High Power Heating of Magnetic Reconnection in Toroidal Plasma Merging Experiments: TS-3, MAST

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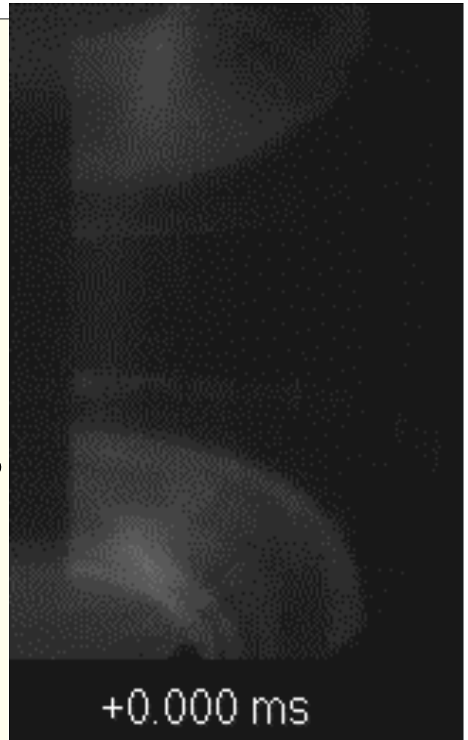

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Why, Where and How much reconnection (FRC merging formation/ ST rec. heating) heats ions and electrons?

TS-3, TS-4, UTST, MAST based on UK-J collaborations

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

1) 2D T_i and T_e measurements TS-3, MAST

2) Ion acc./heating in downstream MAST,TS-3, PIC, Solar

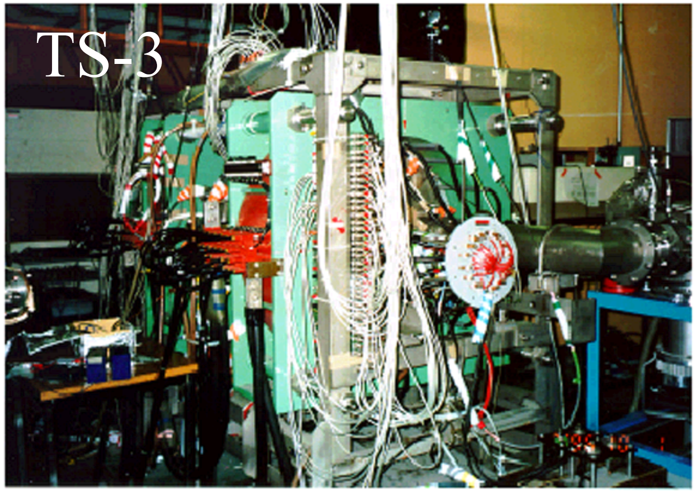
3) Electron heating at X-point MAST, TS-3, PIC

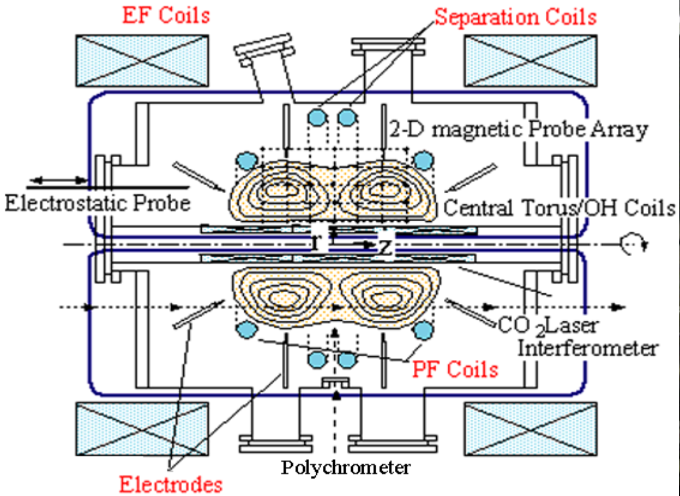
4) Scaling of reconnection heating MAST, TS-3

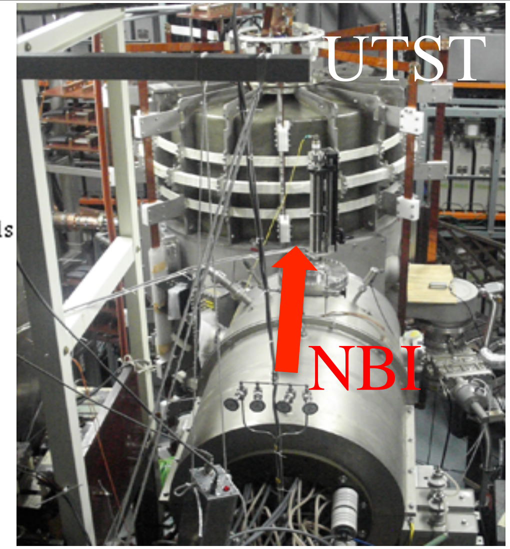
5) Merging formation of high-T/beta tokamak MAST

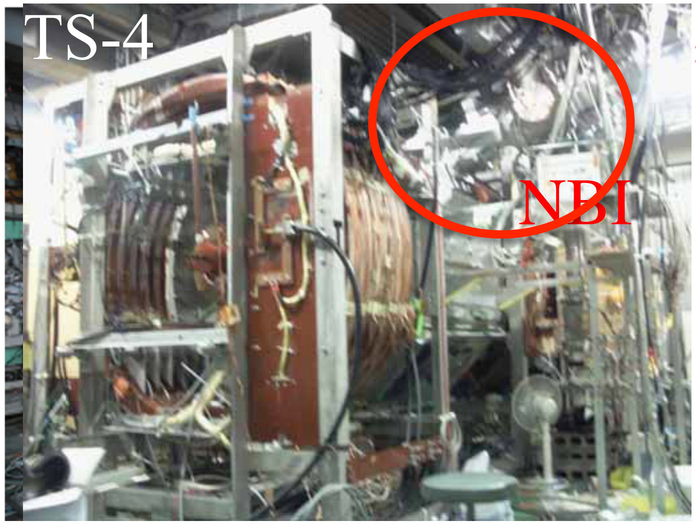
ST rec. heating : Ono et al. PPCF'12, PRL'11, POP'15, POP'93
FRC rec. heating: Ono, Kawamori et al. PRL'05, PRL'96, PFR'86

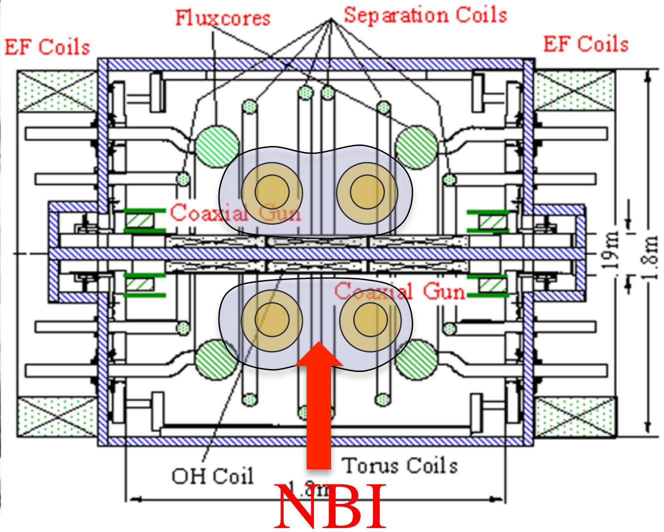
Univ. Tokyo-Culham Merging/ Reconnection Experiment
1986～ TS-3 (R=0.2m)   2000～ TS-4 (R=0.5m)
2006～UTST (R=0.45m)
for physics and application of reconnection heating

