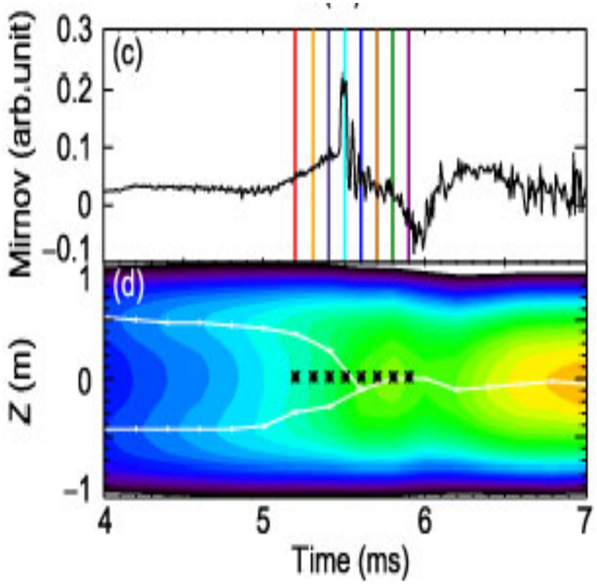


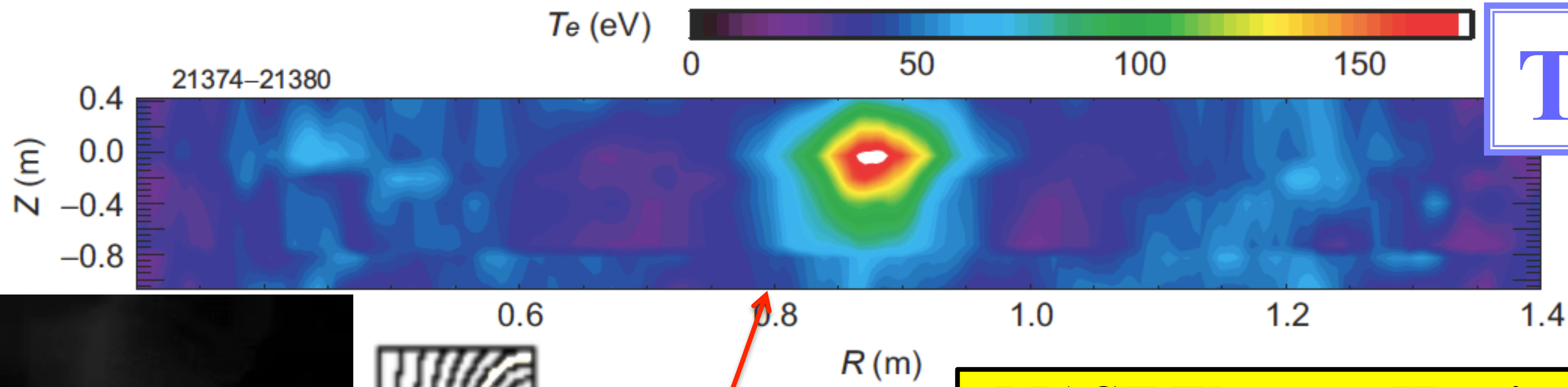

**MAST**

**$B_t \approx 5B_{rec}$**



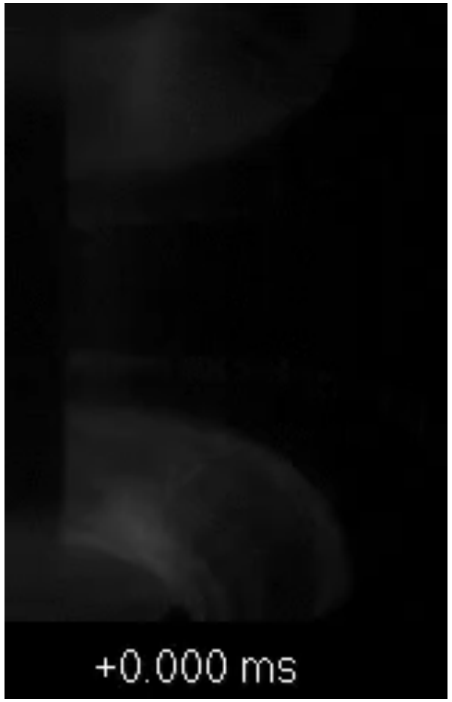



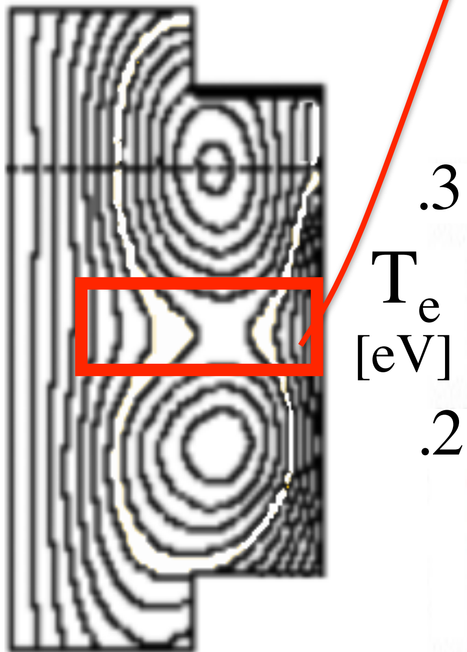



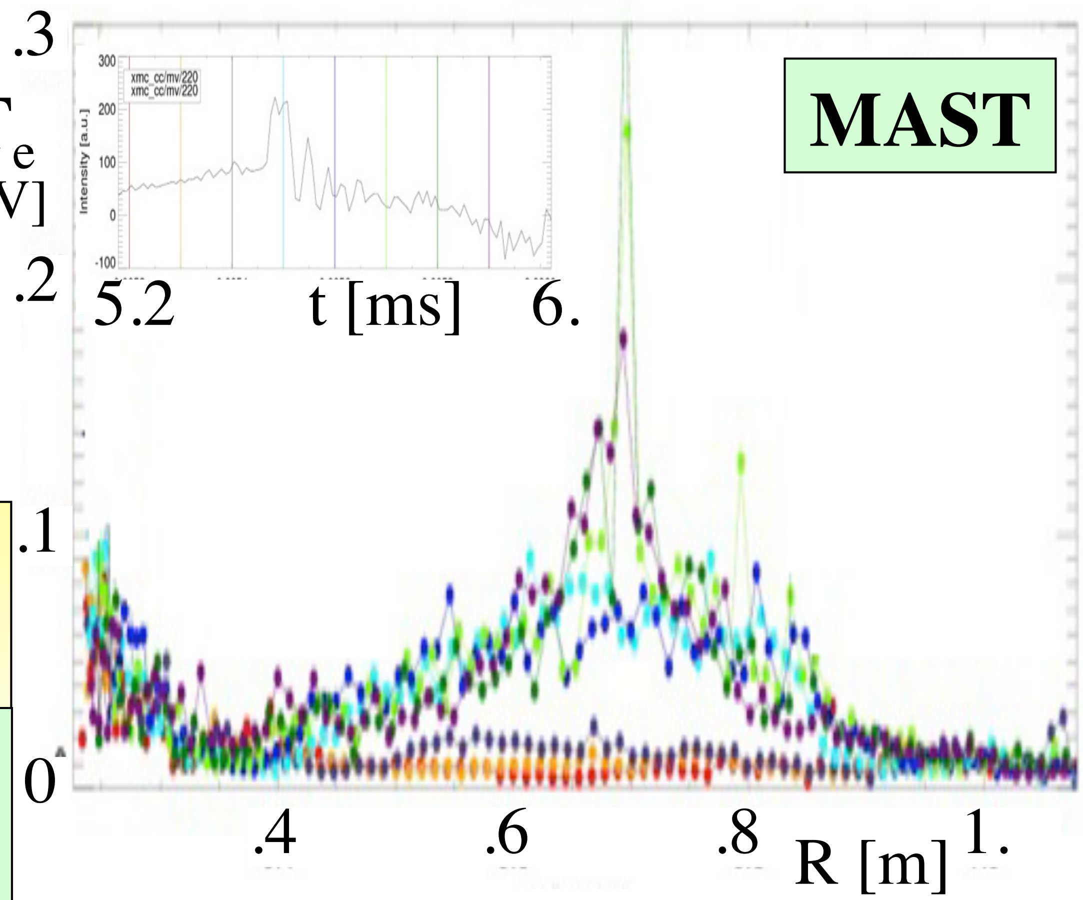



