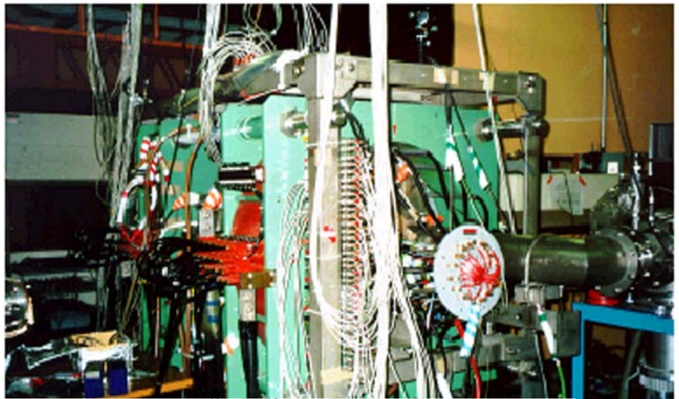
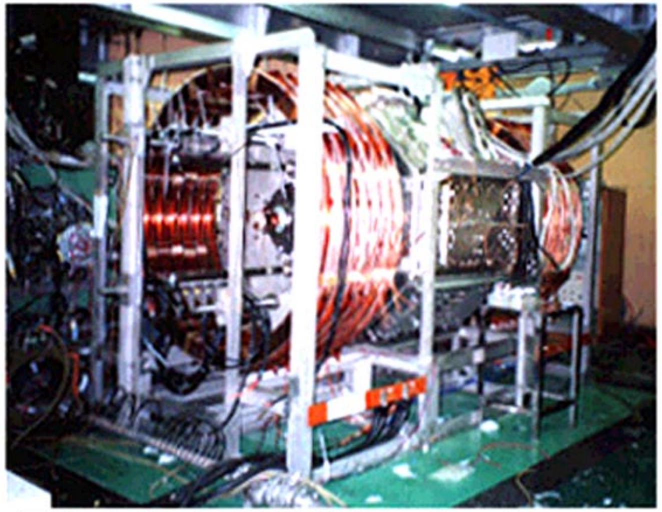
High Power Heating of Magnetic Reconnection in TS-3, TS-4 and UTST Merging Experiments

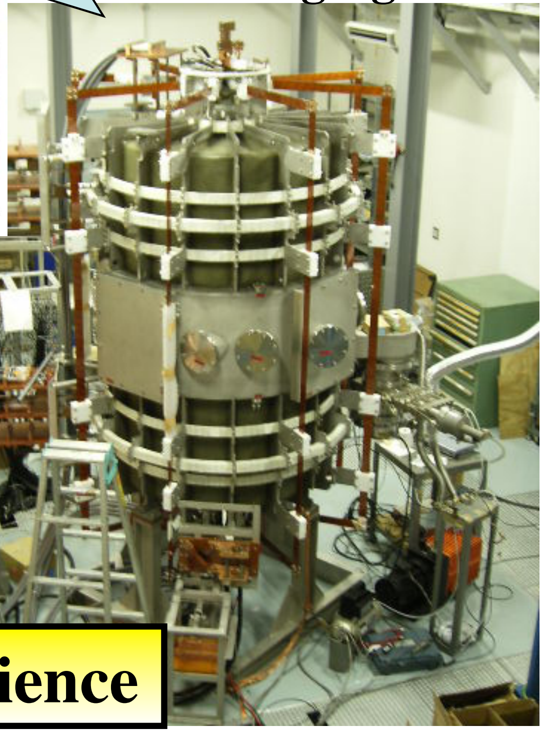
Y. Ono, H. Tanabe, T. Ii, T. Yamada, M. Inomoto, Y. Takase,
M. Gryaznevich, T. Asai, H. Sakakita, F. Cheng , TS/MAST groups
Univ. Tokyo, NAOJ, JAXA, AIST, Japan, CCFE UK, Cheng Kung Univ. Tw