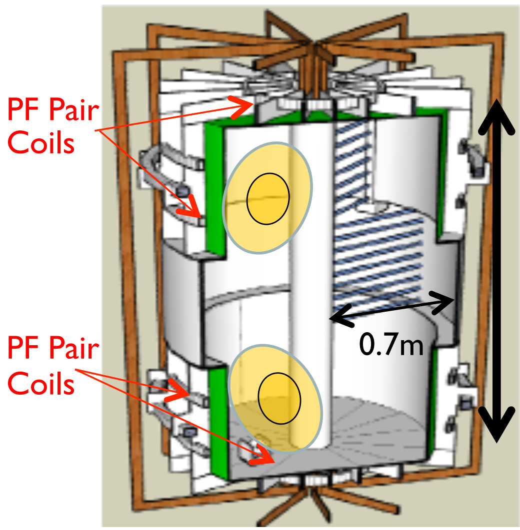


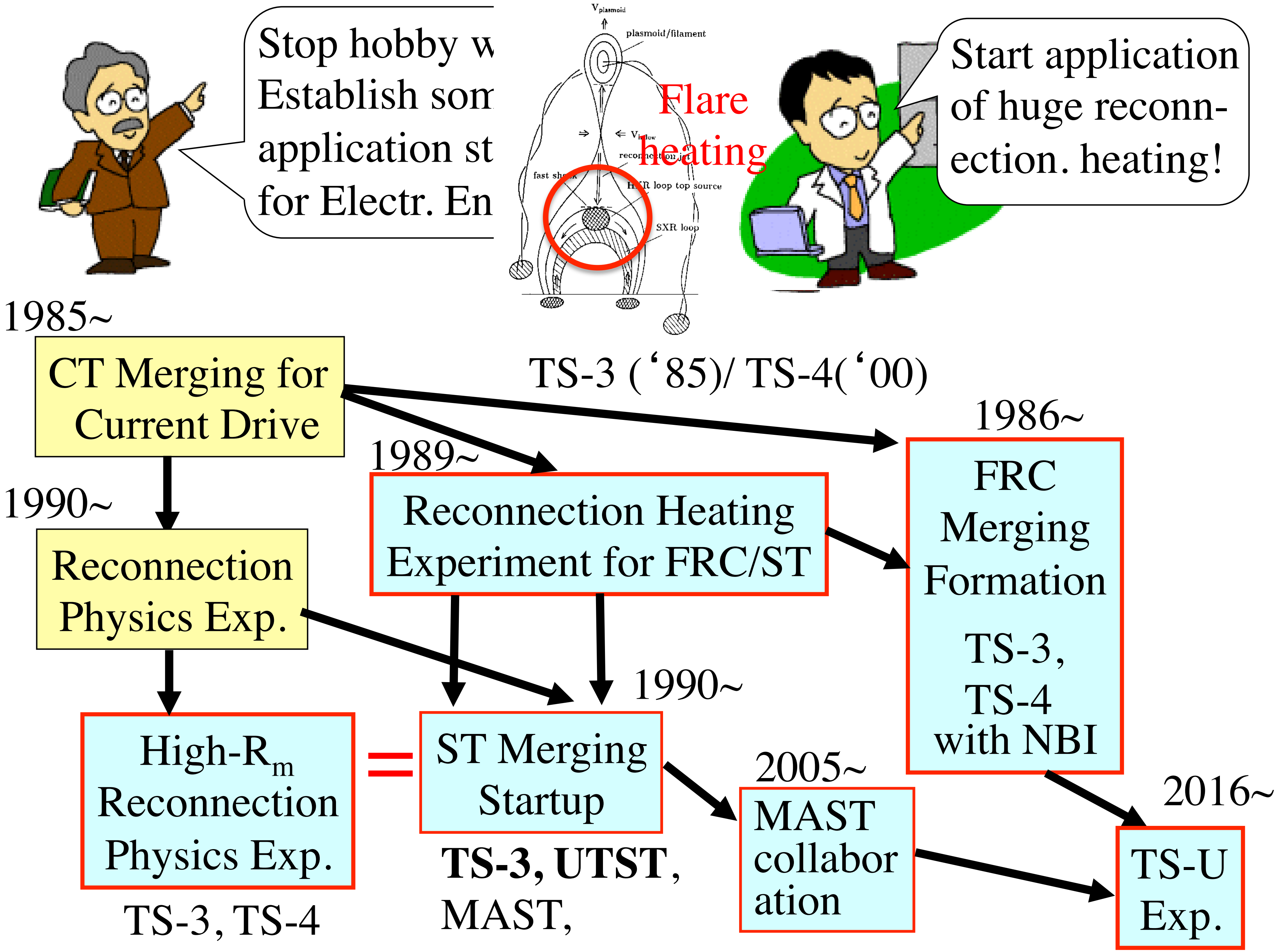











Stop hobby w
Establish som
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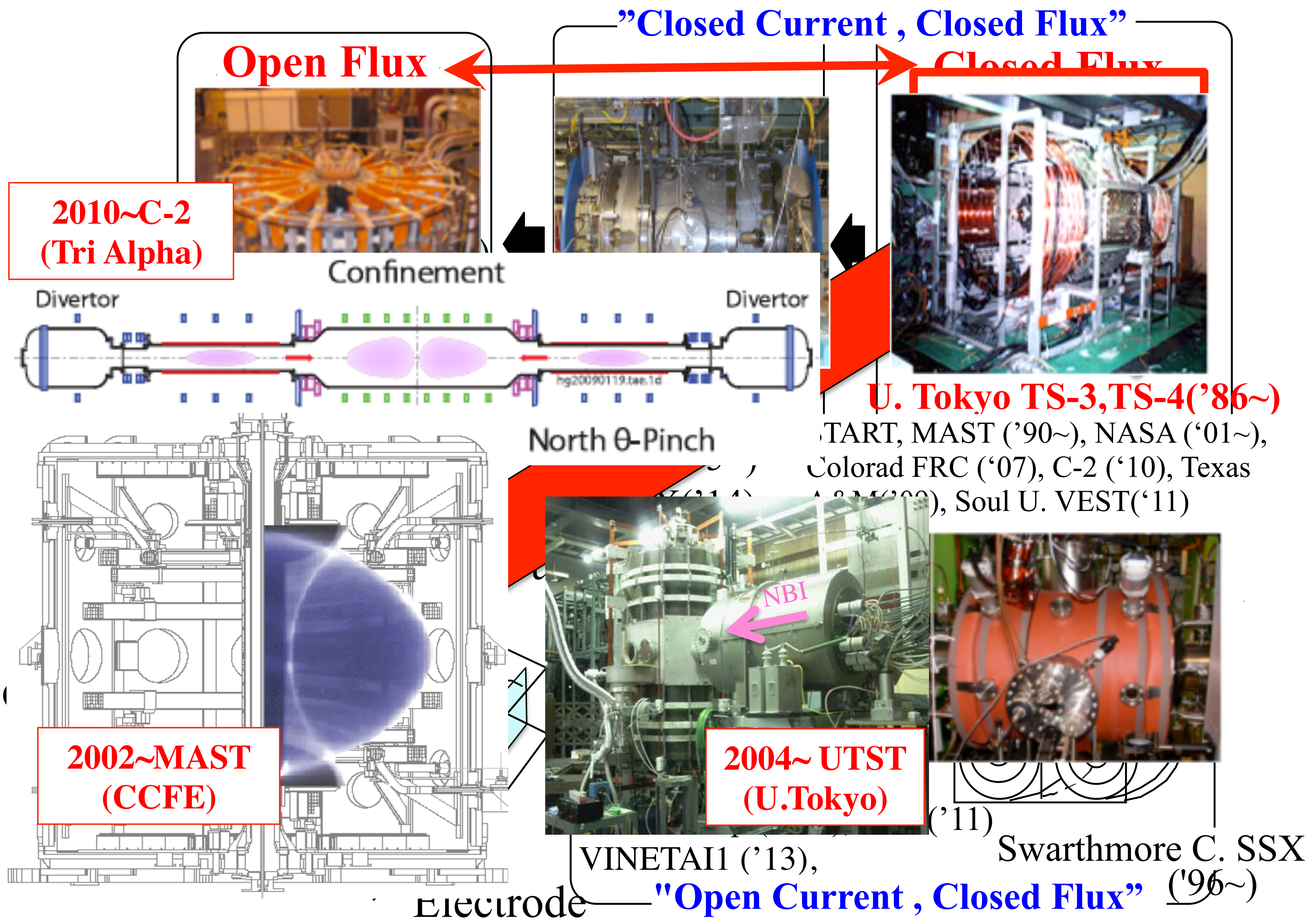
for Electr. En
plasmoid/filament
Flare
heating
SXR loop
Start application
of huge reconn-
ection. heating!
TS-3 ('85)/ TS-4('00)
1985~
CT Merging for
Current Drive
1990~
Reconnection
Physics Exp.
1989~
Reconnection Heating
Experiment for FRC/ST
1986~
FRC
Merging
Formation
TS-3,
TS-4
with NBI
High-R_m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

Number of merging/ reconnection experiments is over 10 now.



Advantages of merging formation over the conventional θ -pinch formation of FRC:

(1) slow formation (elimination of fast capacitor bank).

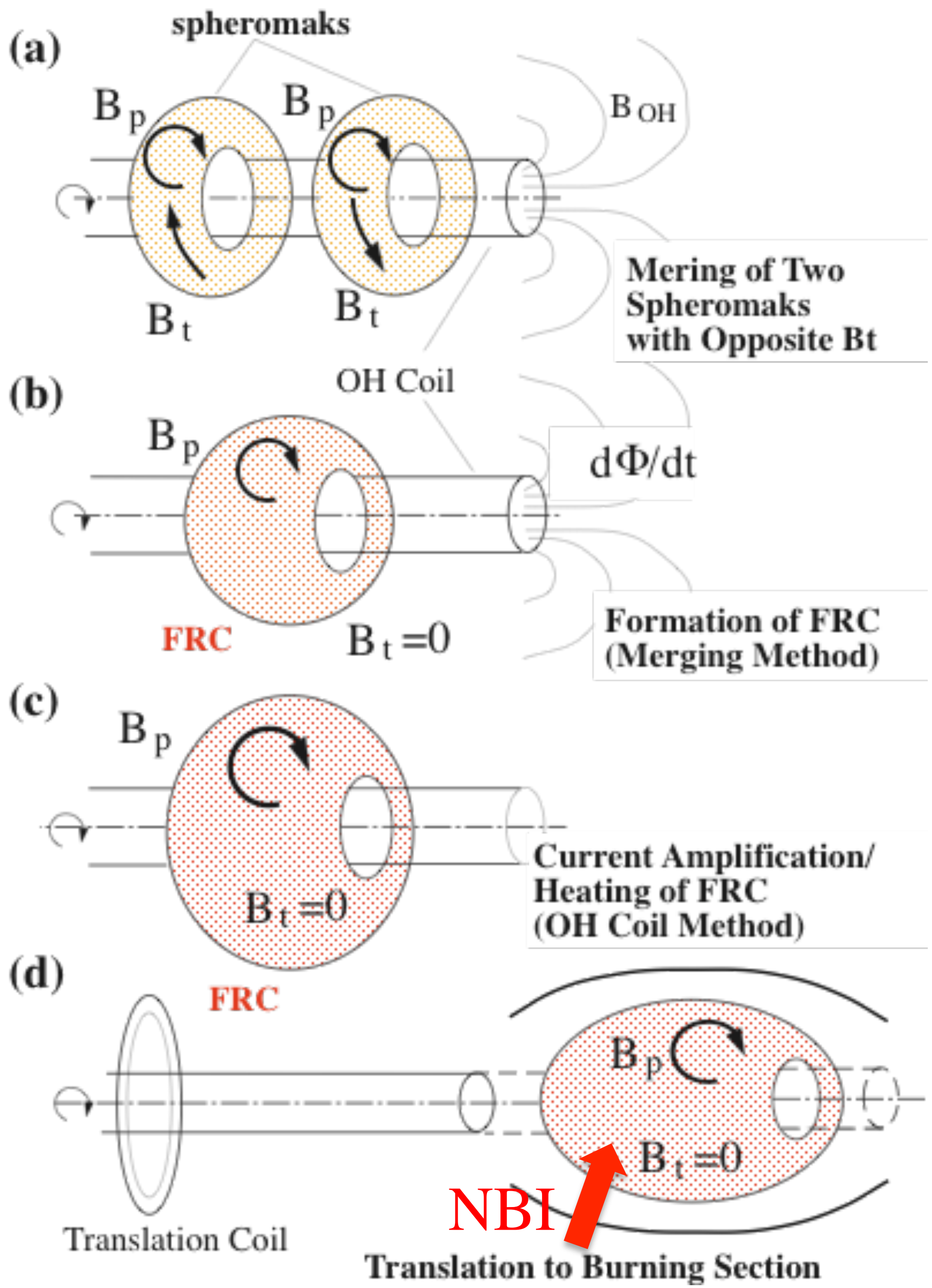
(2) highly efficient and stable formation proces