$T_e$

**MAST Electron Heating**



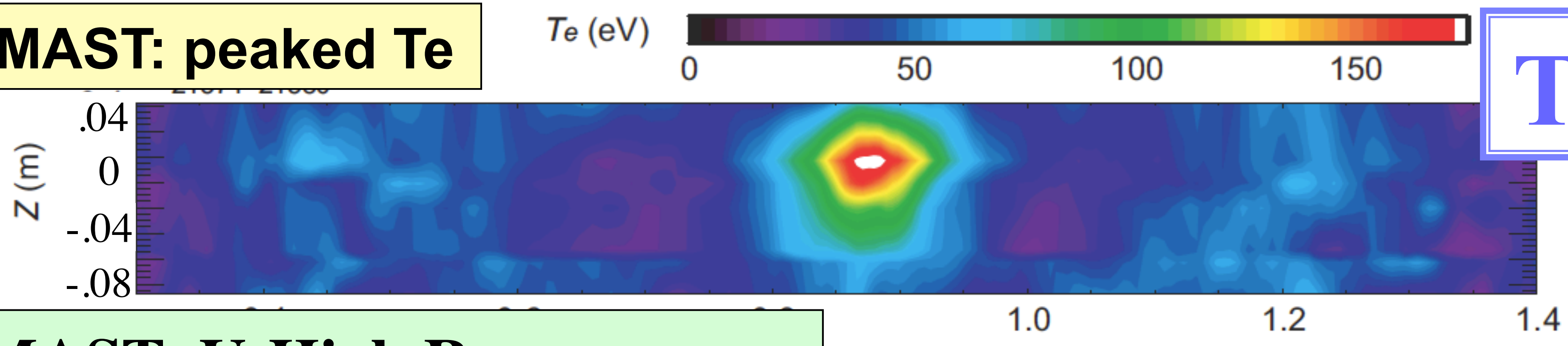



**$T_e$ profile is peaked locally at X-point.**

**MAST: Ultra-High-$R_m$ :**

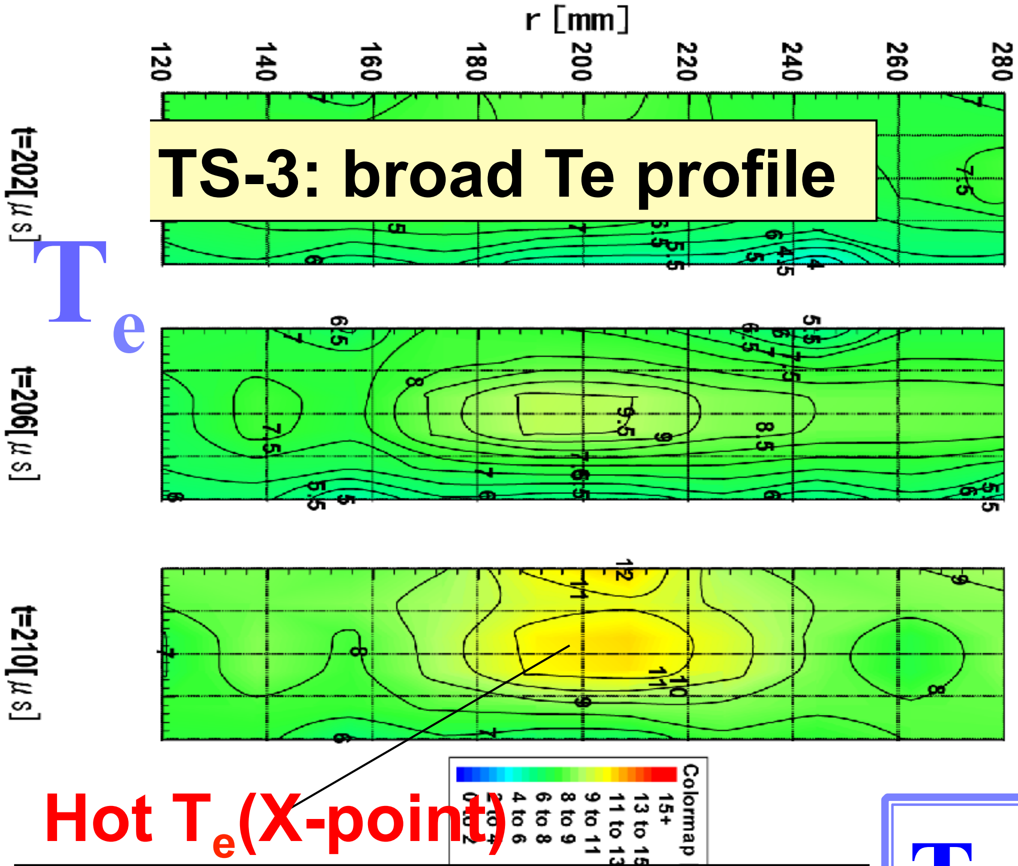
$P_{i,heat} >> P_{i,loss}$ , $P_{e,heat} >> P_{e,loss}$

