Scaling Study of Reconnection Heating in Torus Plasma Merging Experiments

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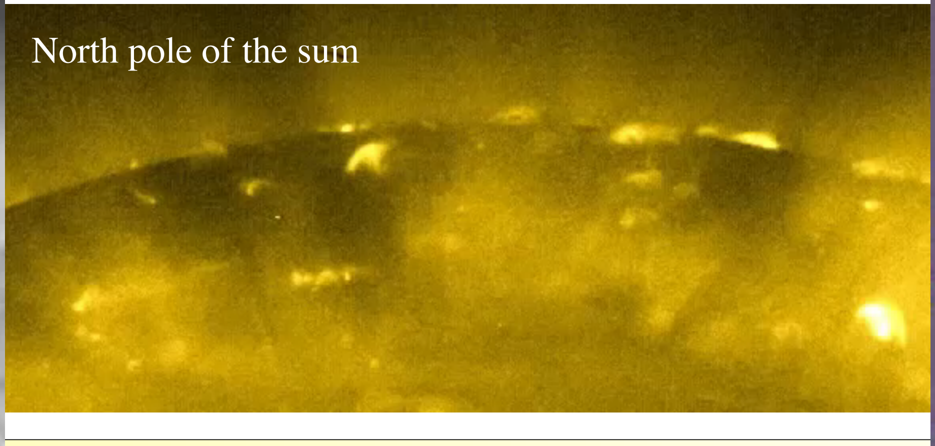
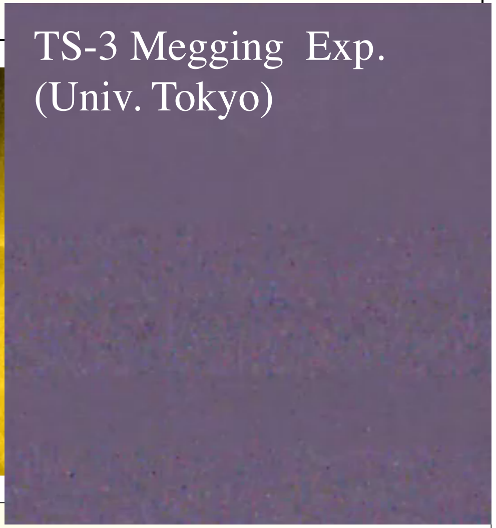
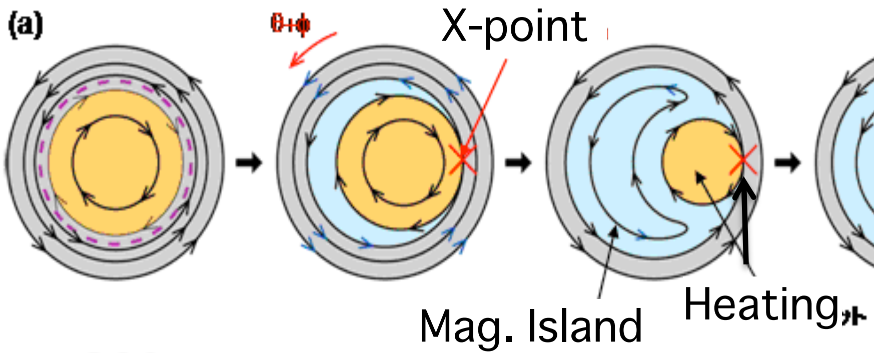
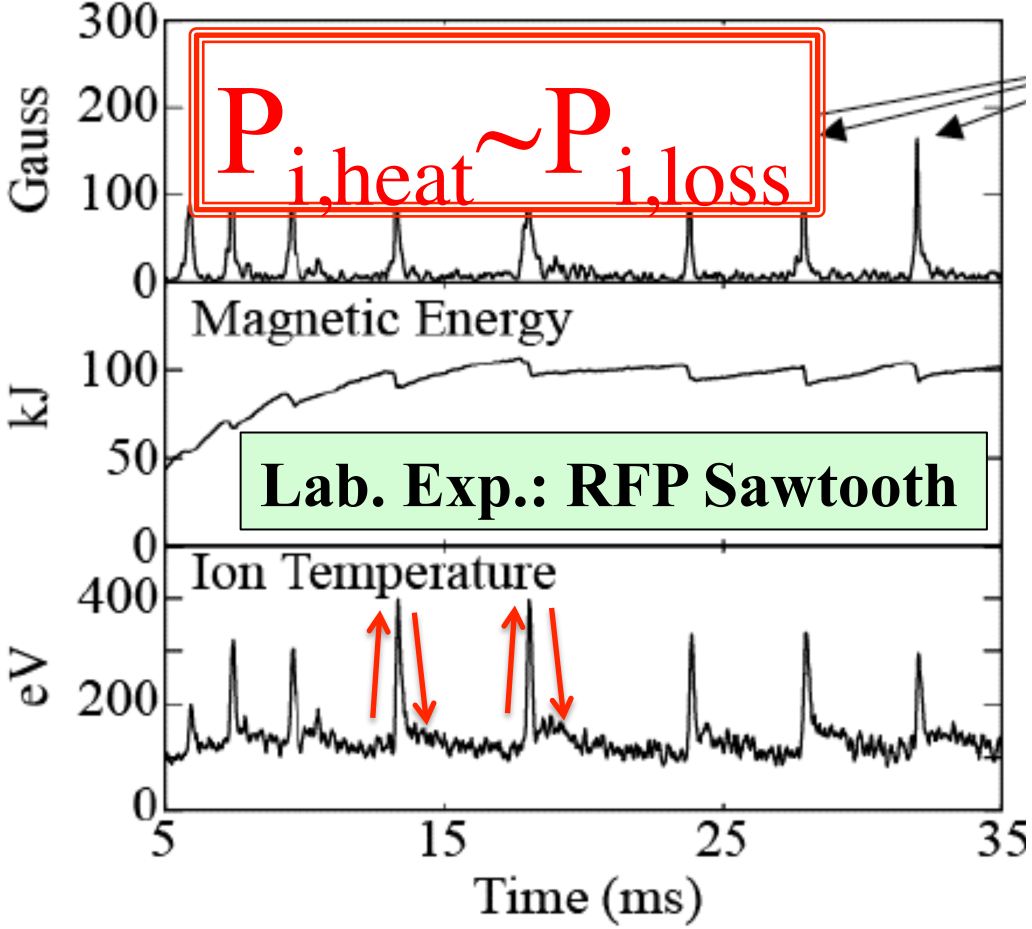




Univ. Tokyo, H. Tanabe, Q. CAO , G. Guo, S. Himeno, K. Nishida, T. Kaneda, H. Hatano, M. Akimitsu, A. Sawada, K. Narihara, **QST: S. Inoue**, Kyusyu Univ.: T. Yamada
Tokamak Energy: **M. Gryaznevich**, A. Sykes, **CCFE**: B. Clowley, N. Conway, R. Scannel, NCKU: **C. Z. Cheng**
NIFS:**R. Horiuchi**, S. Usami, NAOJ: H. Hara, T. Shimizu

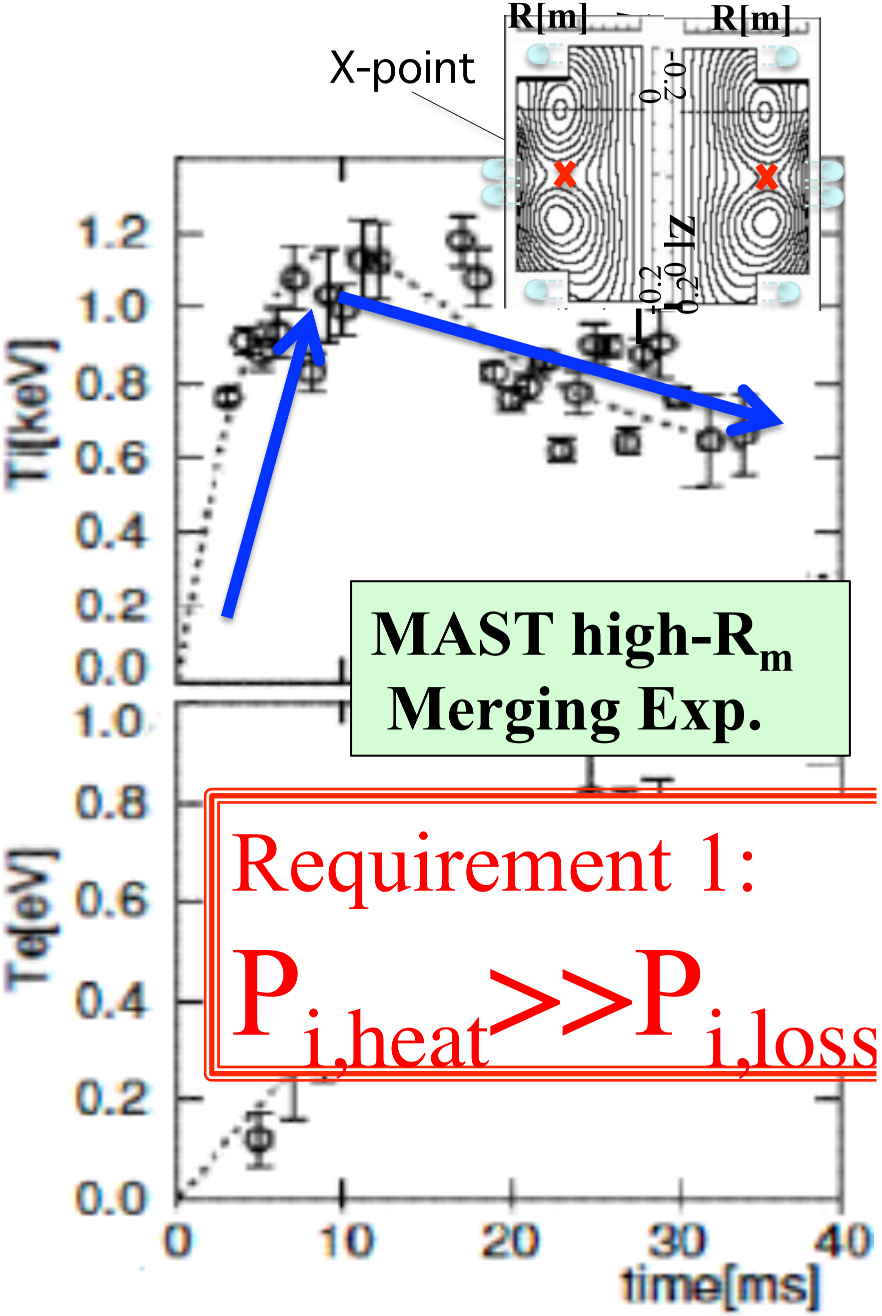
Requirements 1: $P_{\text{ion heat}} >> P_{\text{ion loss}}$, $P_{\text{ion-electron}}$





$P_{i,heat} \sim P_{i,loss}$

Lab. Exp.: RFP Sawtooth



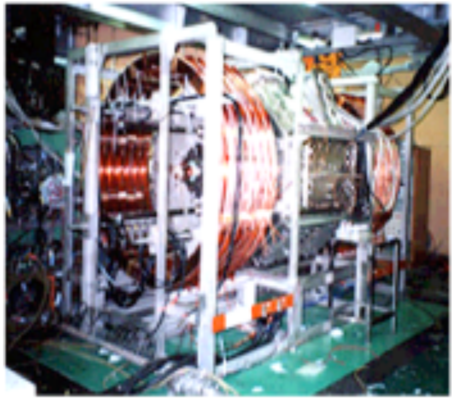
MAST high-R_m Merging Exp.