(3) initial ion heating of merging

(4) applicability of center OH coil for current-drive and heating.

(5) elongation control

Slow-formation and amplification of FRC

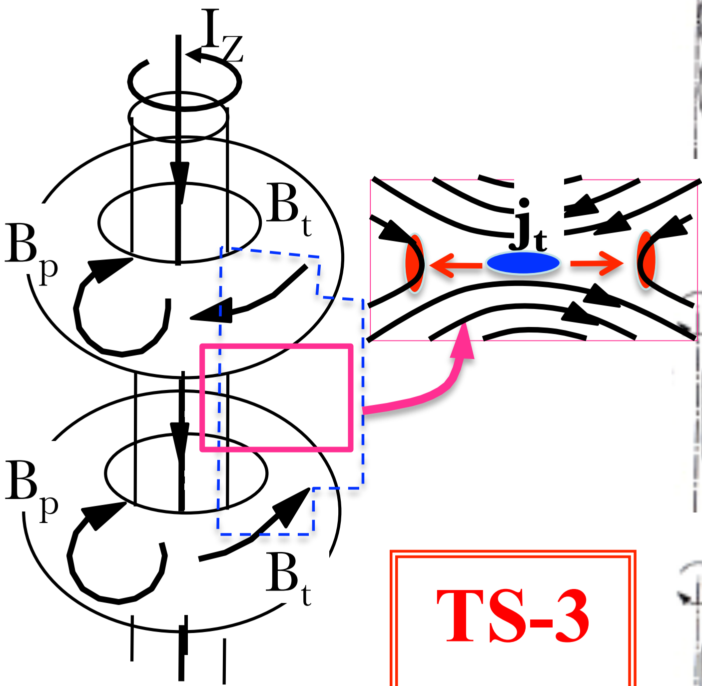


Y. Ono et al., Plasma Physics and Controlled Nuclear Fusion Research 1992

Merging Formation of FRC in 1990

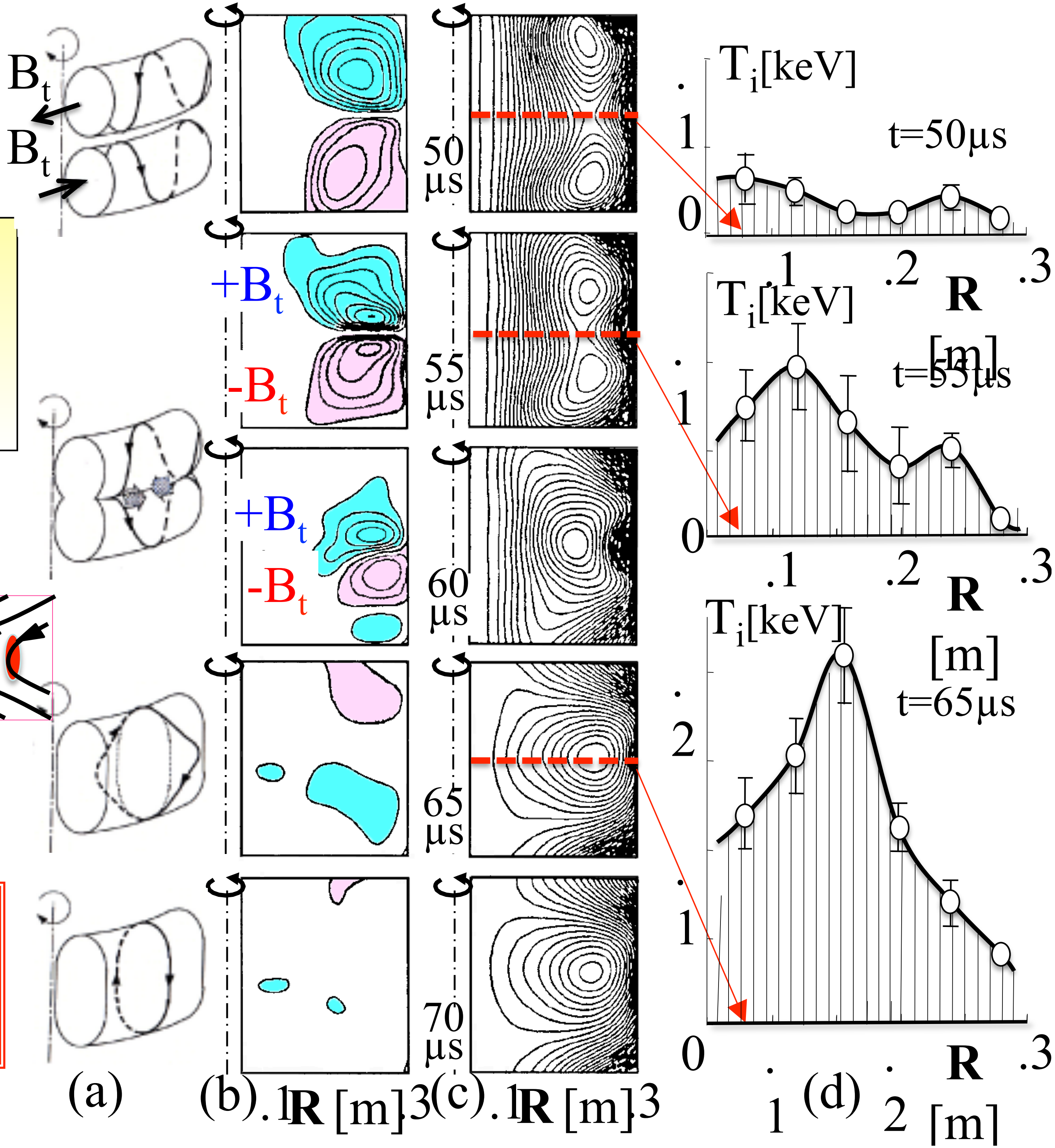
TS−3

Significant ion heating of no-guide field reconnection



TS-3

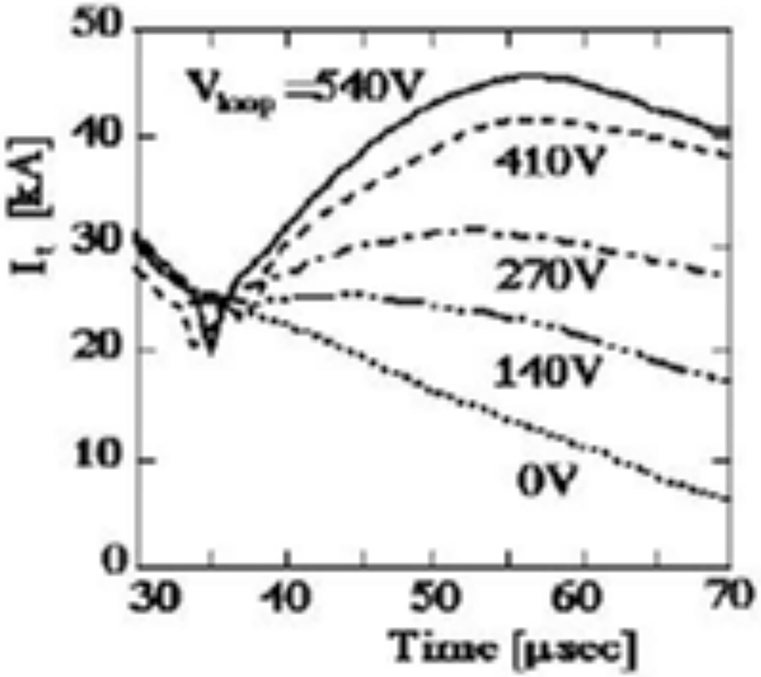