**MAST: peaked Te**



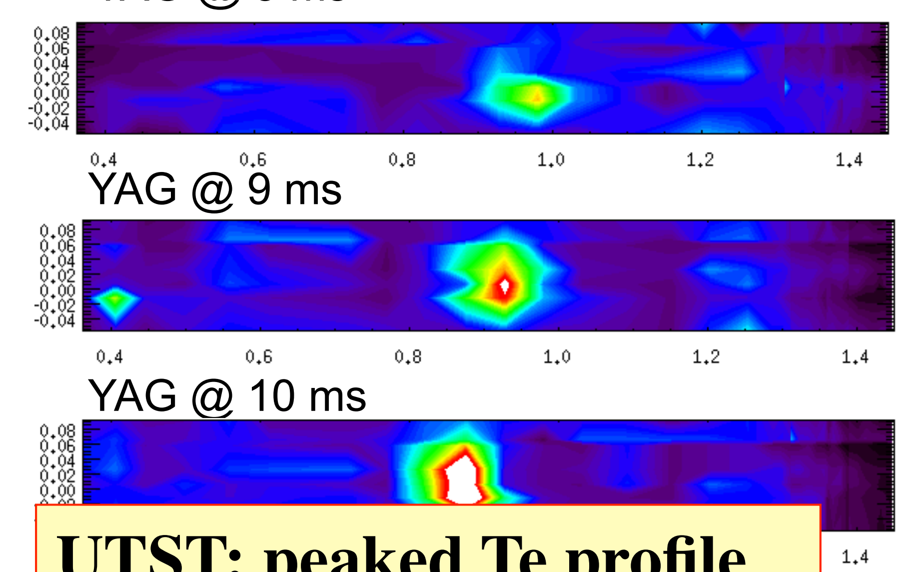

$T_e$

**MAST: U-High $R_m$ $\tau_{e,heat} >> \tau_{e,loss}$**

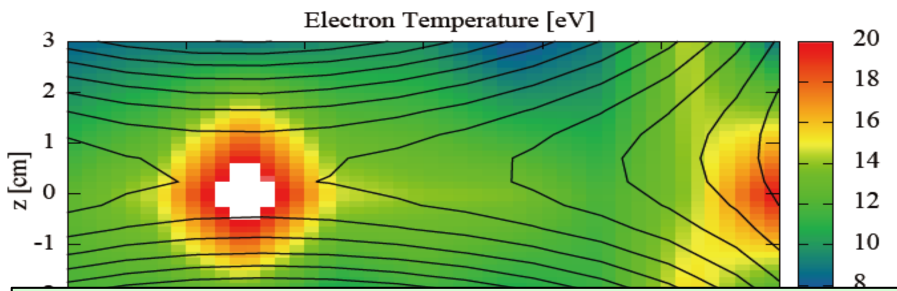



**TS-3: broad Te profile**

$T_e$




**UTST: peaked Te profile**




**Hot $T_e$(X-point)**

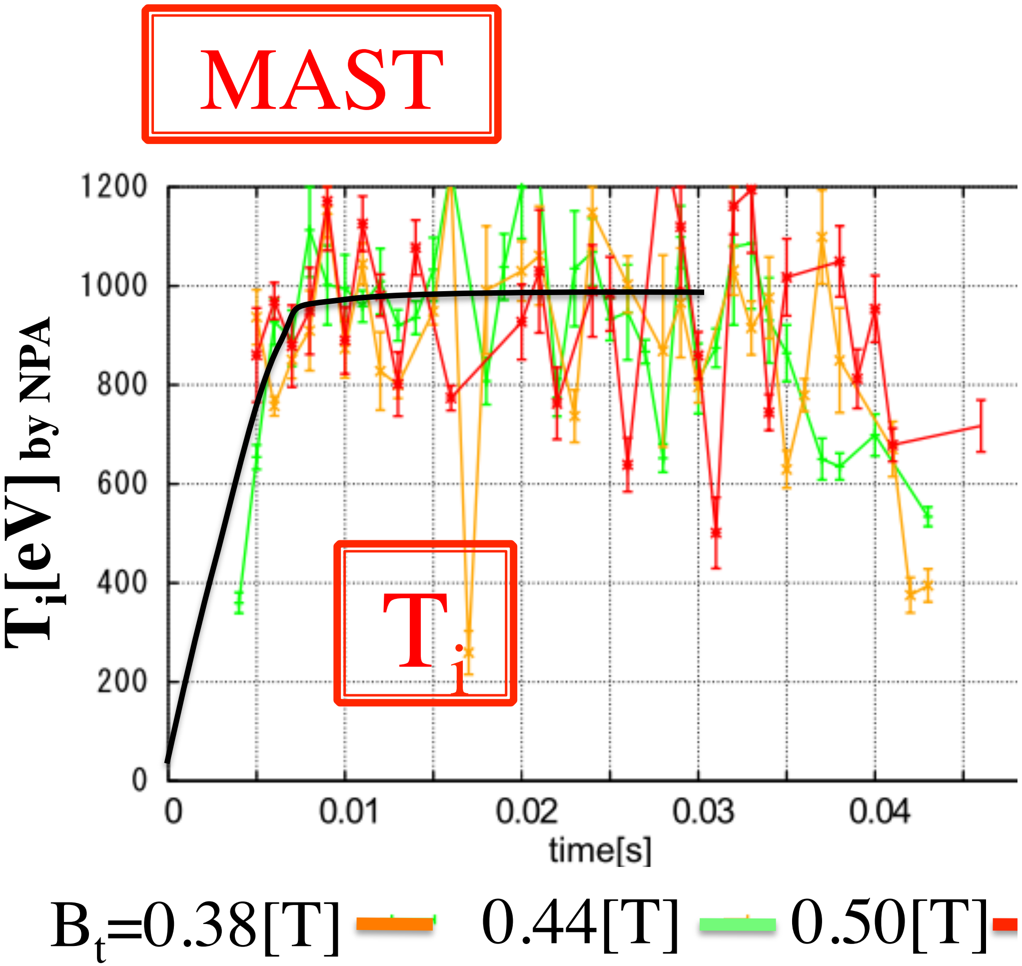
**TS-3: High $R_m$ $P_{e,heat} \sim P_{e,loss}$**