Requirement 1:

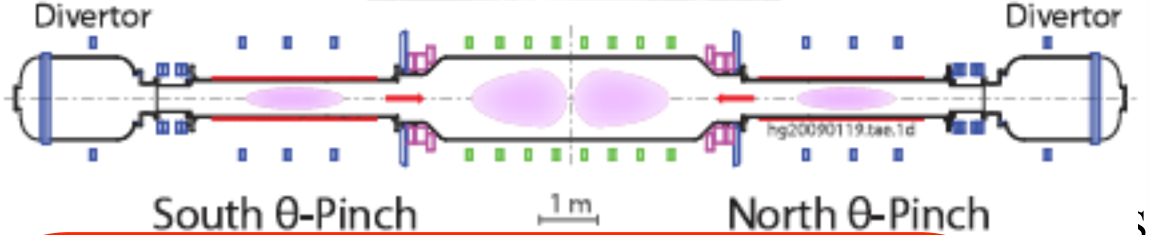
$P_{i,heat} >> P_{i,loss}$

A limited number of plasmas isolated from coil, satisfy $P_{heat} >> P_{loss}$.

1985~ TS-3,4 (U.Tokyo) First Rec. exp.



2010~C-2 (Tri Alpha)

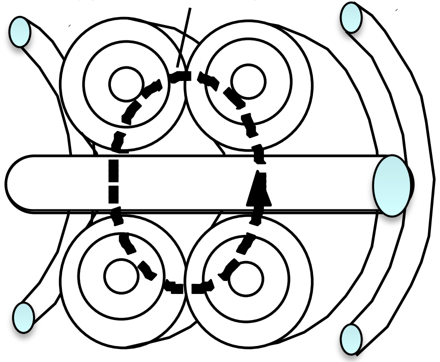


"Closed Current , Closed Flux"

High R_m

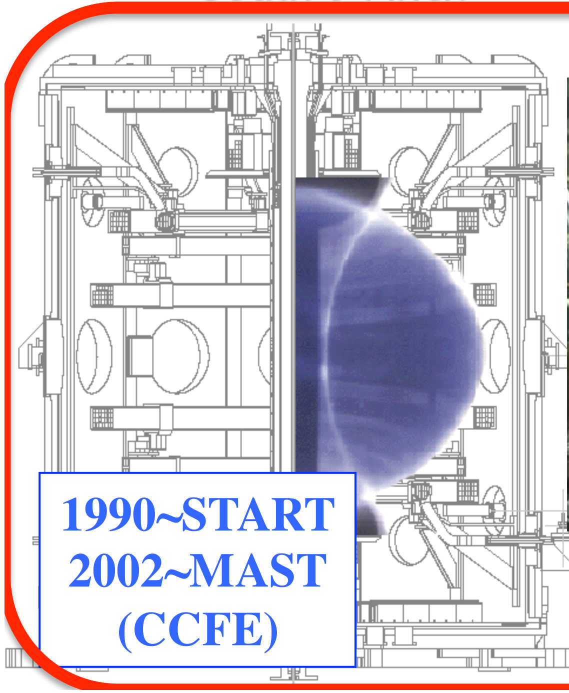
Closed Flux

Sheet Current

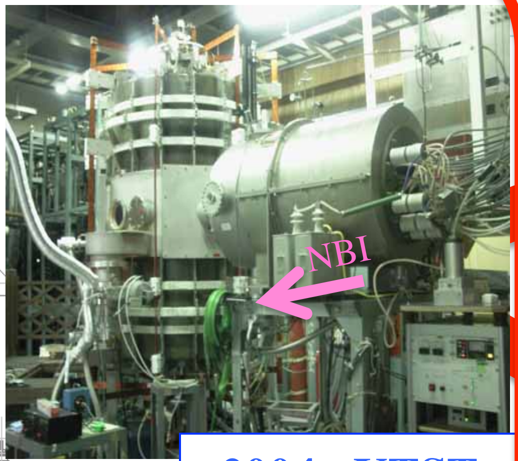


U. Tokyo TS-3,TS-4('86~)

START, MAST ('90~), NASA ('01~), Colorad FRC ('07), Try-Alpha C-2 ('10), Texas A&M('09), Soul U. VEST('11)

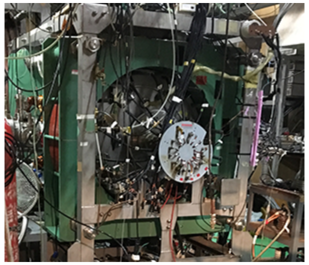


1990~START 2002~MAST (CCFE)

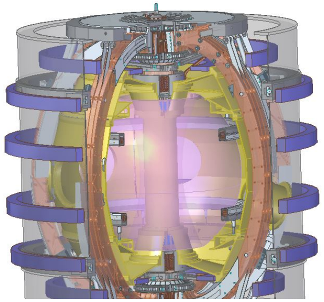


2004~ UTST (U.Tokyo)

TS-U Exp (U.Tokyo) 2016~



ST-40 Exp. (Tokamak Energy) 2016~

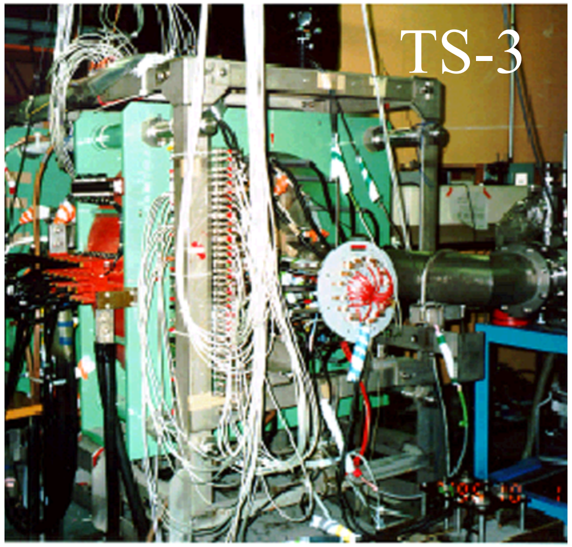


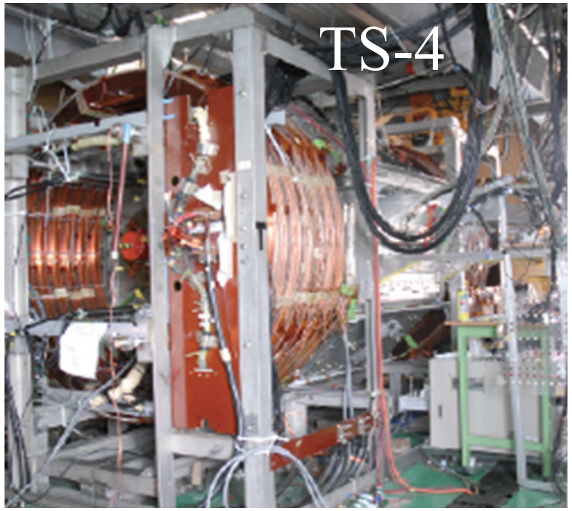
Upgrades of TS merging exps. were accepted by JSPS:

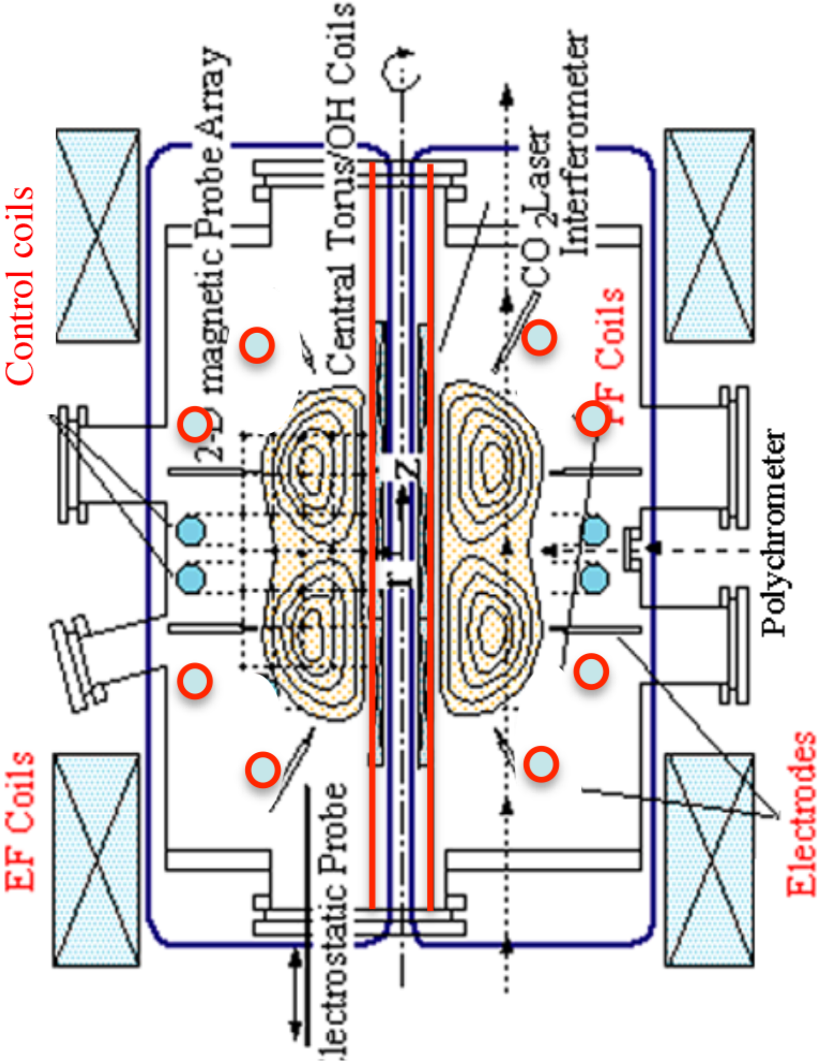
TS-3 (R=0.2m) $B_{rec} < 1$kG → **TS-6 $B_{rec} > 5$kG**