$B_t \approx 0$

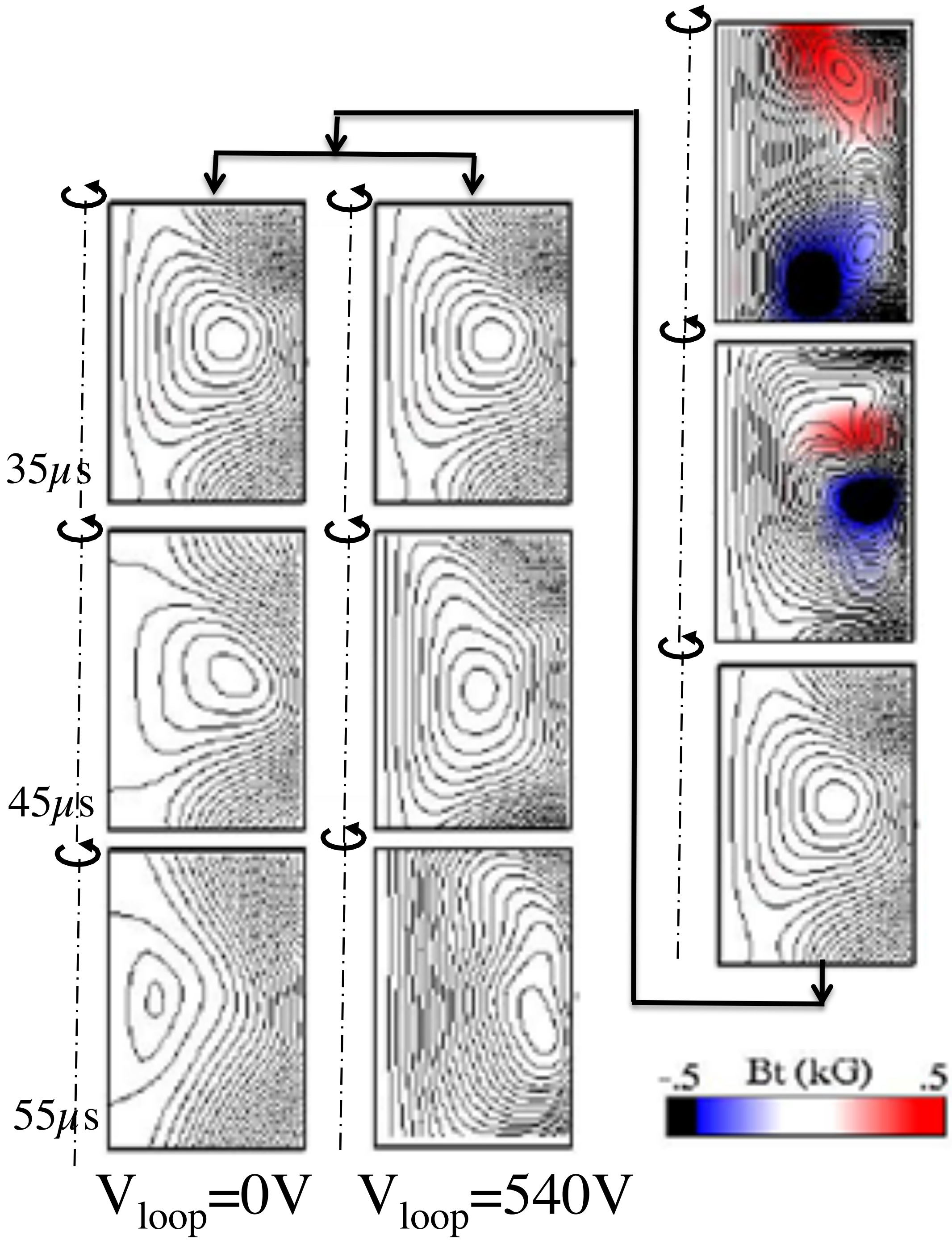


Y. Ono et al., PRL 1996

Current- Amplification of FRC in 1993 TS−3

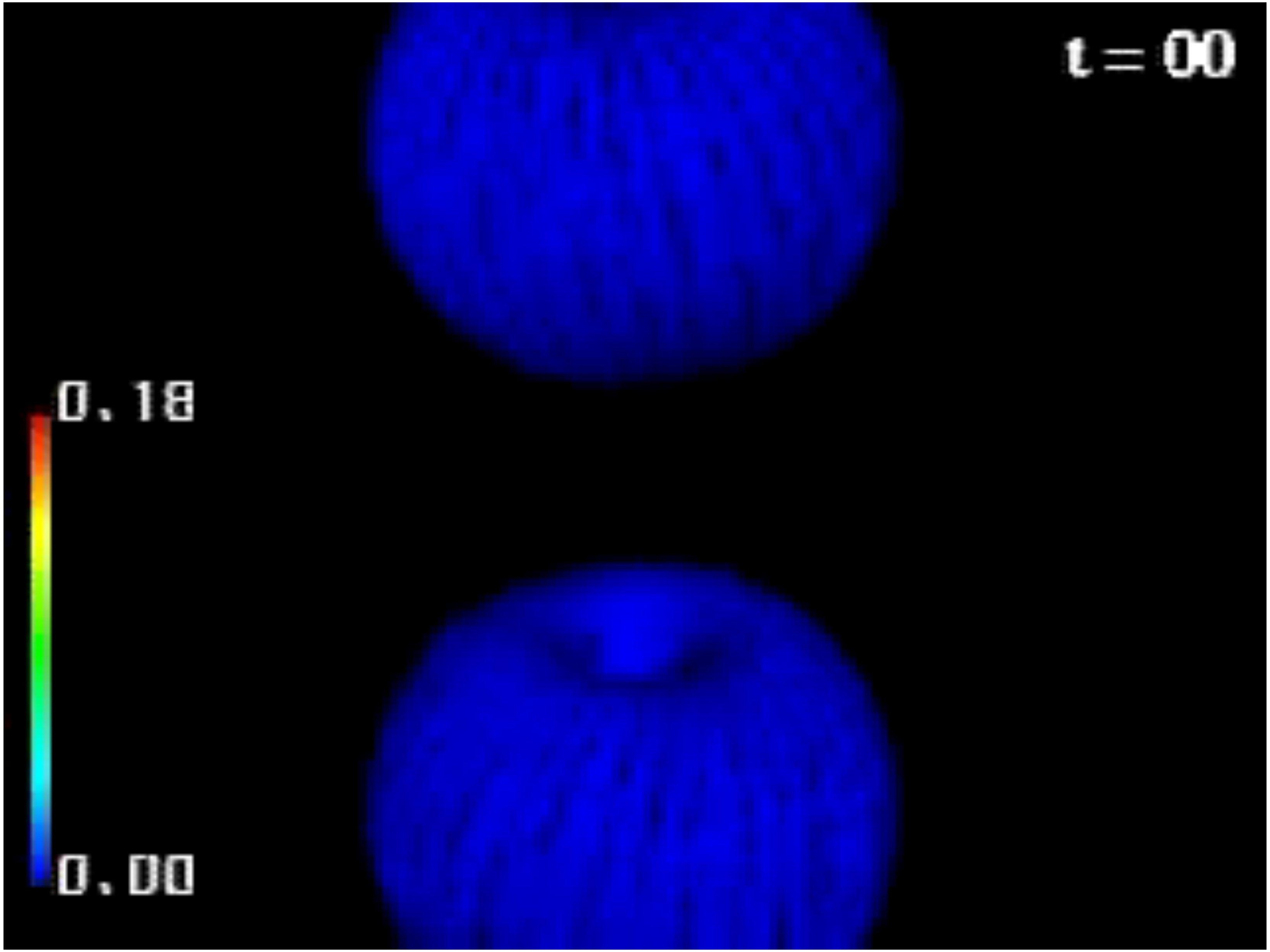
The current of FRC is doubled by center-solenoid coil.





Y. Ono et al., Plasma Physics and Controlled Nuclear Fusion Research 1992

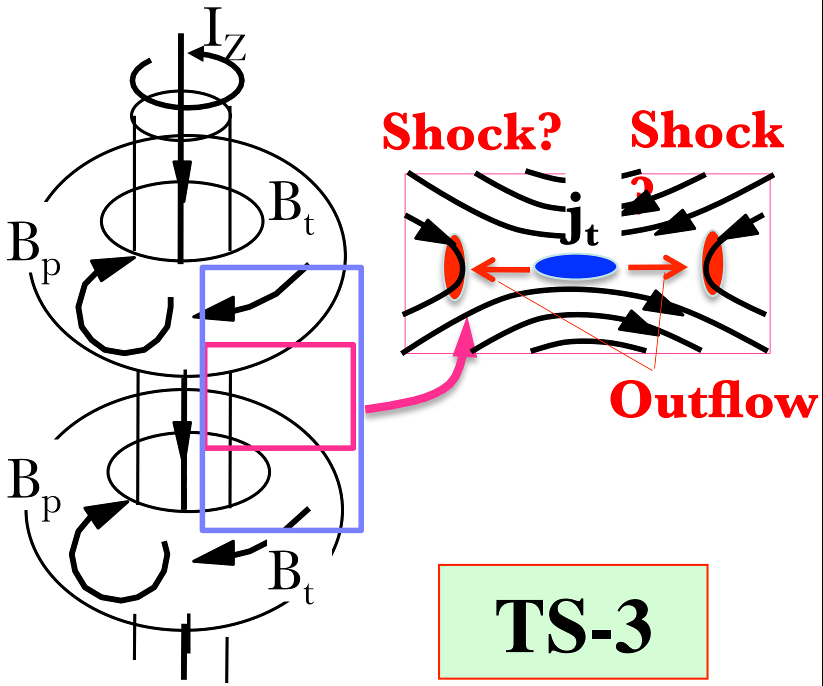
Watanabe (NIFS) PFR'00 made the 2D MHD simulation of couterhelicity merging spheromaks, including its heating effect.