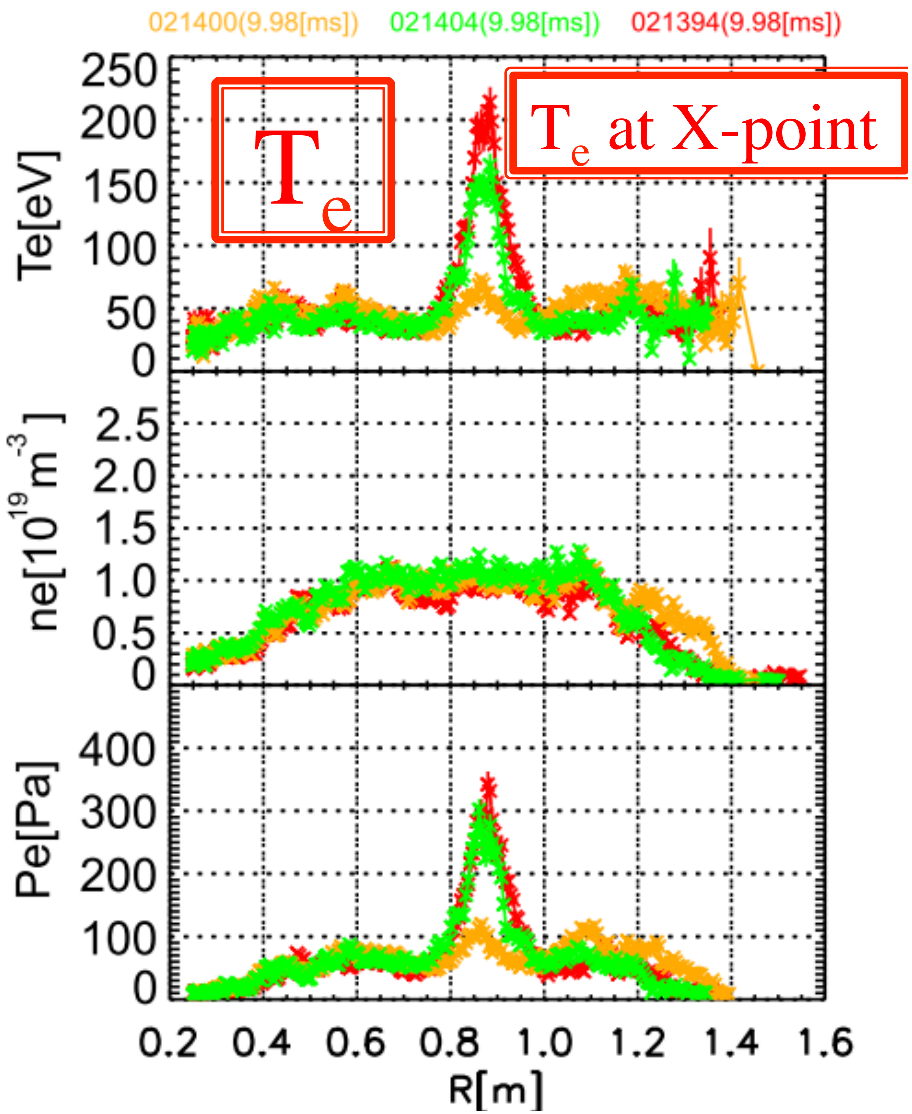
$T_e$

**UTST: UH $R_m$ $P_{e,heat} >> P_{e,loss}$**

## Effect of toroidal (guide) field on rec. heating → small

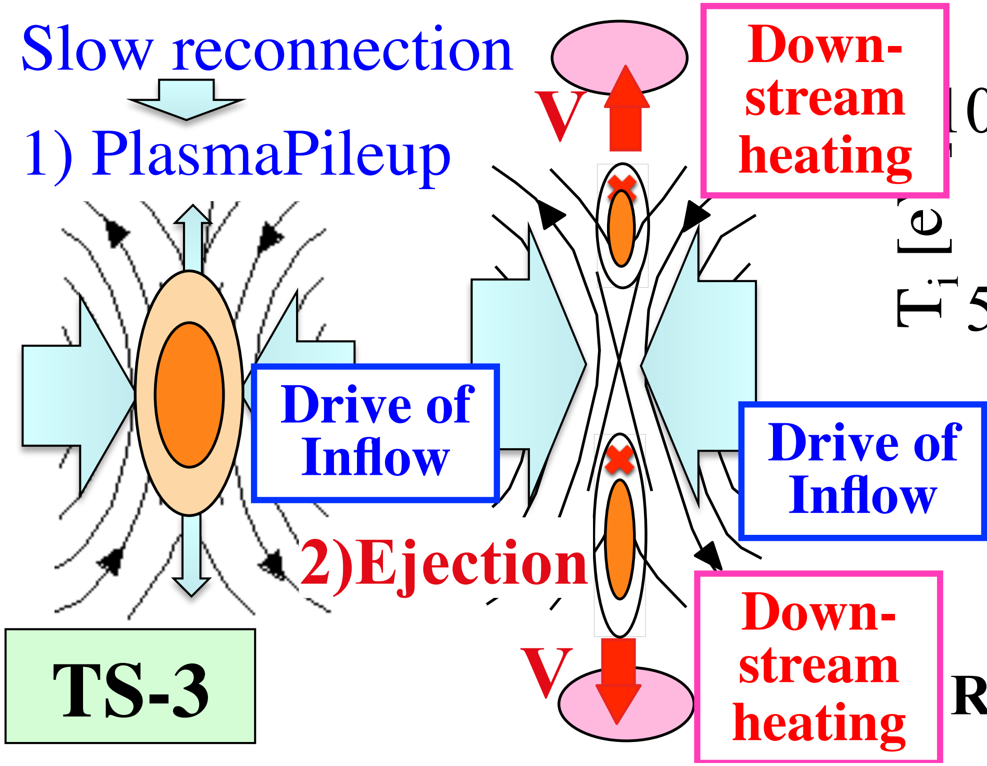
Bulk ion and electron heating does not depend on guide field $B_t$, while local electron heating at X-point does strongly on B