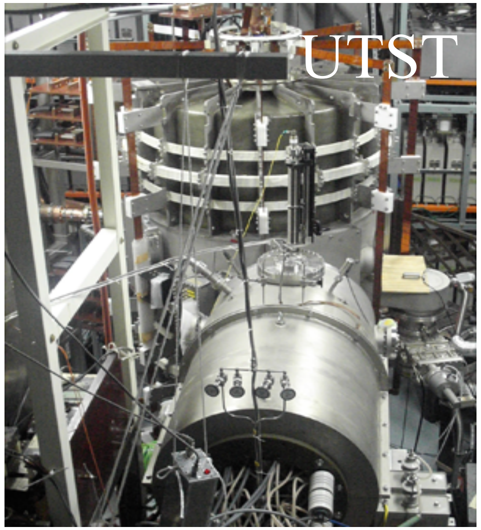
TS-4 (R=0.5m) $B_{rec} < 0.5$kG → **TS-4U $B_{rec} > 3$kG**

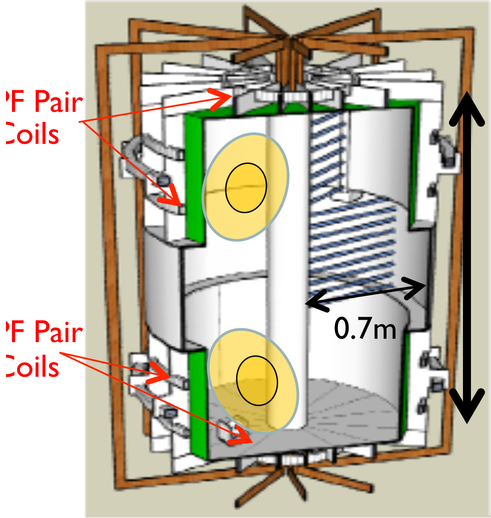
UTST (R=0.45m) $B_{rec} < 0.2$kG → **UTST-U $B_{rec} > 1.5$kG**











How high is the rec. heating? useful for fusion? How does it depend on B_{rec} and B_t?

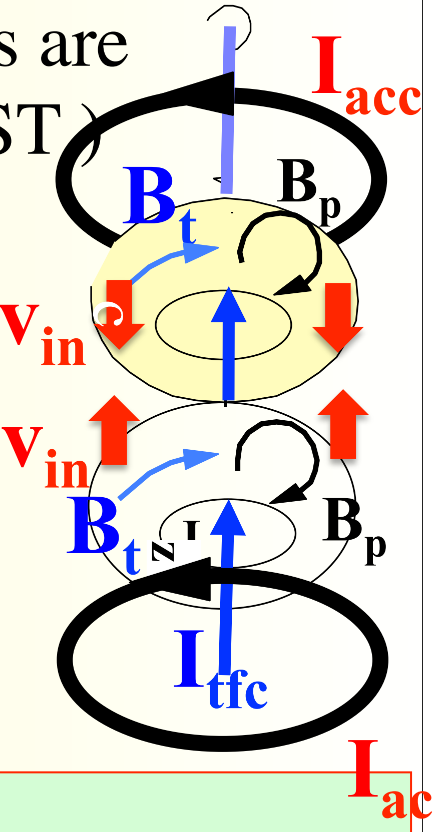
Key: Scaling Low: Ion heating energy $\propto B_{rec}^2$

Requirements:

(1) $P_{\text{ion heat}} >> P_{\text{ion loss}}, P_{\text{ion-electron}}$: merging plasmas are fully isolated from coils/wall (TS-3, UTST, MAST)

(2) δ is compressed as thin as ρ_i.

About 50% of reconnecting magnetic energy is converted to ion thermal energy.



1. **Guide Field B_t Scan**
2. **Inflow V_{in} Scan**
3. **Comparison with PIC simulation**

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

MAST: Ultra-High-R_m

$P_{i,heat} \gg P_{i,loss}$,

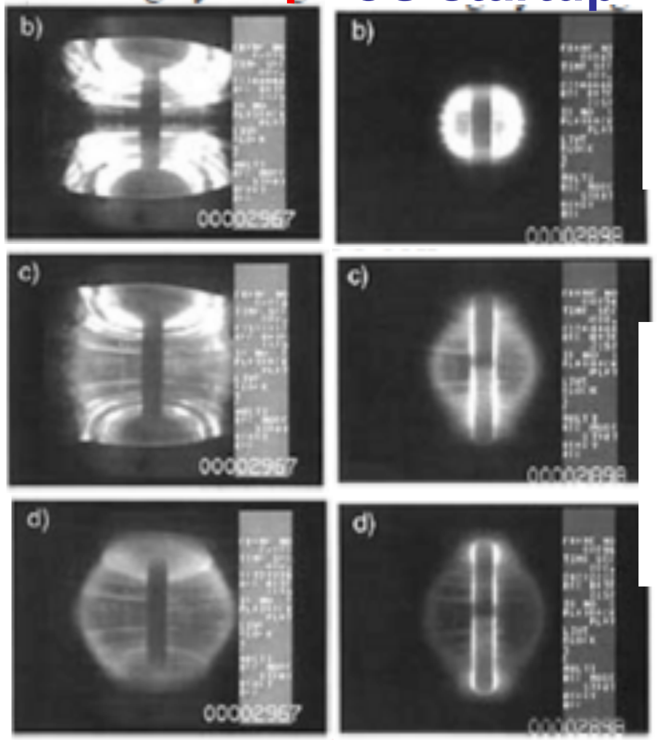
$P_{e,heat} \gg P_{e,loss}$

MAST Reconnection Exp.

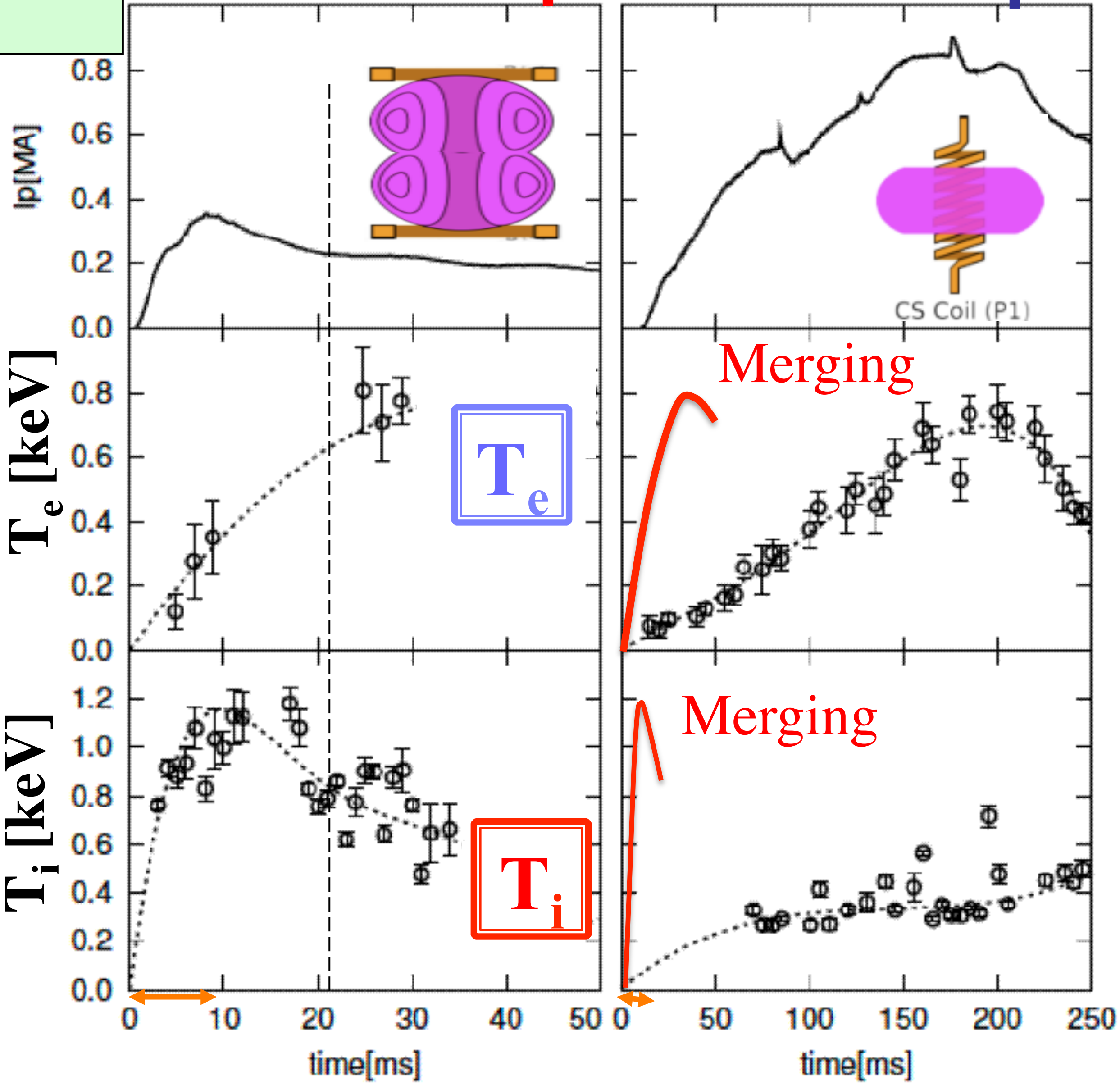
The ST merging/reconnection heats ions to 1.2keV within 10 msec.

Significant Ion Heating in MAST Rec.