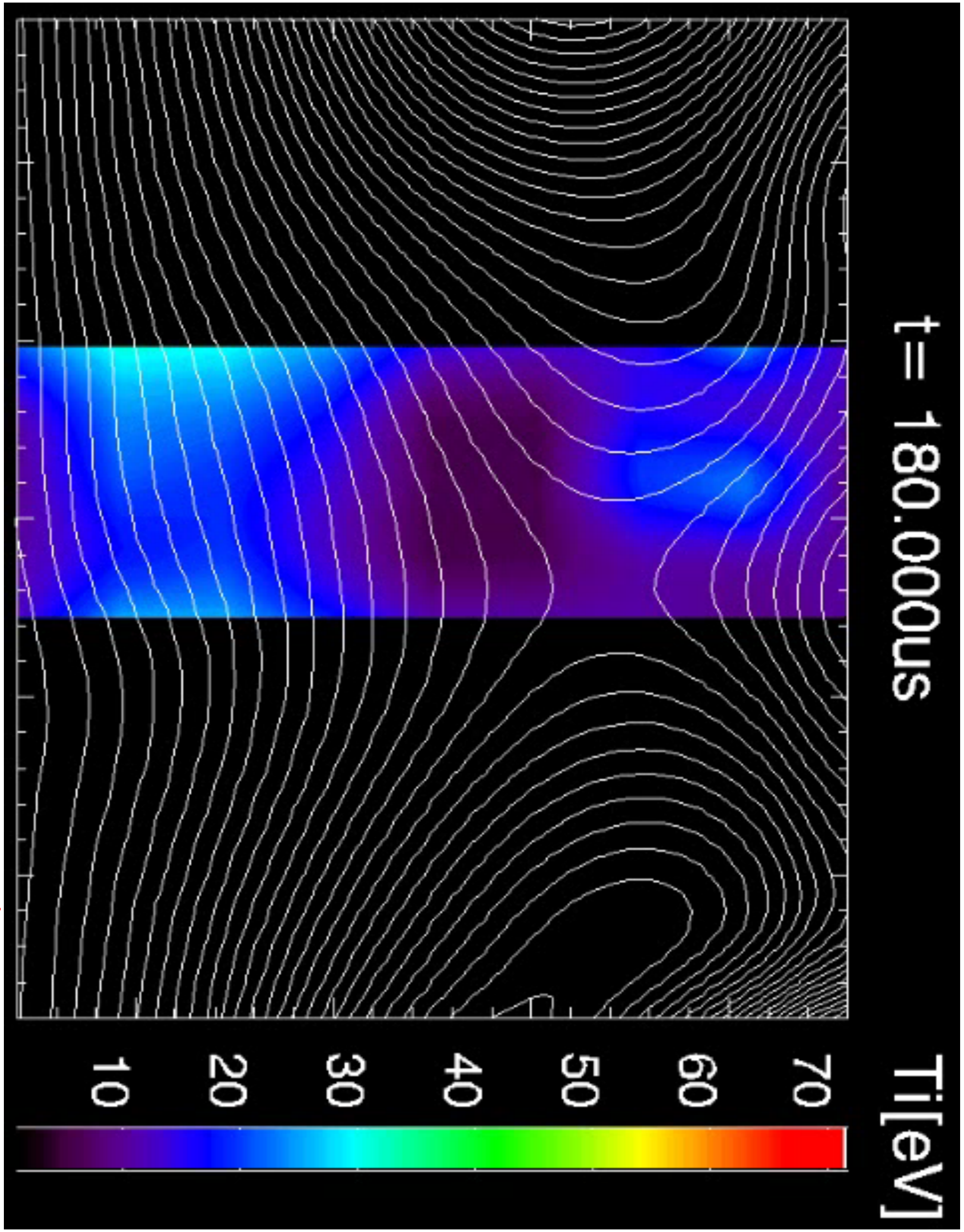
FRC Merging Formation in 2009 TS-3

Significant ion heating in downstream of reconnection outflow.

The heated ions are confined inside the reconnected closed fluxes.



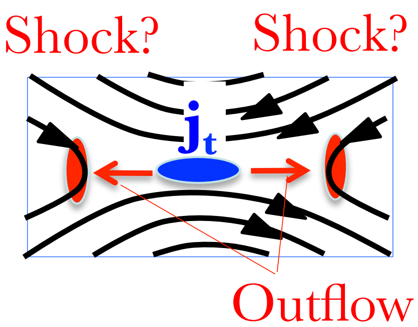
TS-3



ST Rec. Heating TS-3

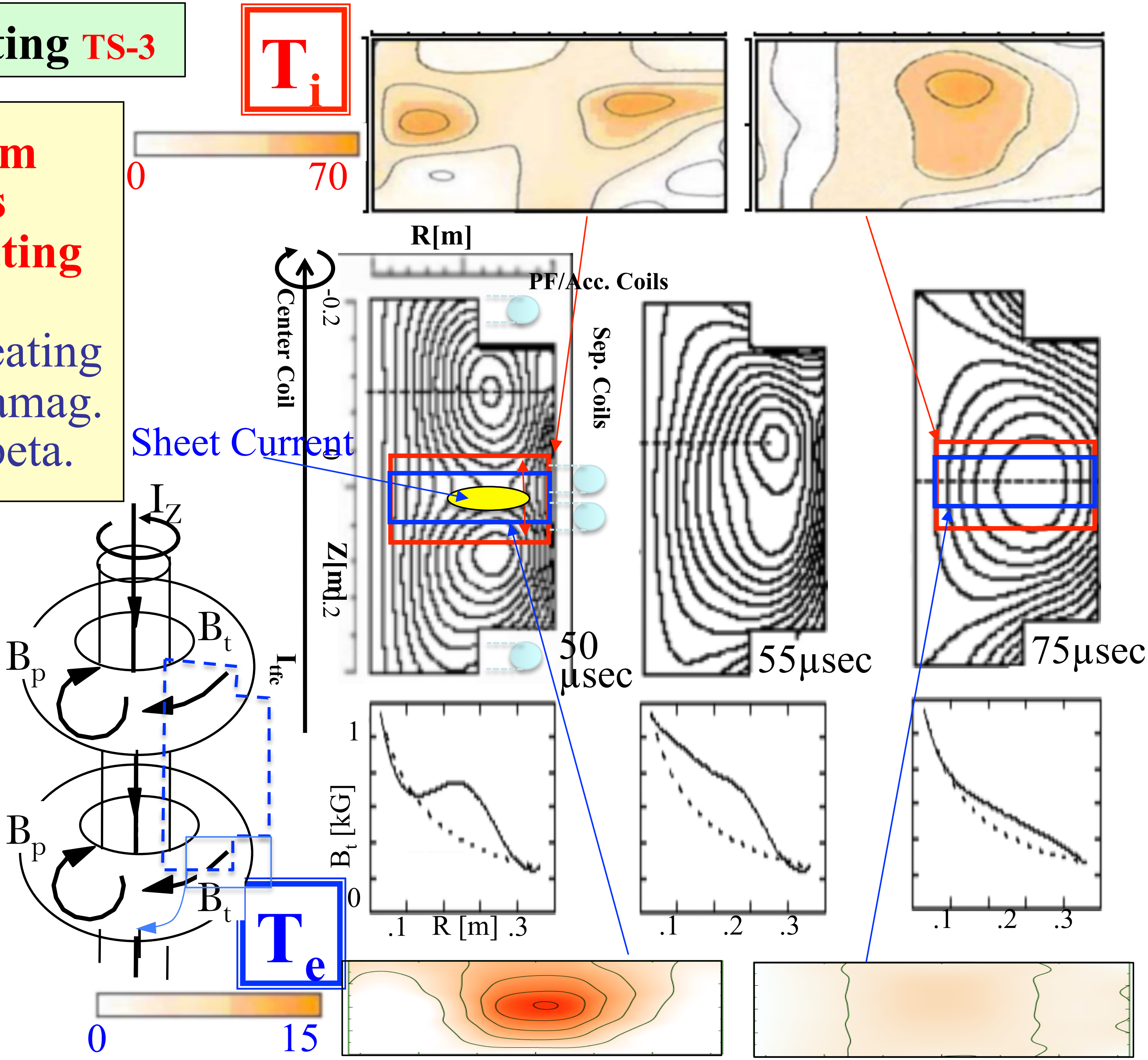
1) Down-stream heating of ions
2) X-point heating of electrons
High power heating suppresses paramag. B_t, increasing beta.