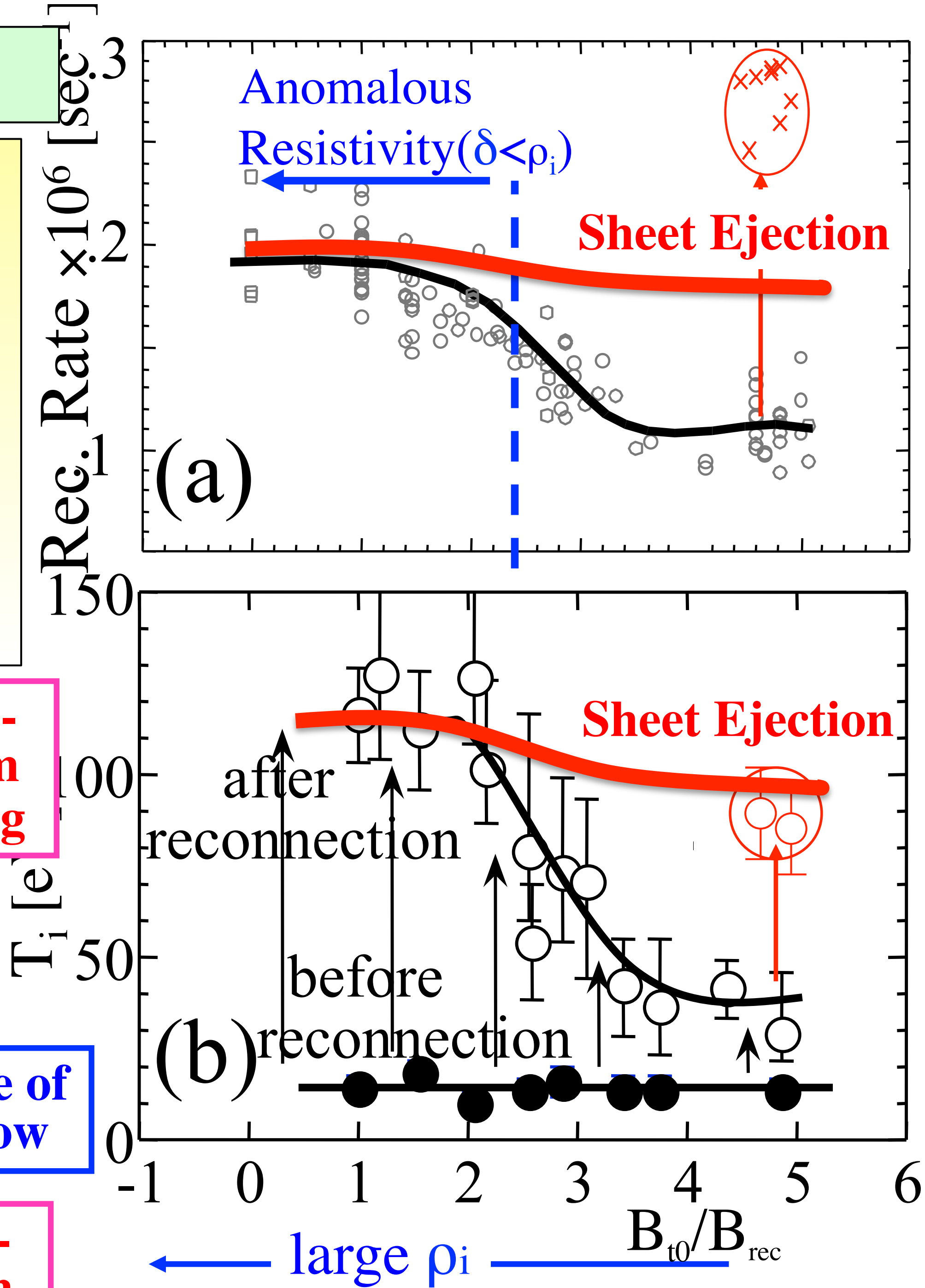


**Rec. heating depends on $B_t$?**

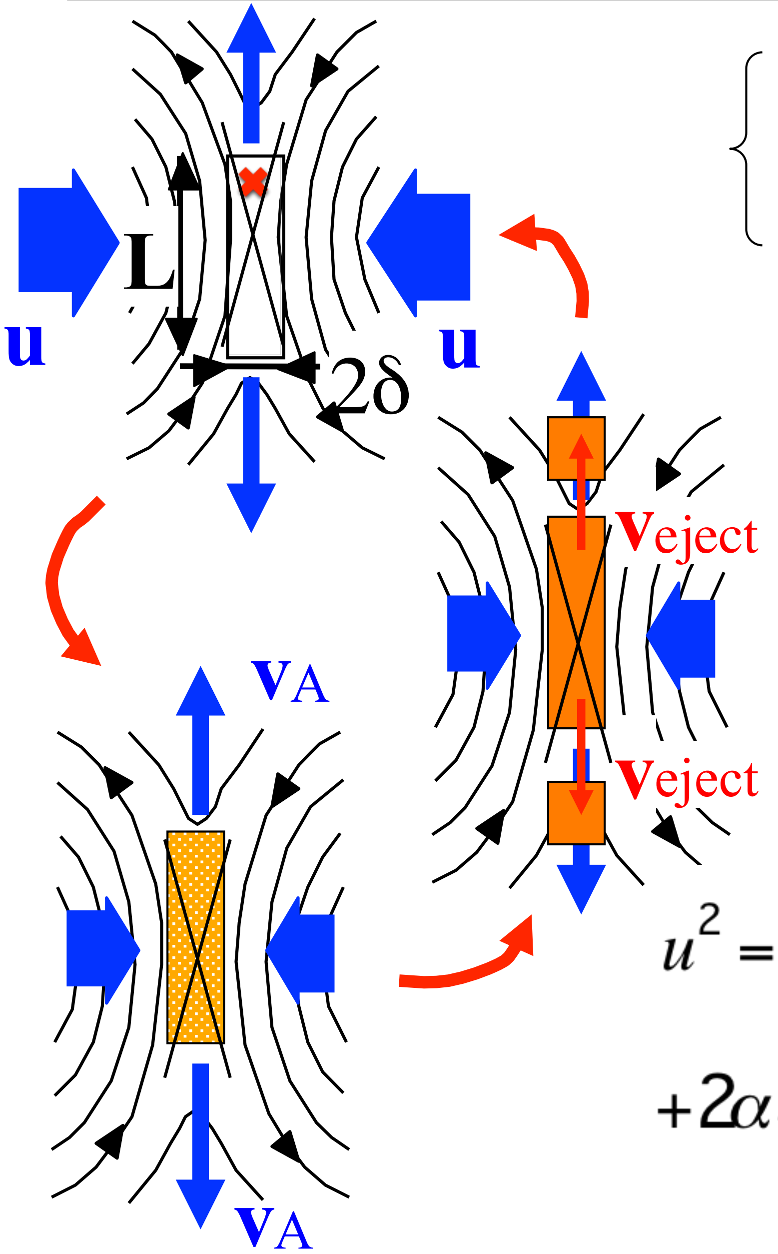
**1) Rec. rate and $\Delta T_i$ decreases with $B_t$ before plasmoid ejection.**
**2) Rec. rate and $\Delta T_i$ are maintained under high $B_t$ after plasmoid ejection.**




**Reconnection rate as a function of Bx**

# The combination of mass pileup and ejection increases effective mass ejection and rec. speed.




$$\begin{cases} uL = 2\delta V_A + \underline{L\delta(d\alpha/dt)} + \underline{2\delta\alpha V_{eject}} \\ u = \dfrac{\eta}{\mu_0 \delta'} \end{cases}$$

Pile-up Ejection

where pileup factor $\alpha = \dfrac{n_{sheet}}{n_0}$

$$u = \sqrt{\frac{\eta}{\mu_0}\left(\frac{2V_A}{L} + \underline{d\alpha/dt} + \underline{\frac{2\alpha V_{eject}}{L}}\right)}$$

Pile-up Ejection

For simplicity,

$$\alpha = n/n_0 = n_1(1 + \sin\omega t)$$

$$v_{eject} = v_1\{1 + \sin(\omega t + \theta)\}$$

$$u^2 = \frac{\eta}{\mu_0 L}[2V_A + \underline{2\alpha_1 V_1} + 2L\alpha_1\omega\cos\omega t + 2V_1\sin\omega t$$