Rec. startup **CS startup**



Rec. startup **CS startup**



2D Steady-State model predicts the outflow ~ V_{Alf}
-The Sweet-Parker 2-D Model for Magnetic Reconnection-

Assumptions: ・2D ・Steady-state

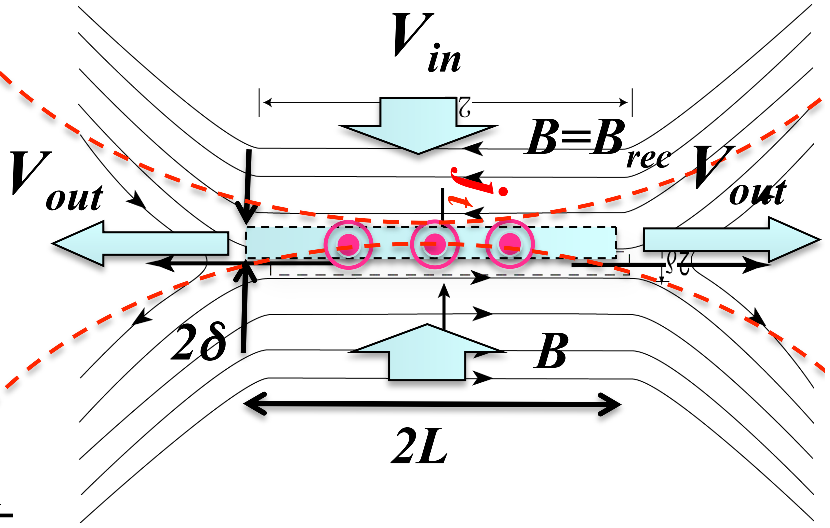
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$$

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

S=Lundquist number

$$\Rightarrow V_{in} B_{rec} = \frac{\eta_{Spitz}}{\mu_0} \frac{B_{rec}}{\delta} \Rightarrow \frac{V_{in}}{V_A} = \frac{1}{\sqrt{S}}$$

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



B is resistively annihilated in the sheet

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

Pressure balance: $\frac{1}{2} m_i n_i V_{out}^2 \approx \frac{B_{rec}^2}{2\mu_0} \Rightarrow \boxed{V_{out} \approx V_A = \frac{B_{rec}}{(\mu_0 m_i n_i)^{1/2}}}$

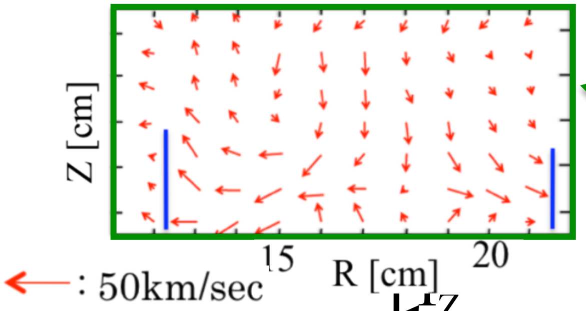
TS-3: Mechanism for rec. heating : $P_{i,heat}>>P_{i,loss}$

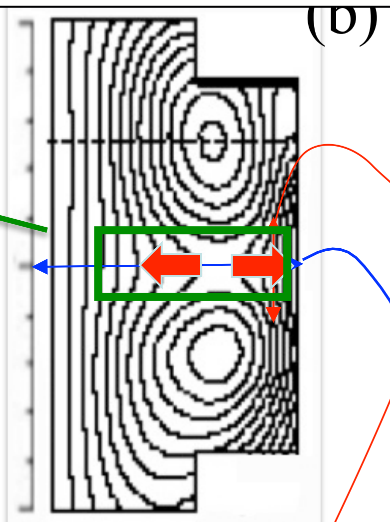
We confirmed

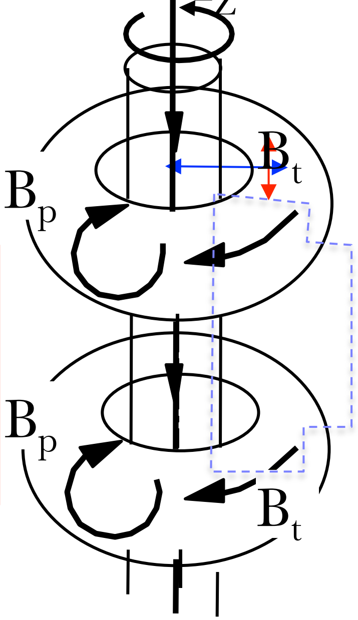
1) ion acceleration up to 70% of V_{PAlf}

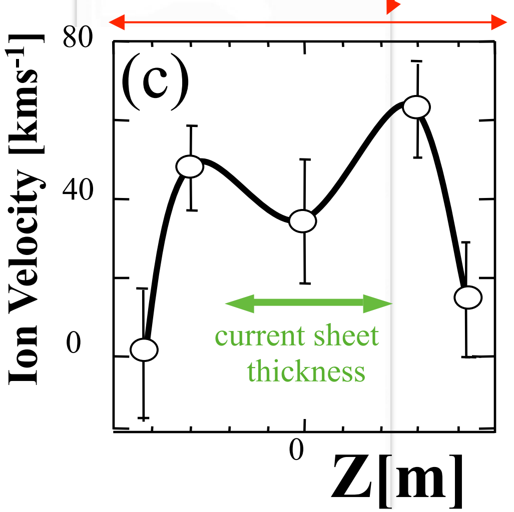
2) downstream heating of ions

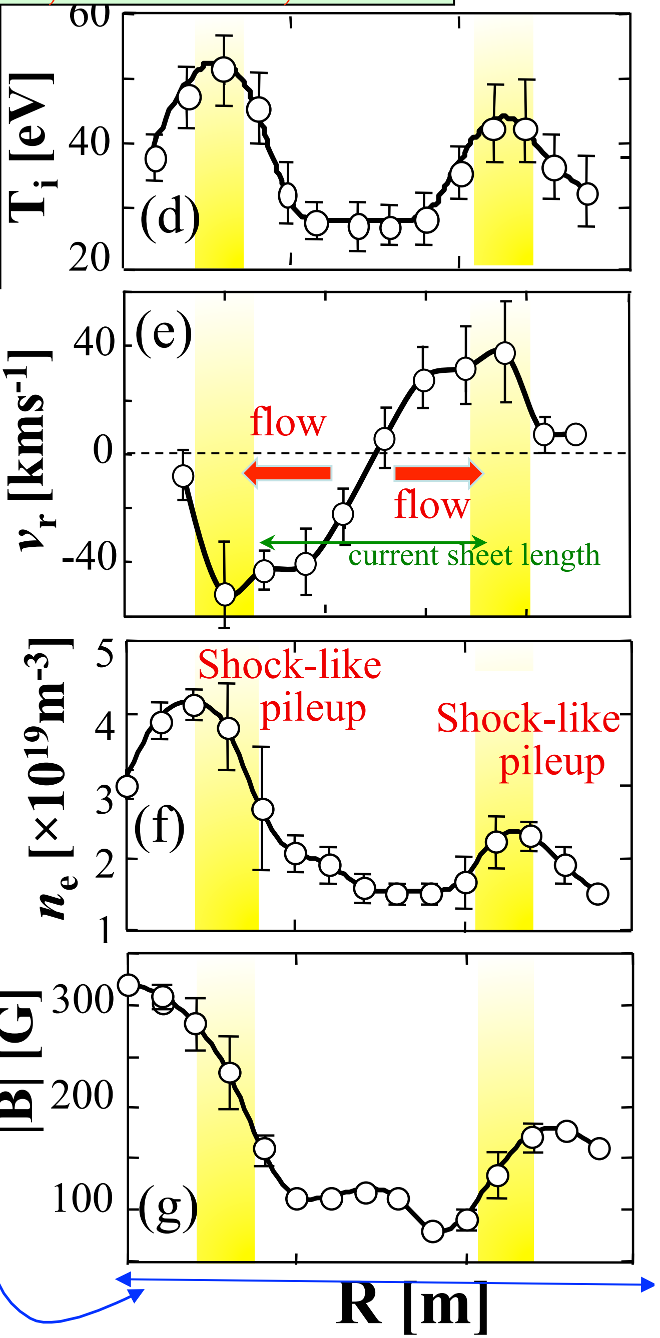
$n_1/n_2 \sim B_1/B_2 \sim v_1/v_2$,











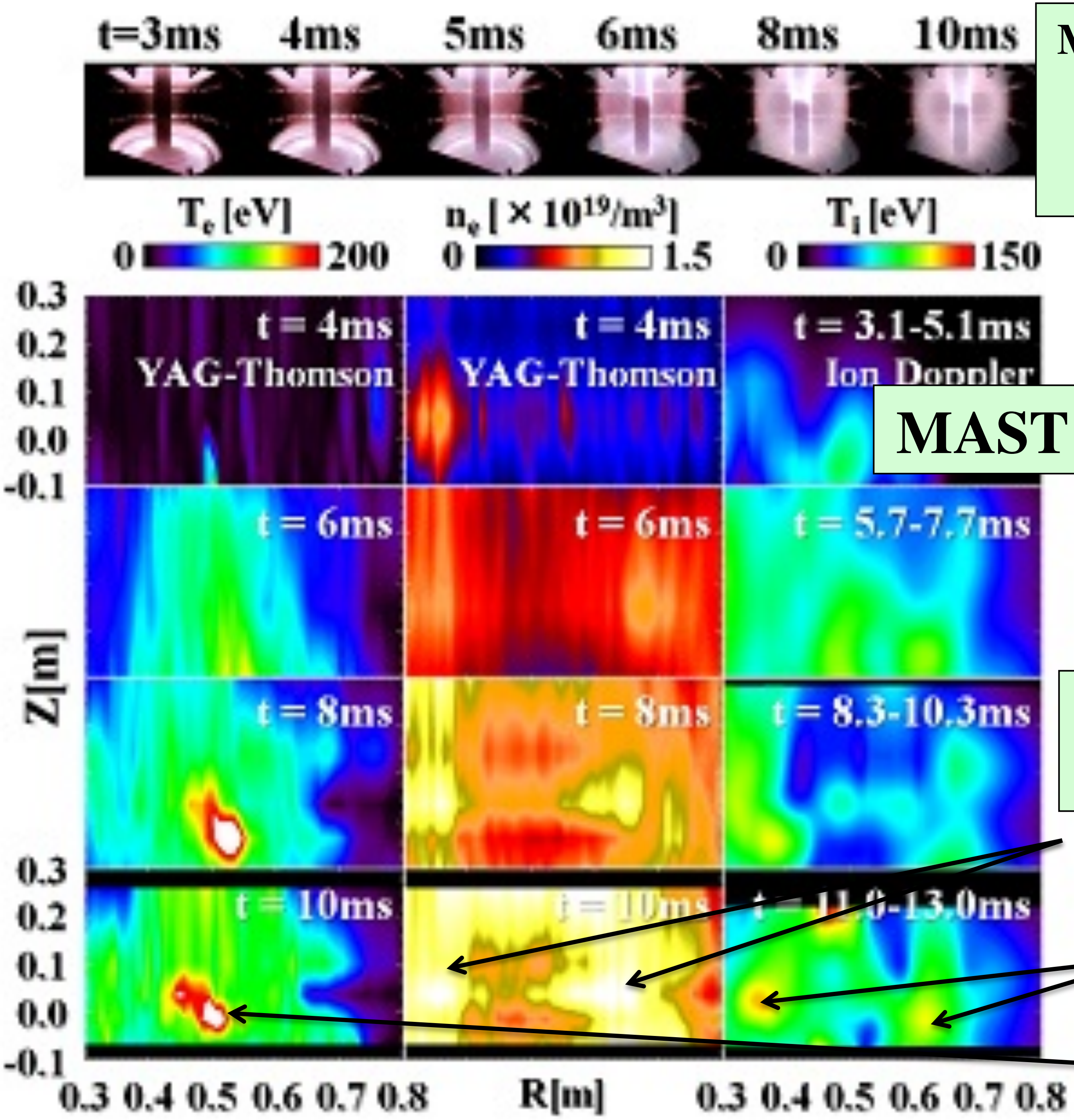
High Guide-Field Rec.