High Guide Field
$B_t \approx 5B_{rec}$



$B_t \sim 5B_{rec}$

Y. Ono, PRL 2011



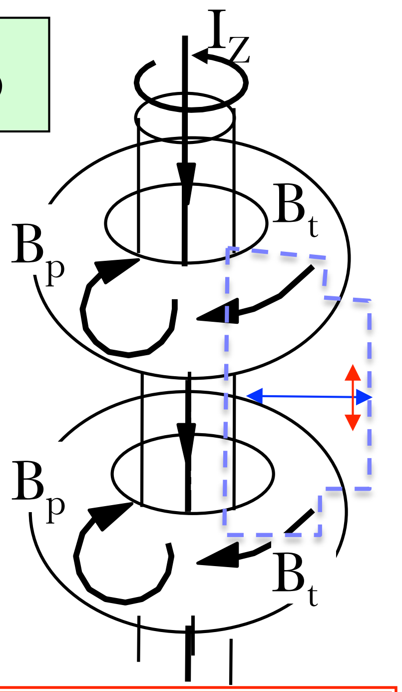
ST Rec. Heating TS-3

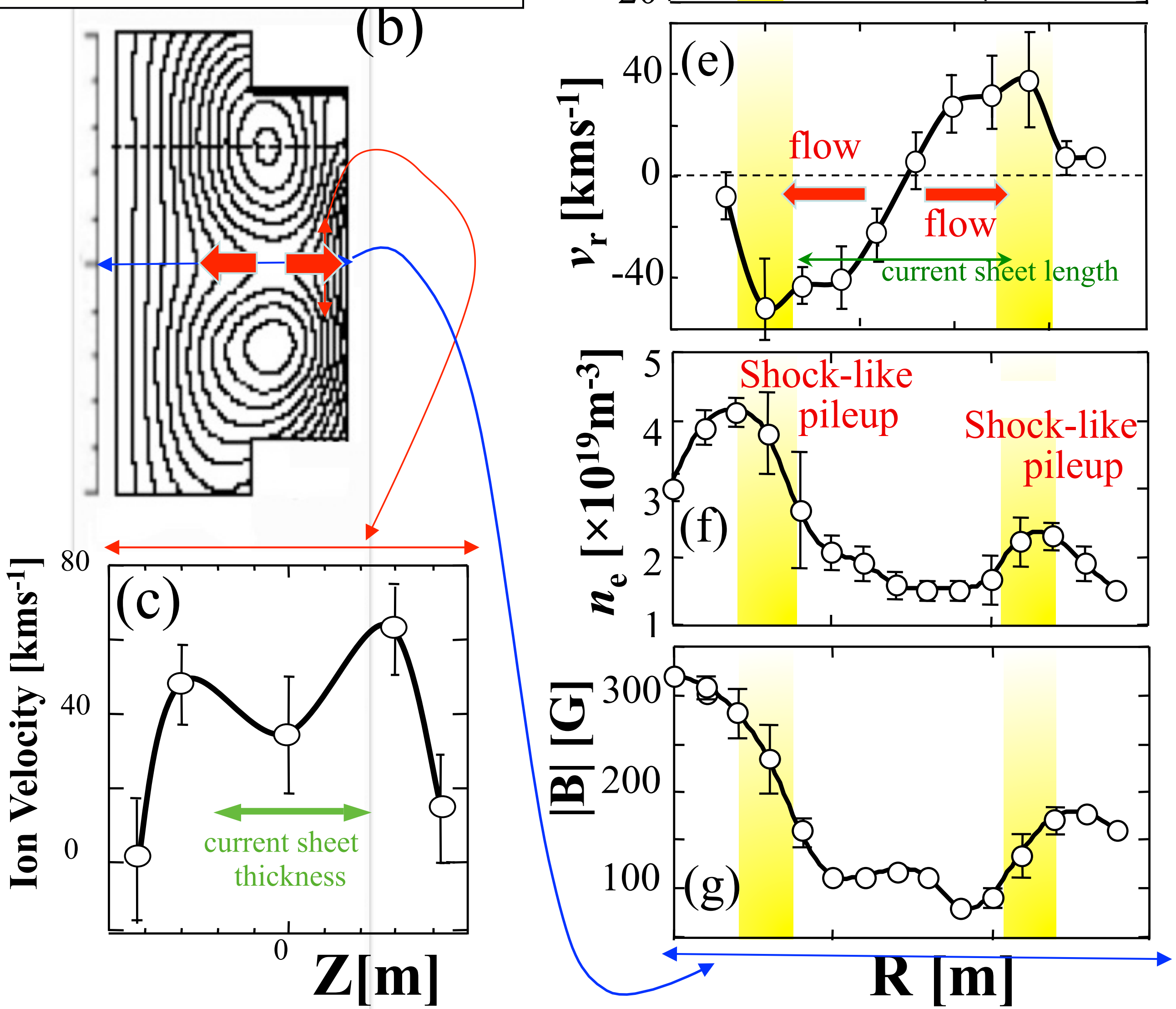
In the downstream, hot T_i spot, steep increase in n_e B and dumping of flow appear, indicating fast shock form.

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

$n_1/B_1 \sim n_2/B_2$

TS-3





High Guide-Field

Y. Ono et al., PRL 2011

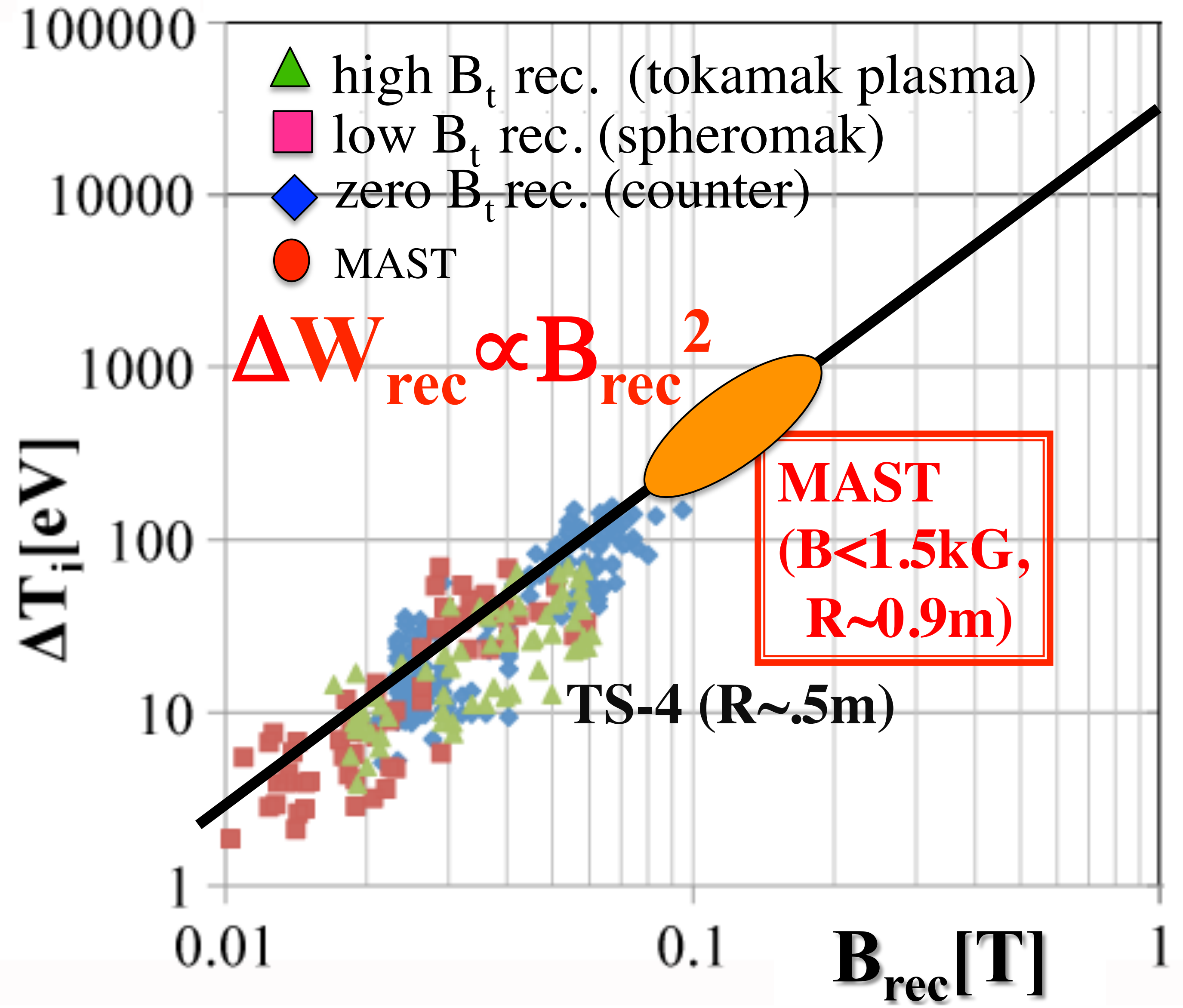
B_{rec}^2 -Scaling of Rec. Heating → High-B_{rec} Merging Exp.