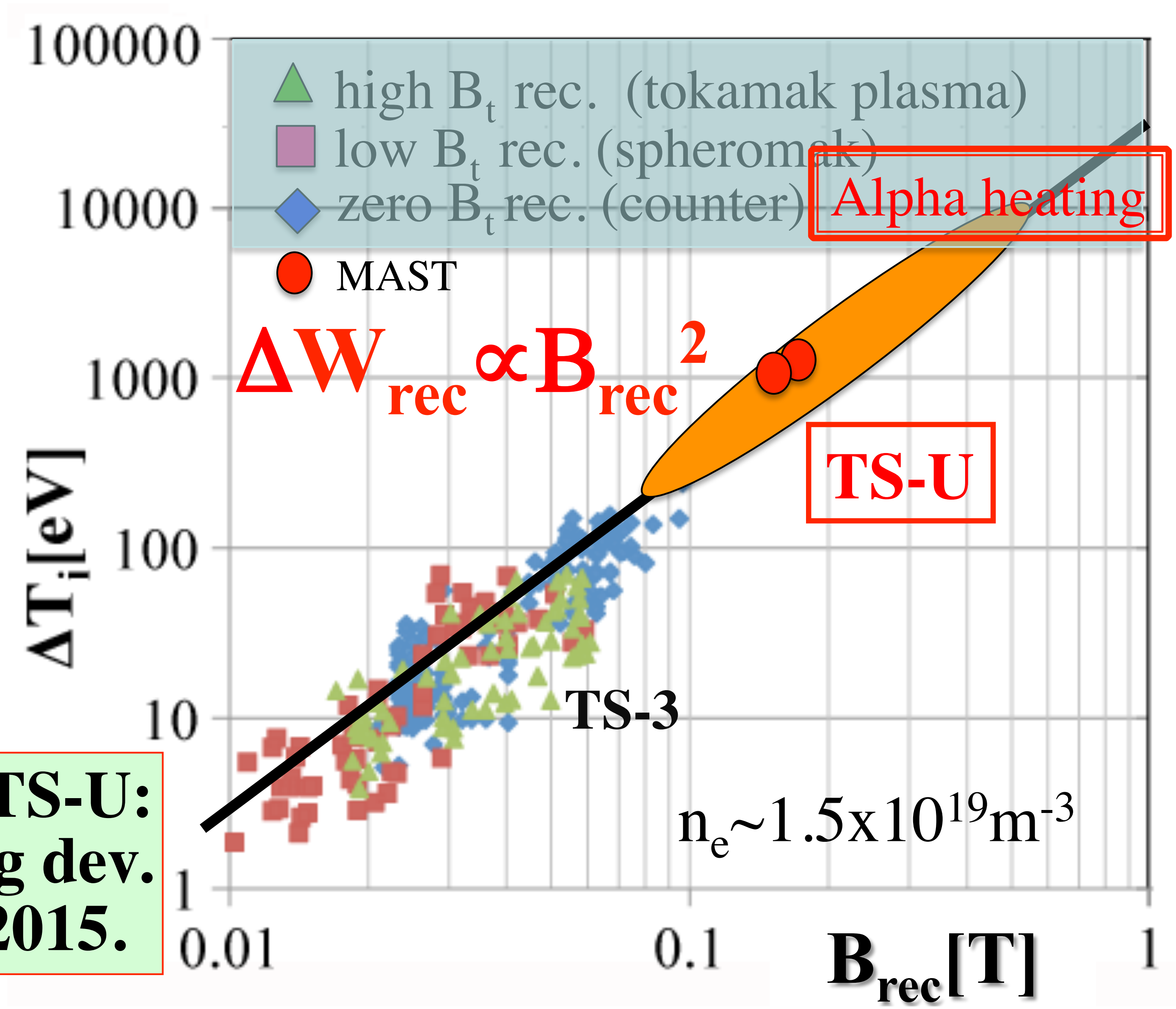
$$+2\alpha_1\sin(\omega t + \theta) + \underline{2\alpha_1 V_1 \sin\omega t \cdot \sin(\omega t + \theta)}$$

Ejection

# The $B_{rec}^2$-scaling of reconnection heating indicates a direct access to alpha-heating without NBI, leading us to a new high-$B_{rec}$ heating exp.: TS-U.

$\Delta W_{th} \sim \Delta W_{ion}$
$\propto \Delta(nT_i)$
$\propto \Delta T_i$
(n~normalized)
$\propto B_{rec}^2 \propto B_p^2$

$V_{outflow} \sim$
$V_{pA} \propto B_p / n^{1/2}$



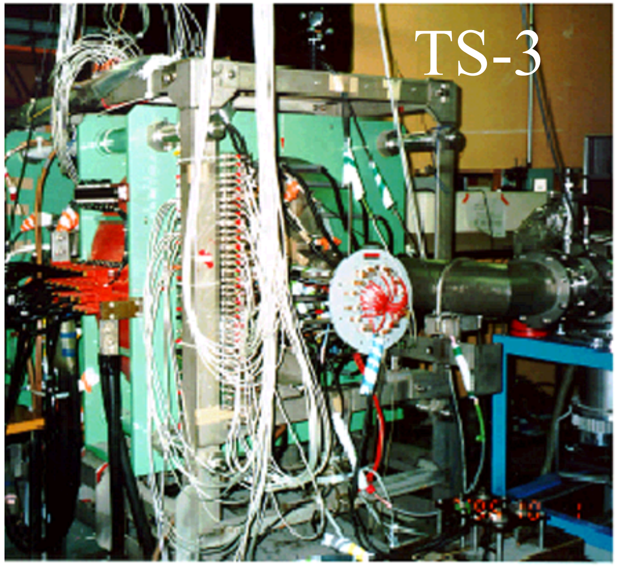

**Construction of TS-U: high-$B_{rec}$ merging dev. started in Jun, 2015.**

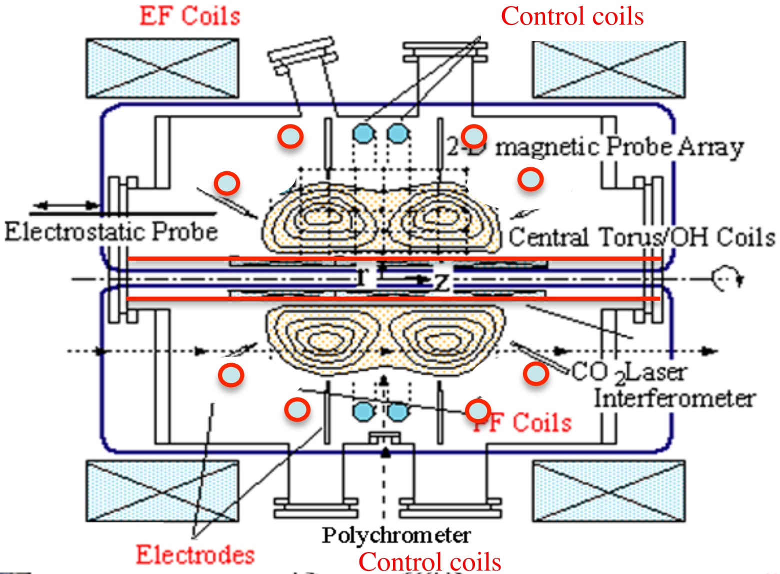
**Upgrades of TS merging exps. were accepted by JSPS:**