Y. Ono PRL2011

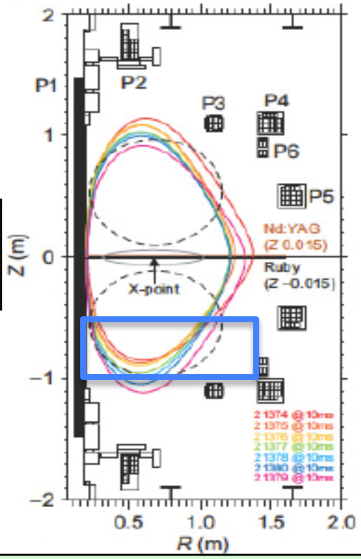
MAST: Ultra-High-R_m :

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

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



MAST

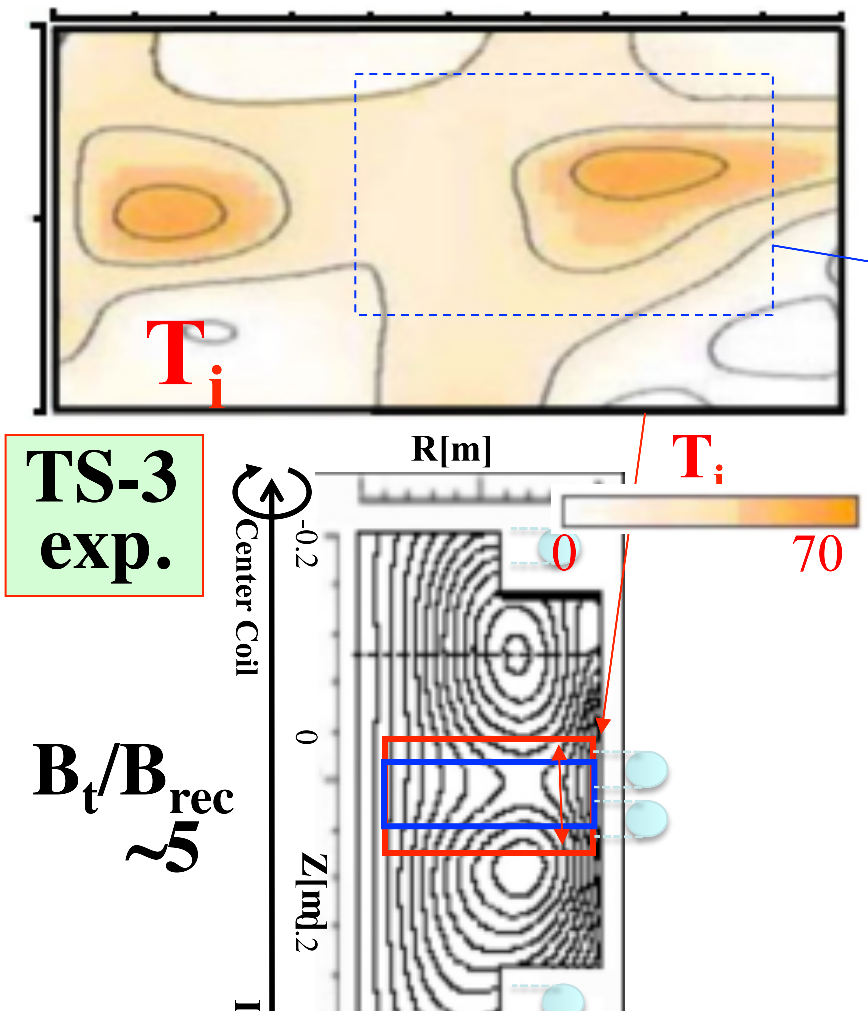


2D profiles of
T_e, n_e, T_i

Shock-like n_e profile

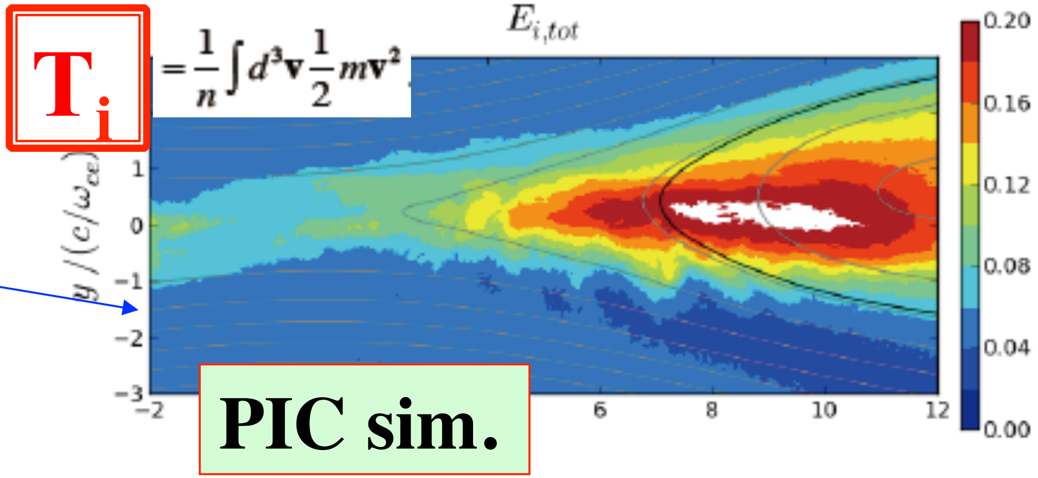
Ion heating
in downstream

Electron heating
at X-point



TS-3 exp.