B_{rec}^2-scaling for direct ion heating by reconnection

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

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

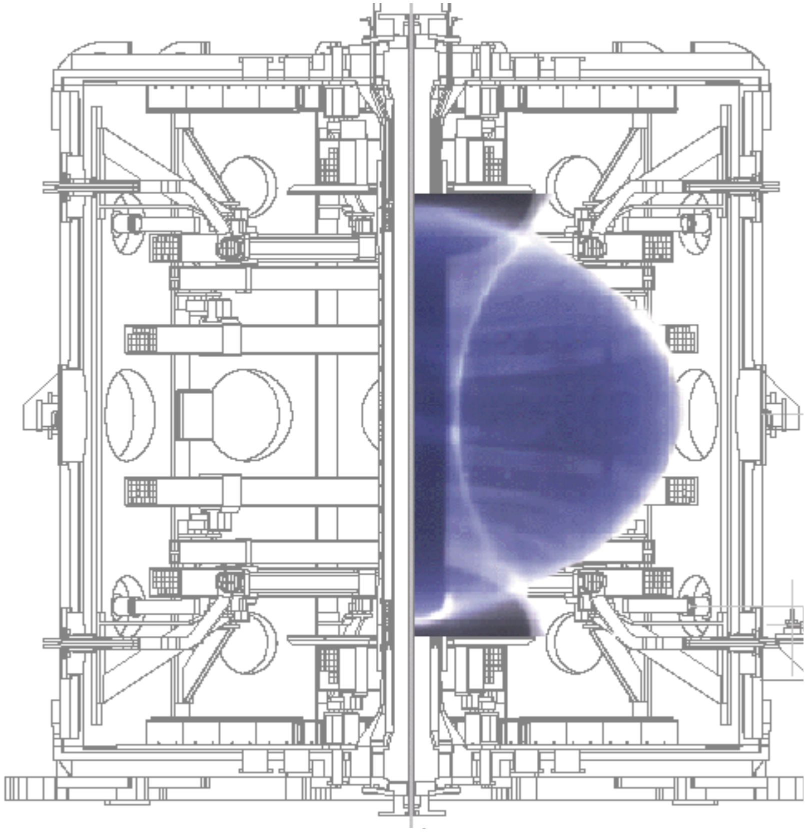
TS-3, TS-4
MAST



Y. Ono et al., PRL 2011

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

Up-scaled Reconnection Experiment in MAST



$>10^5$ ← R_m — $>10^3$

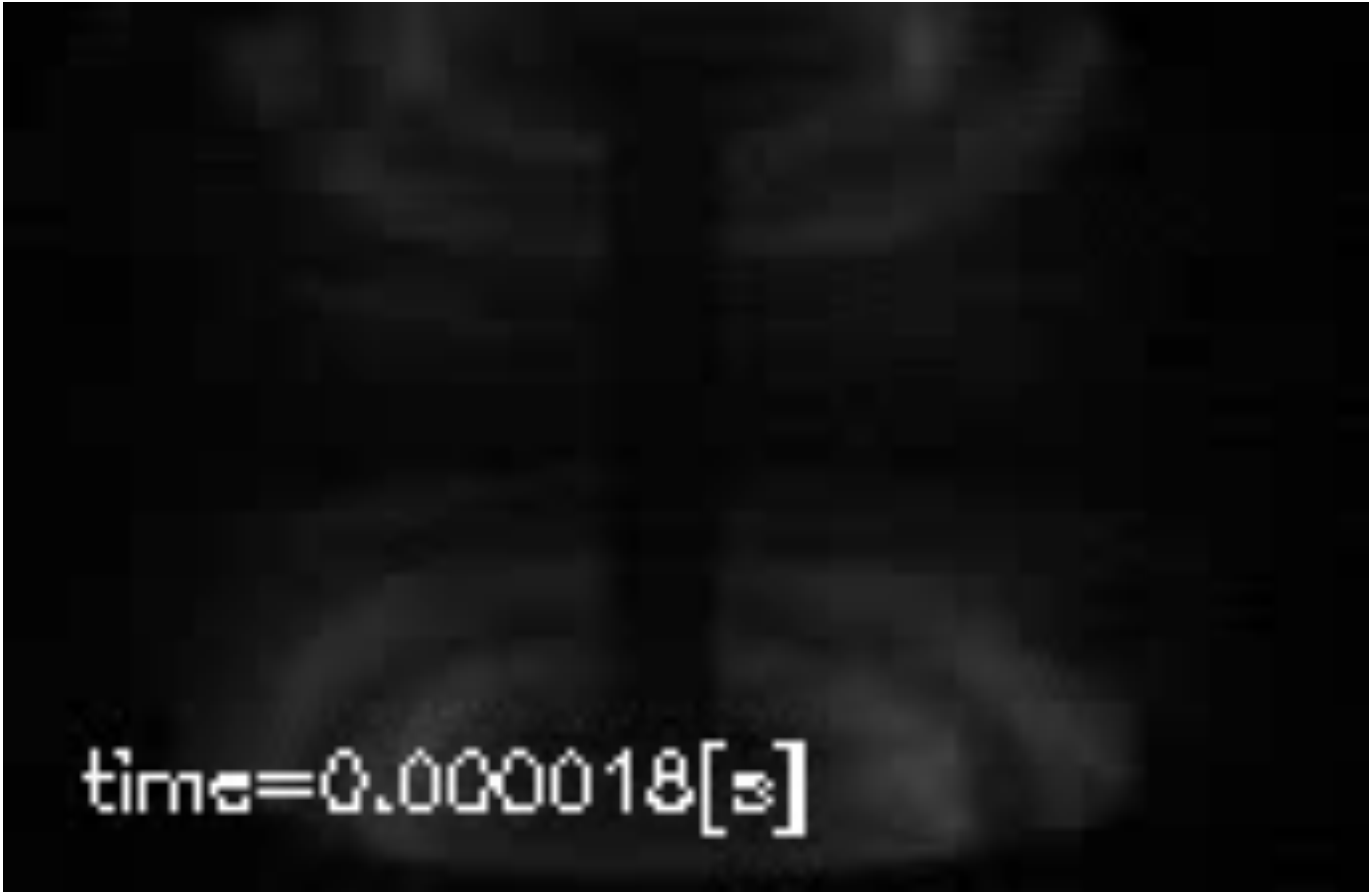
	MAST	TS-4	TS-3
R [m]	0.9	0.5	0.2
a [m]	0.7	0.4	0.15
I_p [MA]	2	0.1	0.07
B_t [T]	0.4-0.7	0.1	0.2
B_p [T]	0.1-0.2	0.03	0.05

1D measurements of T_i and T_e :
1) 32ch. Ion Doppler, 1') NPA
2) 200ch. Thomson scattering

From MAST data (UKAEA, Gryaznevich)

The MAST plasma has lower collisionality R~10^5 and higher reconnecting B field than TS-3 and TS-4.

MAST: Visible light image of two merging tokamaks

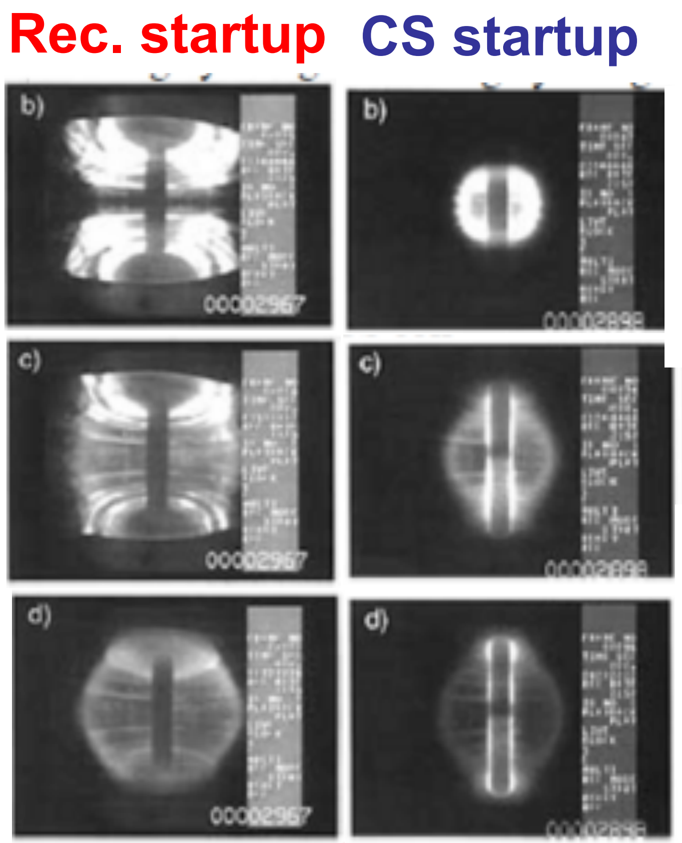


High B_{rec} Merging in MAST

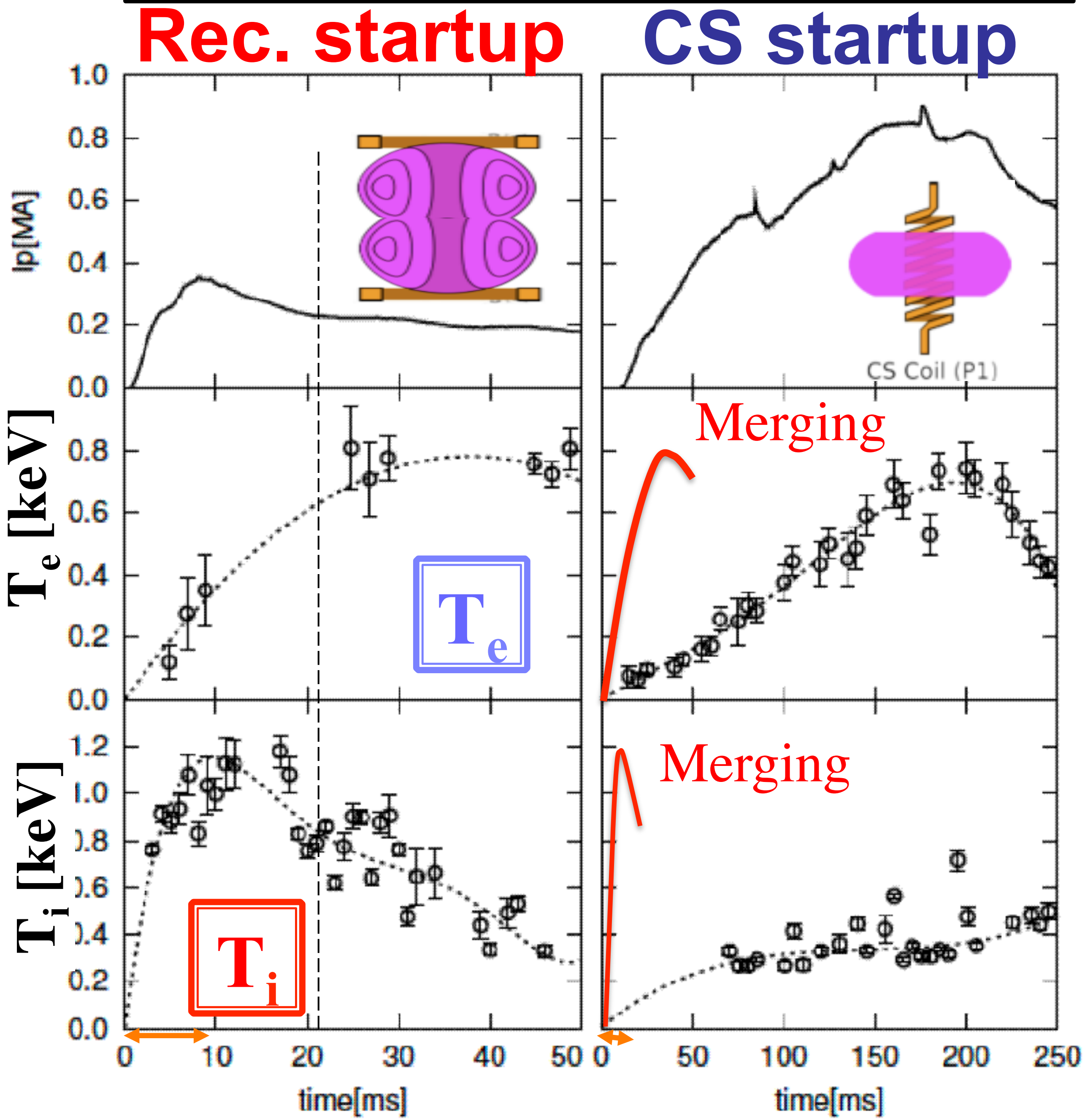
Significant Ion Heating in MAST Rec.