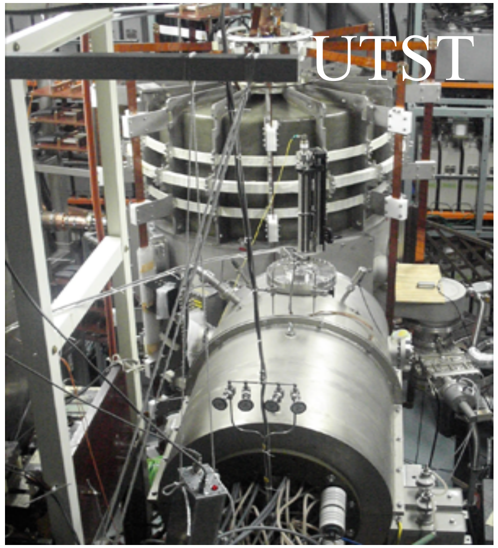
**TS-3 (R=0.2m) $B_{rec}$ < 1kG ⟹ $B_{rec}$ > 5kG**

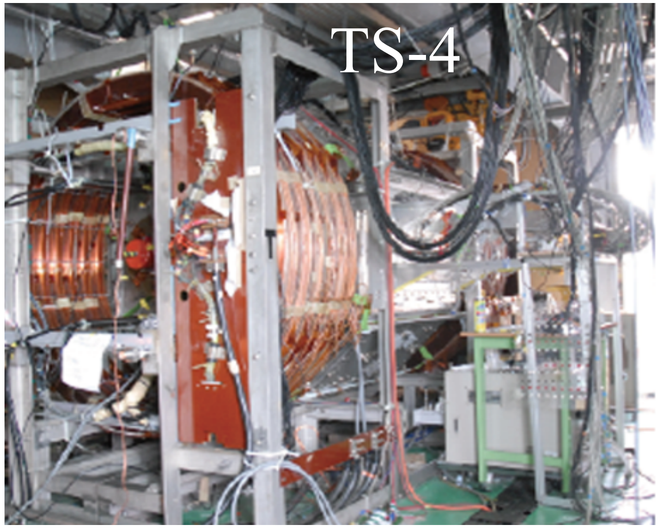
**TS-4 (R=0.5m) $B_{rec}$ < 0.5kG ⟹ $B_{rec}$ > 3kG**

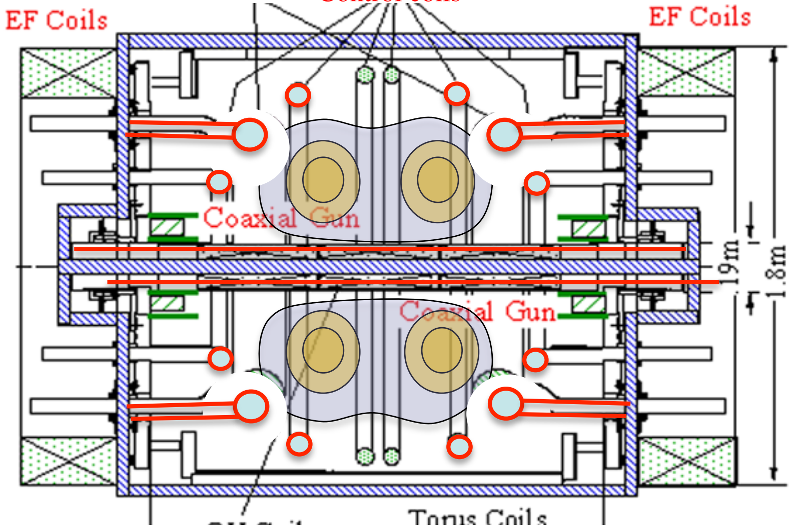
**UTST (R=0.45m) $B_{rec}$ < 0.2kG ⟹ $B_{rec}$ > 1.5kG**

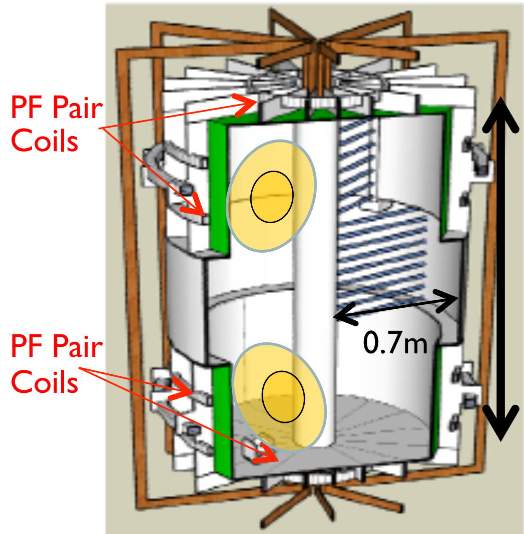


# Summary and Conclusions

1) Reconnection outflow heats ions in two shock-like downstream regions.
2) Electron heating occurs inside current sheet and $T_e$ peaks at X-point.
3) Triple peak $T_i$ and $T_e$ profiles during reconnection
4) Ion heating power >> Electron heating power
5) Ion heating energy and $T_i$ increase with $B_{rec}^2$.

➡ The rec. heating exp. in MAST extended the $B_{rec}^2$-scaling to $T_i$~1.2keV ($T_e$~0.8keV) for the $B_{rec}$~0.15T.

➡ Direct ion heating by rec. is a promising method for heating ions > 10keV: direct access to alpha heating.

➡ The new JSPS project of high $B_{rec}$ ST merging started in U. Tokyo for fusion plasma heating / rec. heating physics.