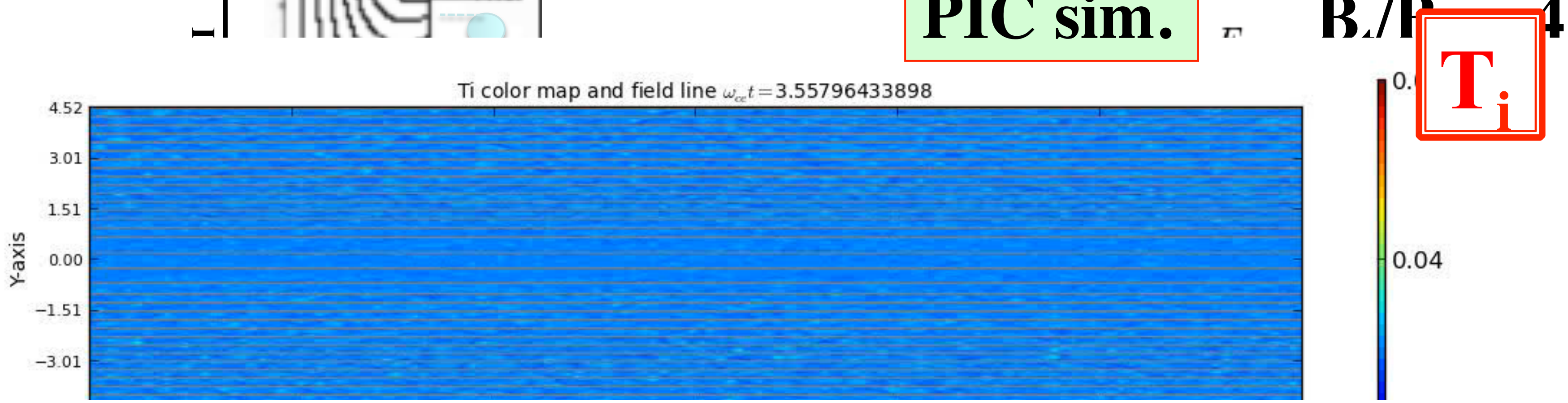
B_t/B_{rec} ~5



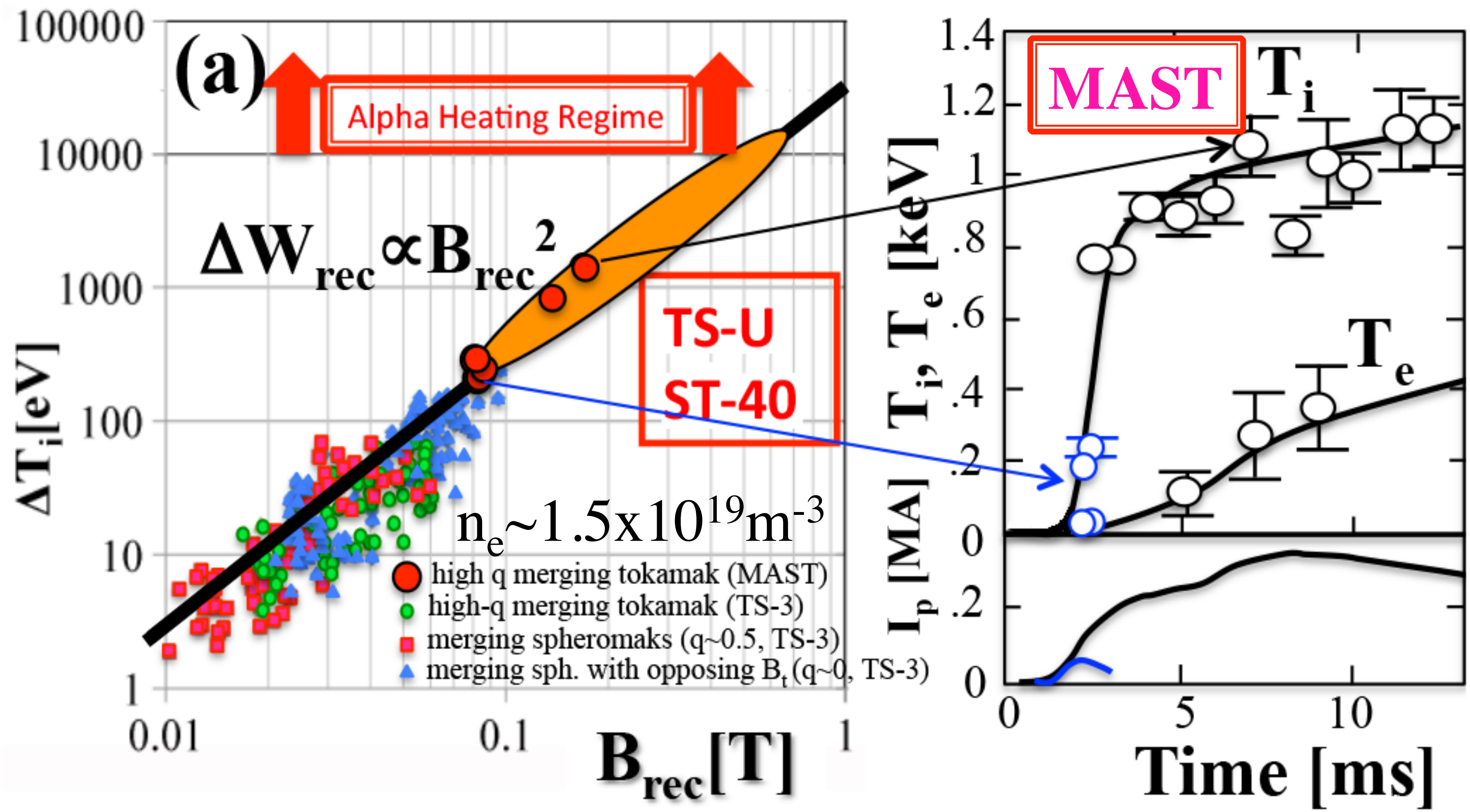
PIC sim.

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

PIC sim.



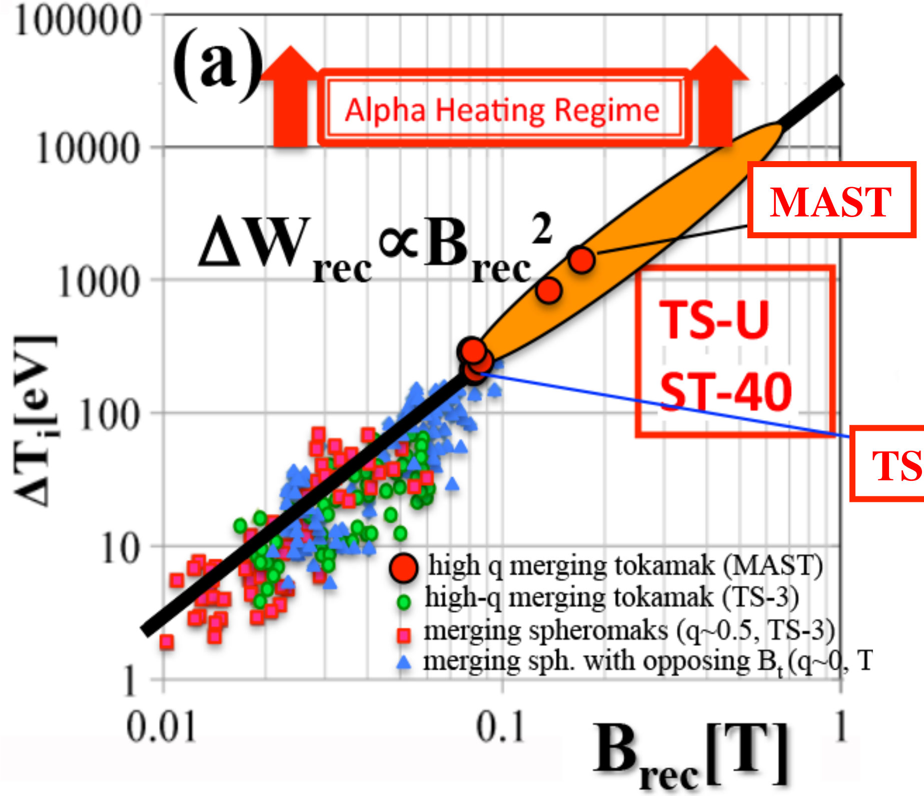
B_{rec}^2-scaling for ion outflow heating



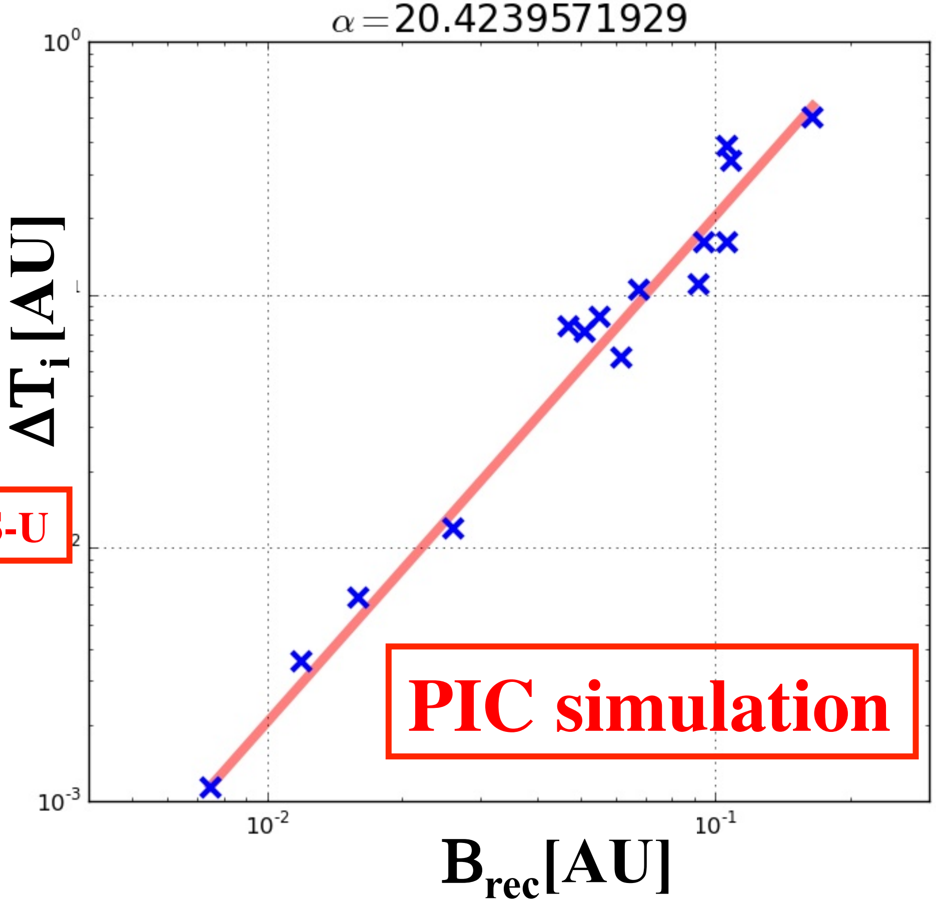
$$\Delta W_{th} \sim \Delta w_{ion} \propto \Delta(nT_i) \propto \Delta T_i \ \text{(n~normalized)} \propto B_{rec}^2 \propto B_p^2$$

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

The PIC simulation confirmed the $B_{rec}{}^2$-scaling of reconnection heating.



ST/Spheromak Merging Exp.



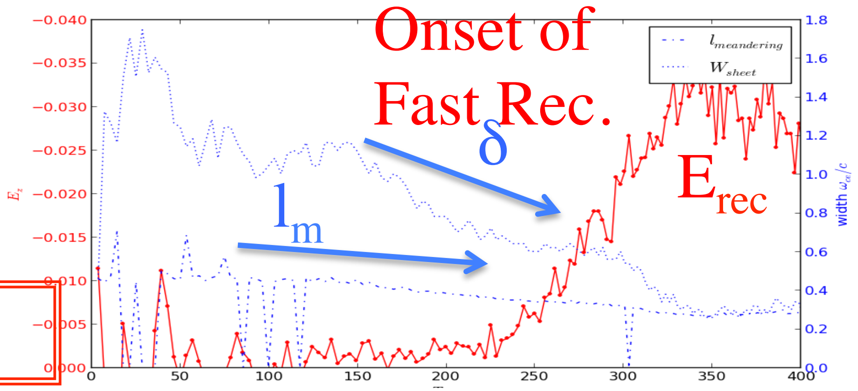
PIC Simulation by Inoue/Horiuchi/Cheng

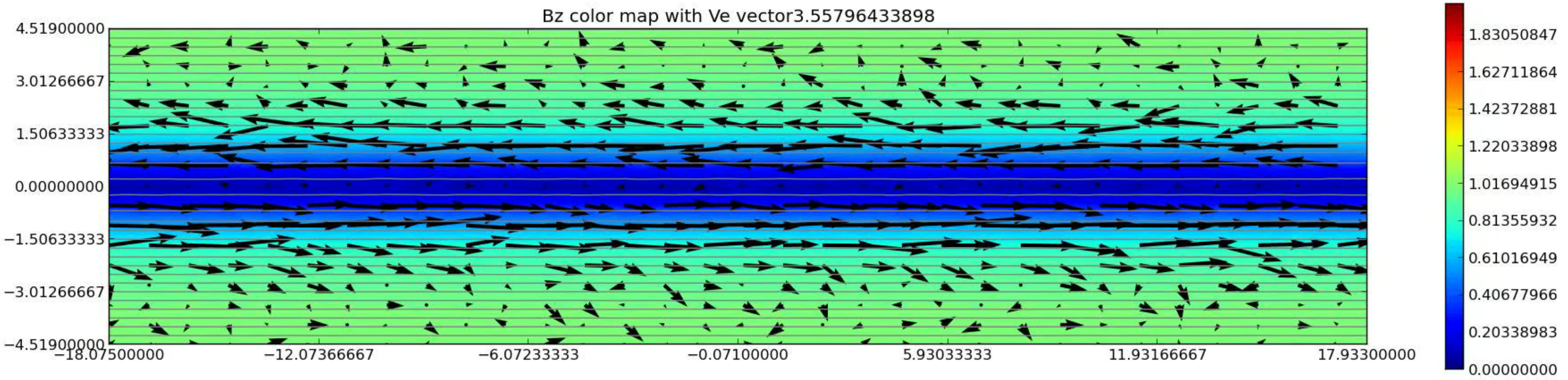
$$\Delta w_{ion} \propto \Delta(nT_i) \propto V_{PAlf}{}^2 \propto B_{rec}{}^2 \propto B_p{}^2$$