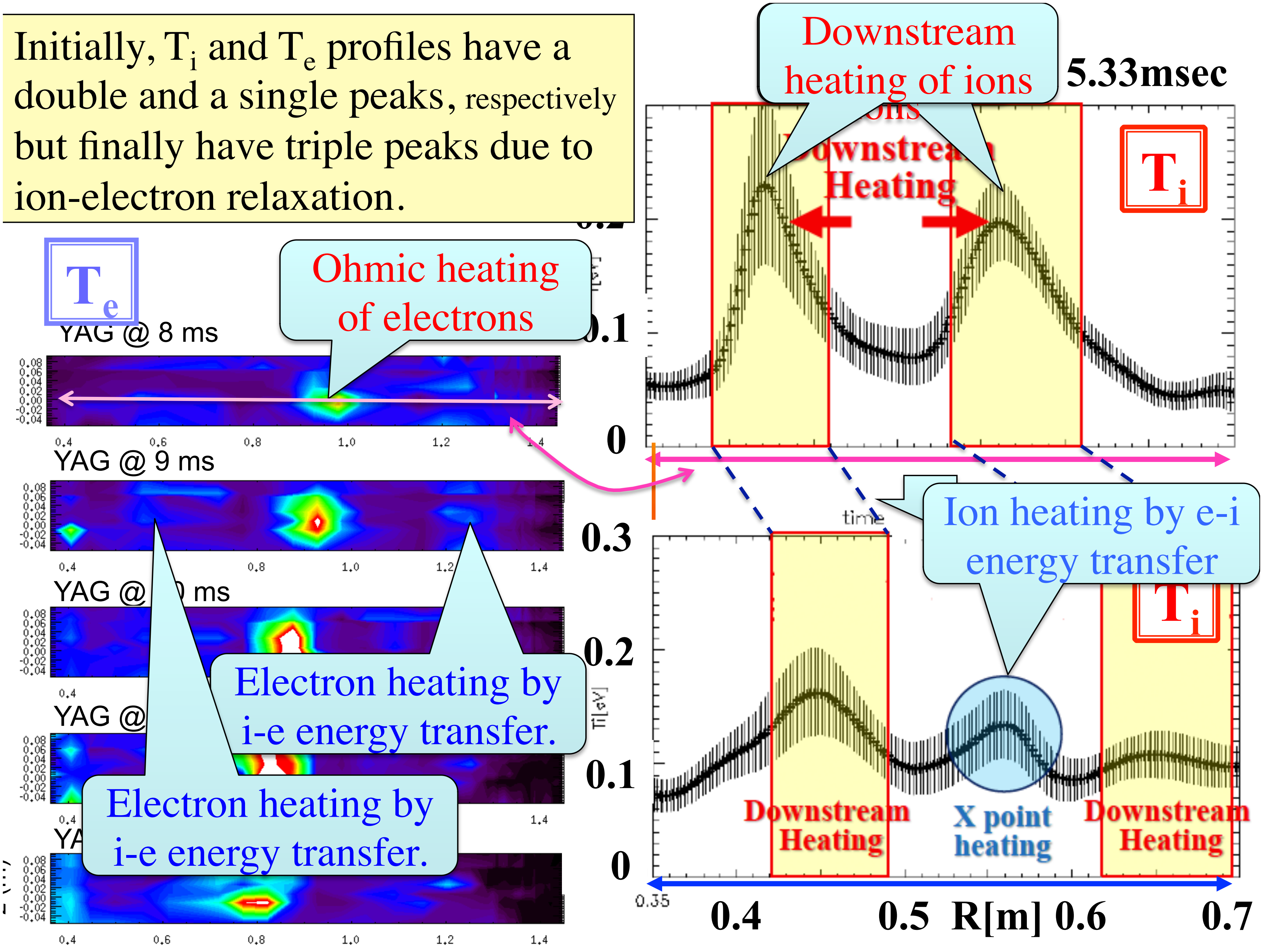
MAST Reconnection Exp.

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



Y. Ono et al., PPCF 2012





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.
Downstream heating of ions
5.33msec
T_i
Downstream Heating
T_e
Ohmic heating of electrons
YAG @ 8 ms
YAG @ 9 ms
Electron heating by i-e energy transfer.
Electron heating by i-e energy transfer.
Ion heating by e-i energy transfer
time
X point heating
Downstream Heating
Downstream Heating
0.3
0.2
0.1
0
0.35
0.4
0.5
R[m]
0.6
0.7

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

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

Small localized electron heating

Electron heating Energy ≈ 0.07, 0.07

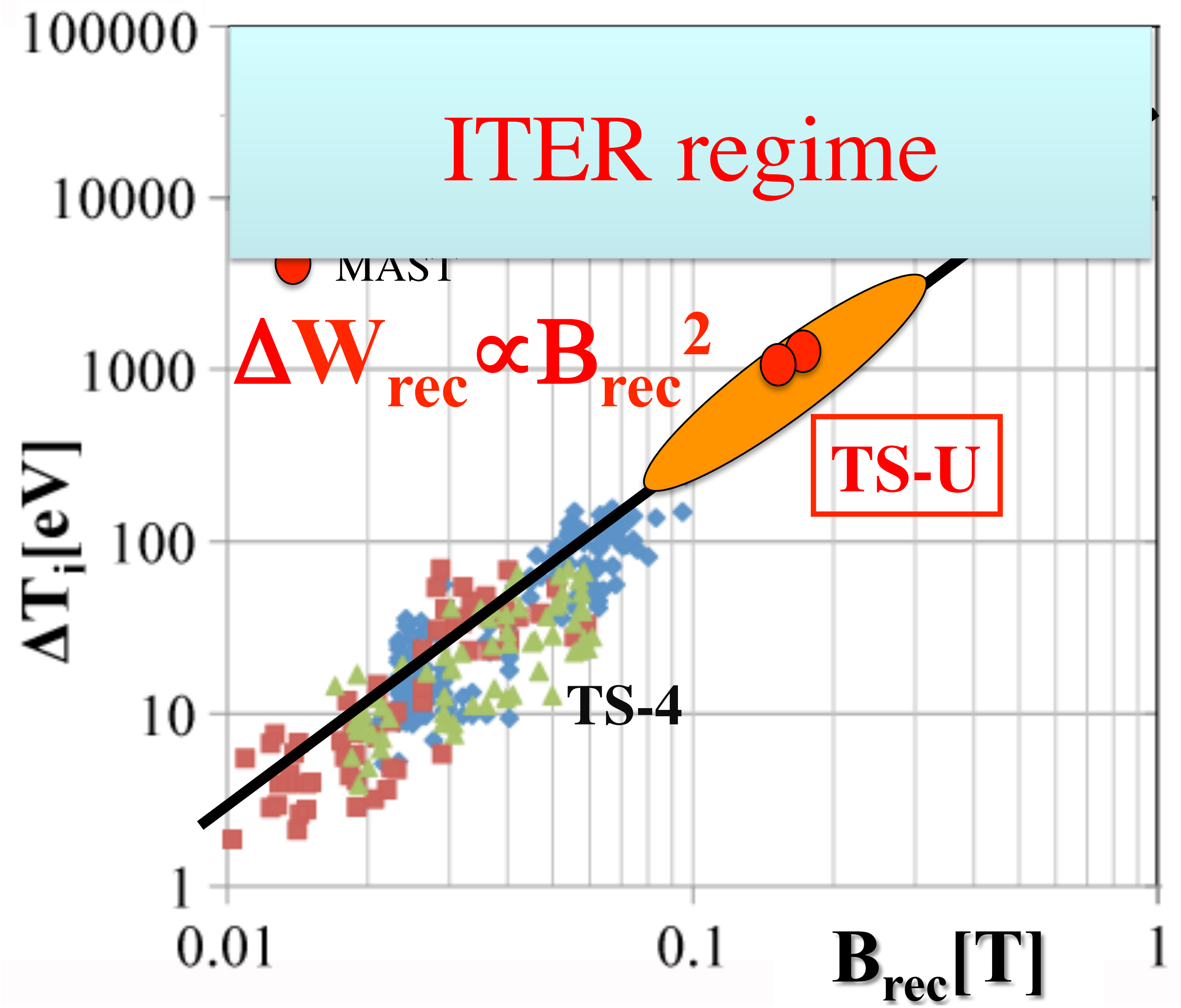
High B_{rec} Merging in MAST

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

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

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

TS-3
TS-4
MAST



Summary and Conclusions

1) Reconnection outflow heats ions significantly in two downstream regions. ⇨ Rec. heating of FRC/ST
2) Electron heating occurs locally at X-point inside current sheet.
3) Ion heating power >> Electron heating power
4) The ion heating energy (T_i) increases with B_{rec}^2.

➡ FRC formation by two spheromak with opposing Bt.

➡ The rec. heating in MAST heats ions to 1.2keV and electrons to 0.8keV due to its higher B_{rec}~0.15T

➡ High R_m exp. is important to solve electron heating of rec.

➡ Direct ion heating by rec. is a promising method for heating ions > 10keV for fusion plasmas.