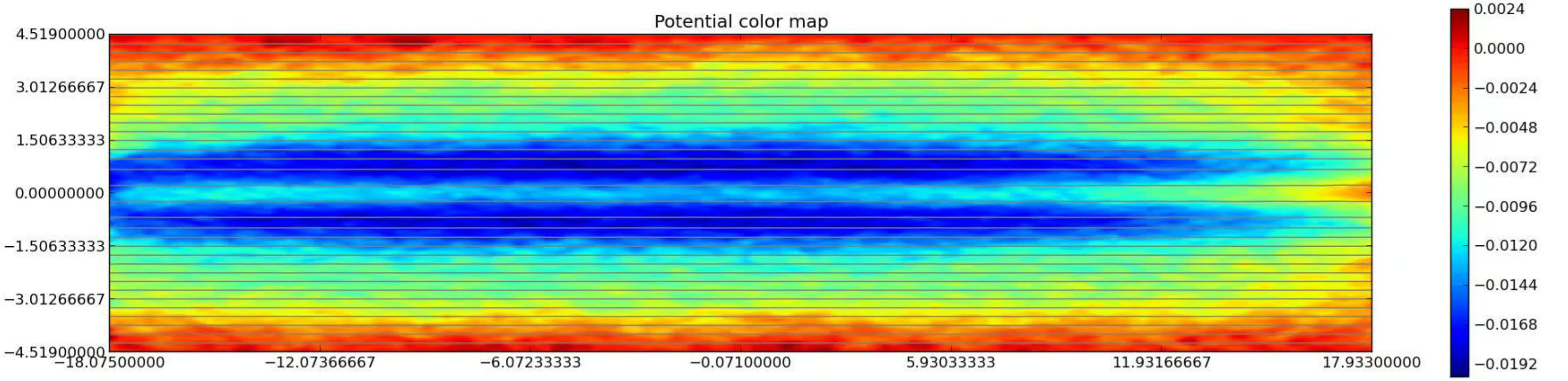
Requirement 2: Onset of fast rec. when δ is compressed as thin as ρ_i.

The onset of fast rec. at t=250μsec forms the negative potential well.

PIC (Inoue, Horiuchi, Cheng) $B_t \approx B_{rec}$

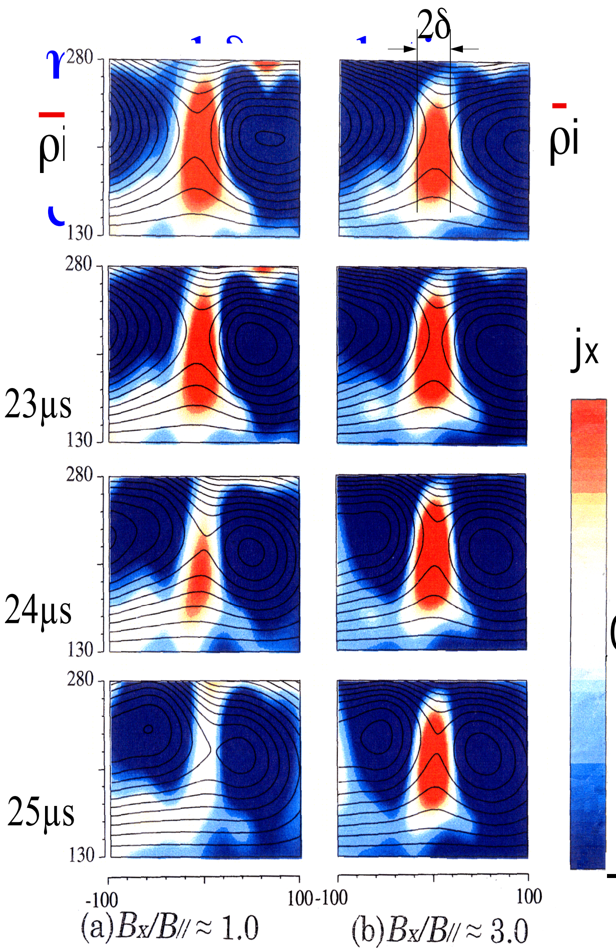


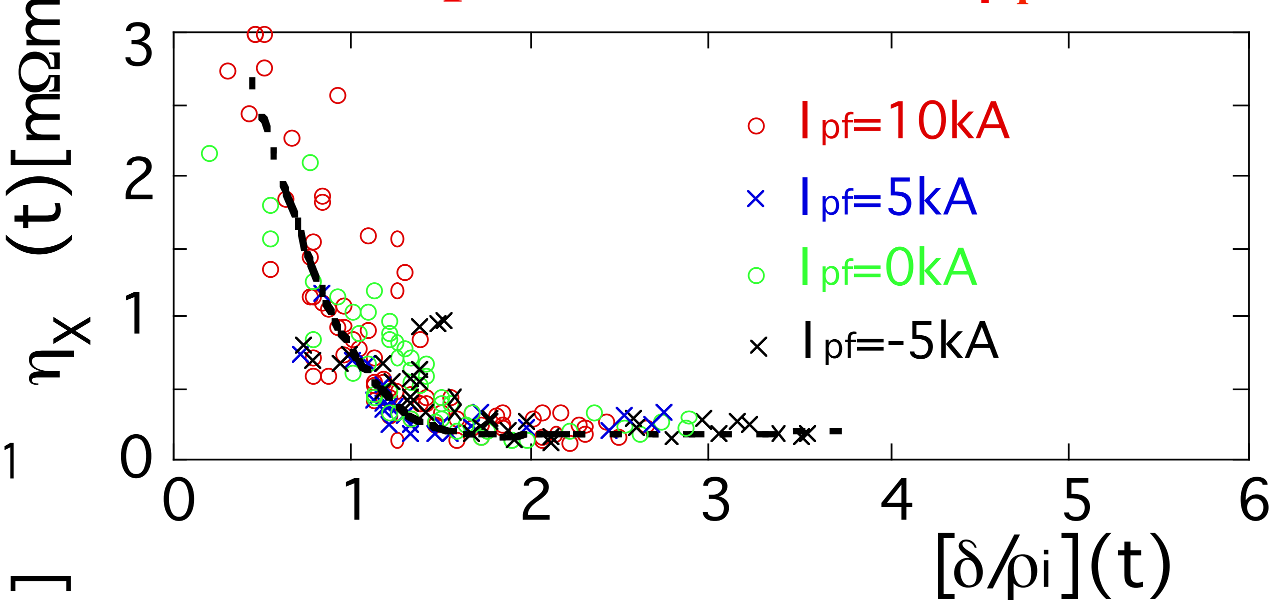


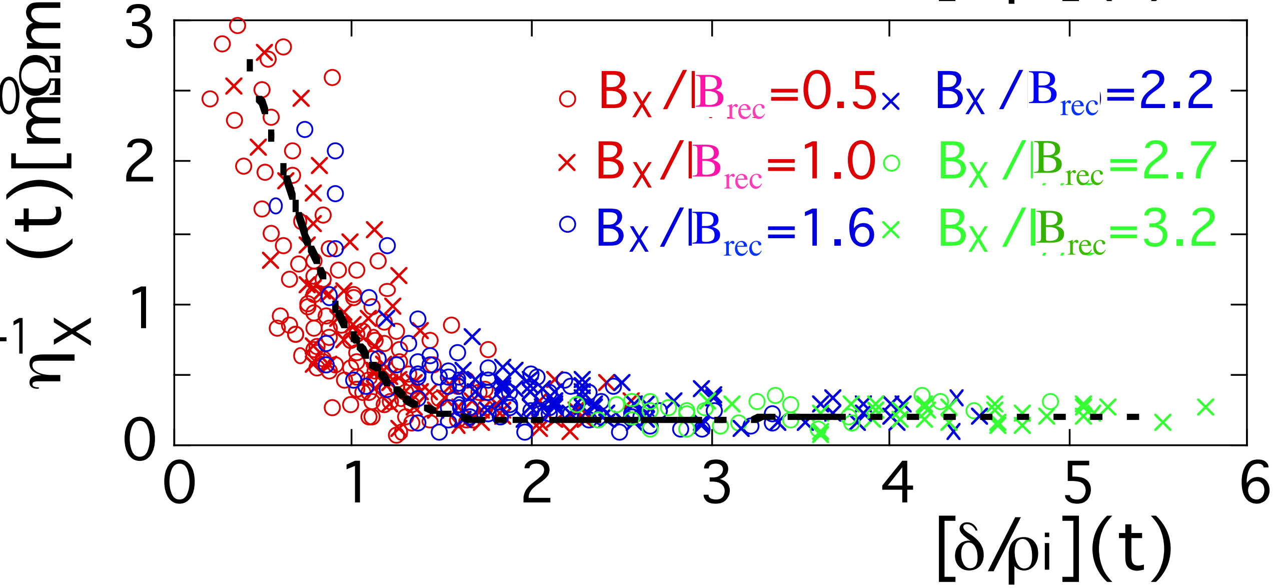


Requirement 2: δ is compressed as thin as ρ_i.

Effective resistivity η_x increases markedly when sheet width δ is compressed as thin as ρ_i.

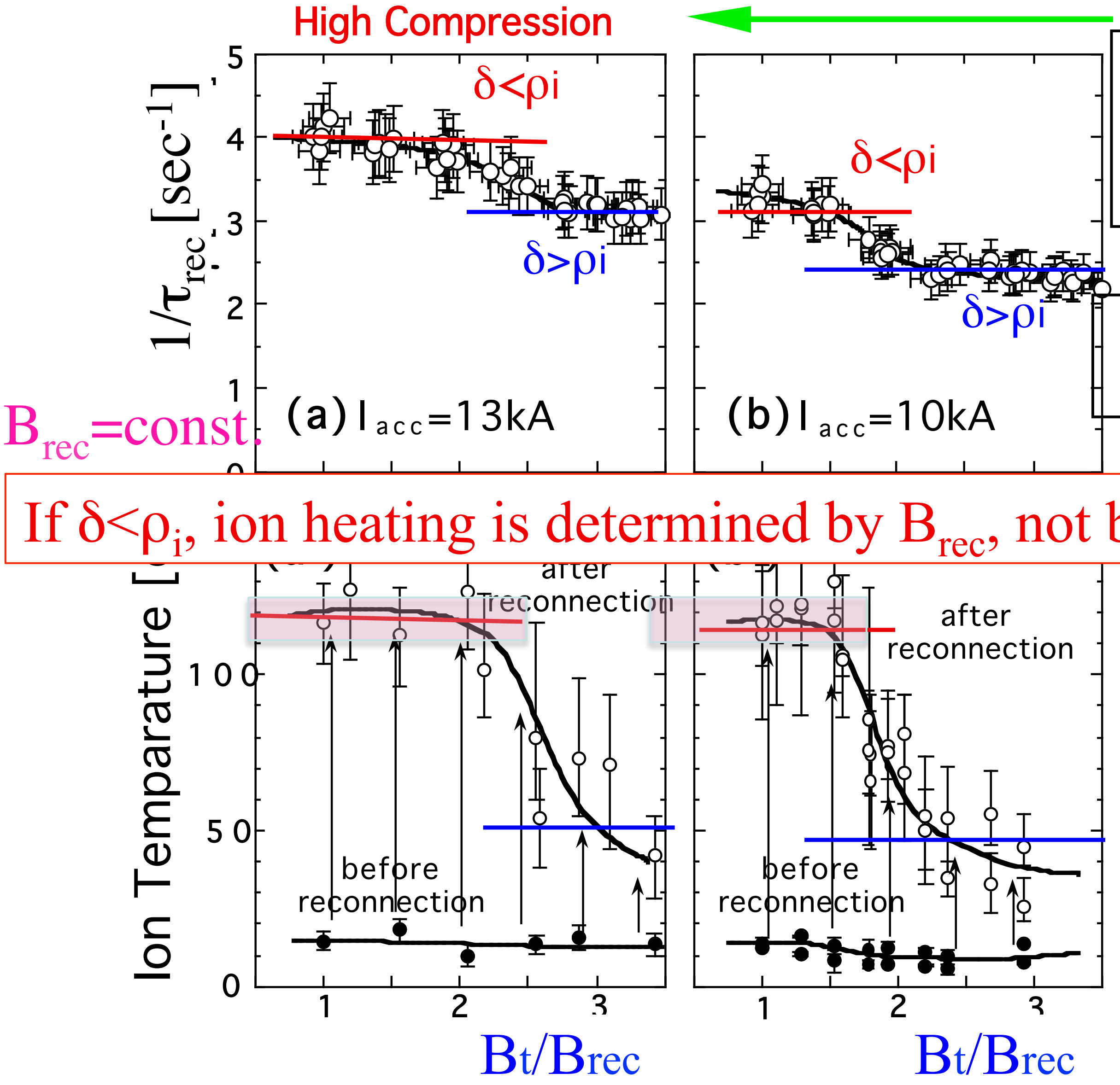






Requirement 2: δ is compressed as thin as ρ_i.

A fix value of ion heating is probably caused by
1) outflow speed ~ 0.6-0.7V_{pAlf}, 2) δ as **thin as** ρ_i.

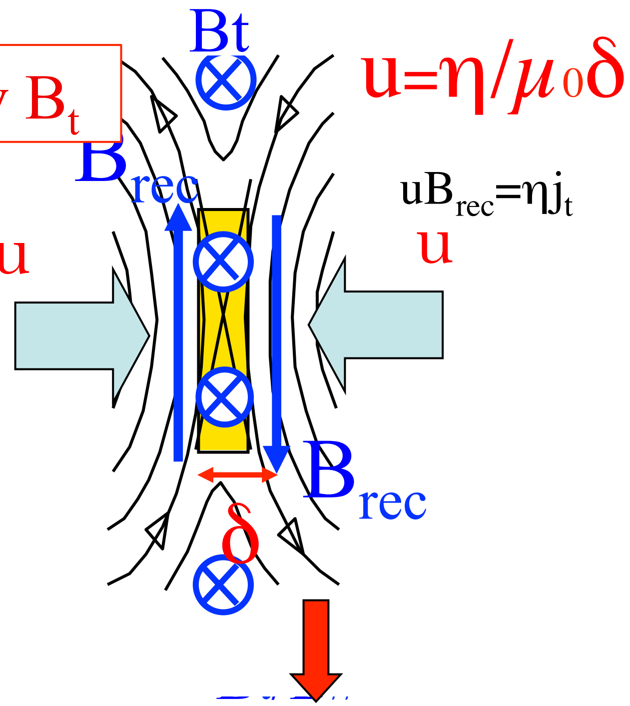


Large Compression Force

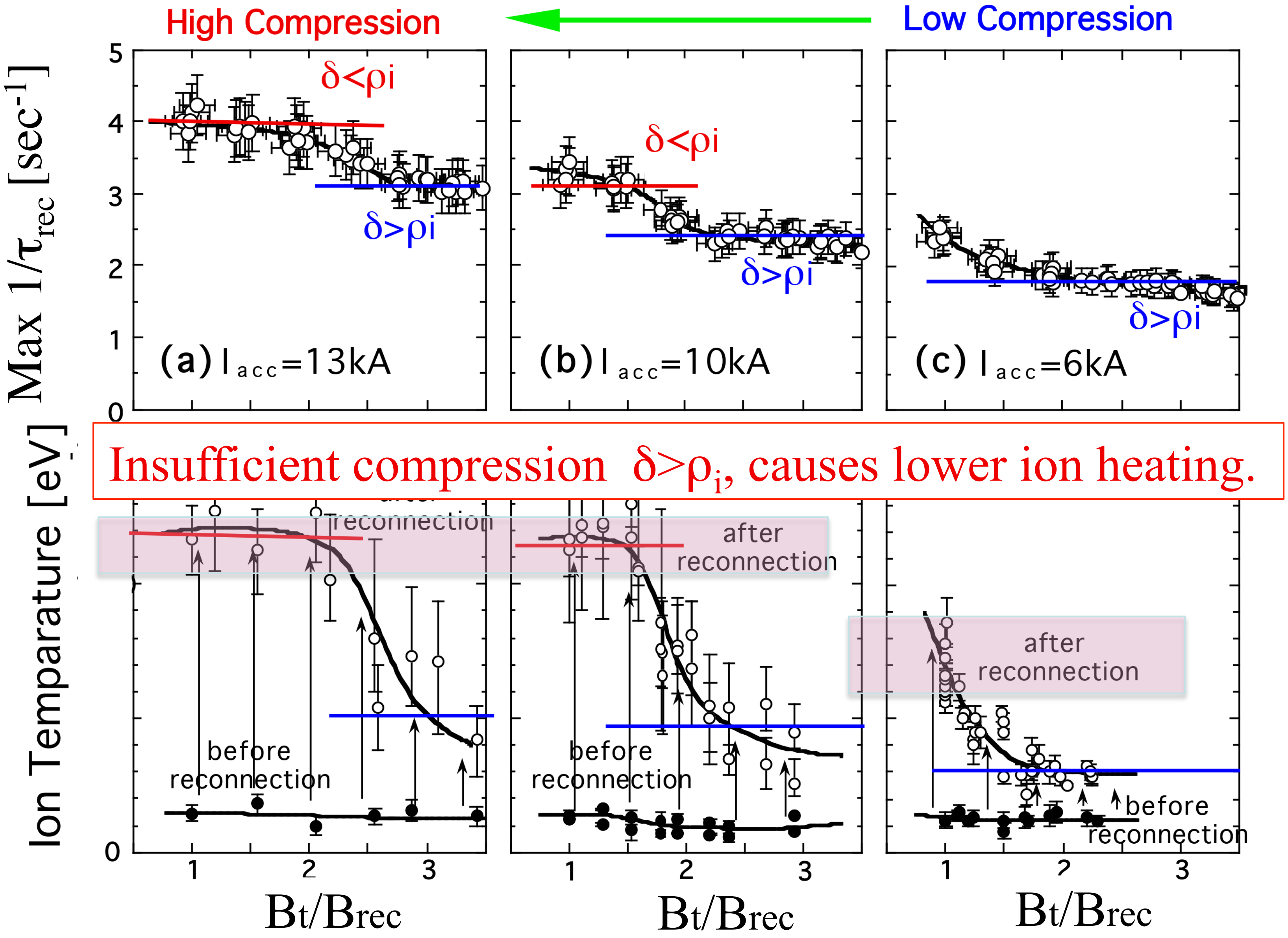
Small Bt
(X-line component)

Fast Reconnection

If δ<ρ_i, ion heating is determined by B_{rec}, not by B_t



Requirement 2: Insufficient compression $\delta > \rho_i$, causes ion heating lower than the B^2-scaling prediction.



Insufficient compression $\delta>\rho_i$, causes lower ion heating.

Summary and Conclusions

1) Ion heating energy and T_i increase with $B_{rec}^{2.}$

if (1) δ is compressed as thin as ρ_i.

(2) $P_{ion\ heat} >> P_{ion\ loss}$, $P_{ion\text{-}electron}$ (TS-3, UTST, MAST)

2) $P_{ion\ heat} >> P_{electron\ heat}$

3) Rec. accelerates ions up to 60-70% of V_{pAlf} , transforming ~50% of rec. magnetic energy into $W_{the,\ ion}$ in downstream.

4) Current sheet (plasmoid) ejection as a fast rec. mechanism weakens the B_t dependence of reconnection heating.

5) Global electrostatic potential structure

➡ UK-Japan team extended the B_{rec}^{2}-scaling to T_i~1.2keV (T_e~0.8keV) for the B_{rec}~0.15T in MAST.

The rec. is a promising method for heating ions > 10keV: direct access to alpha heating. The new projects of high B_{rec} ST merging started in U. Tokyo and Tokamak Energy.