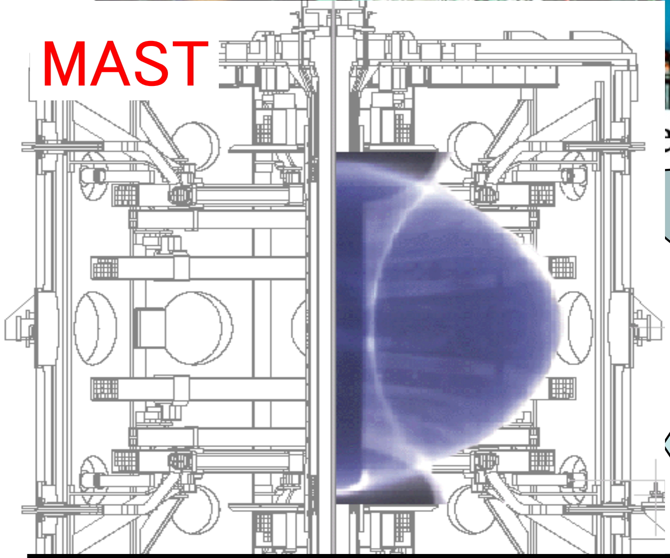


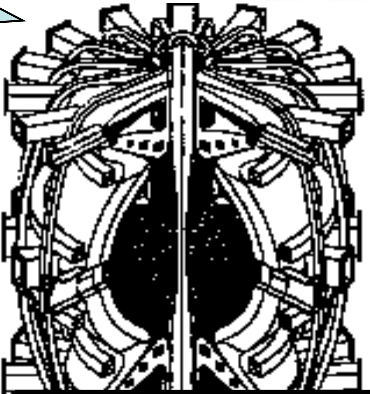


TS-4 ST/FRC Merging Device

UTST
Spherical Tokamak
Merging Device







Large Scale Merging Exp.

ST/CT Fusion Science

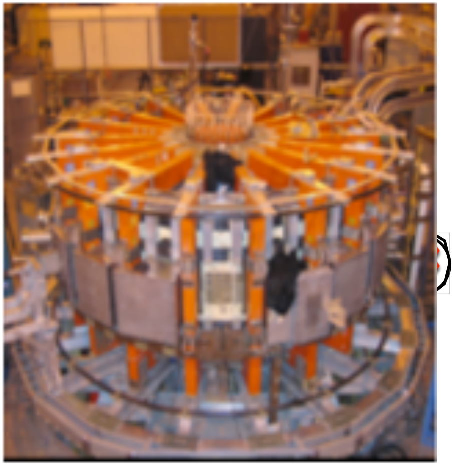
Number of merging-type reconnection experiments is over 10 now.

"Closed Current, Open Flux"

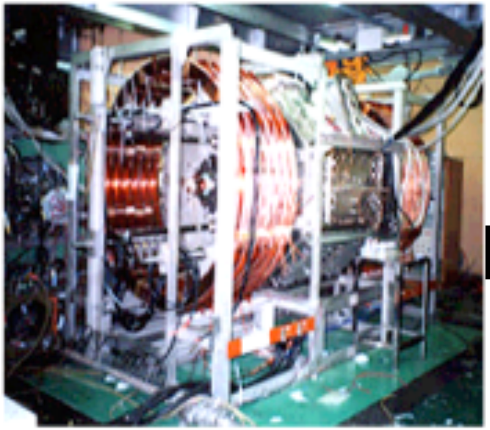
"Closed Current, Closed Flux"

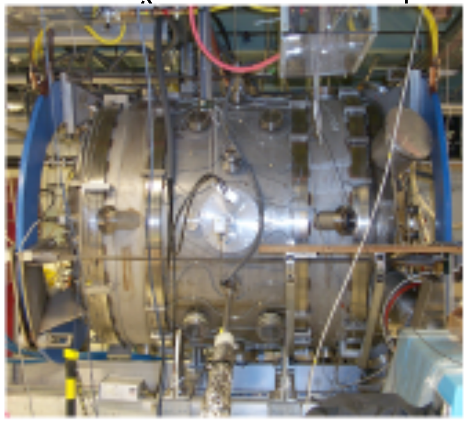
Open Flux ↔ Closed Flux

Closed Current



VTF('00~)

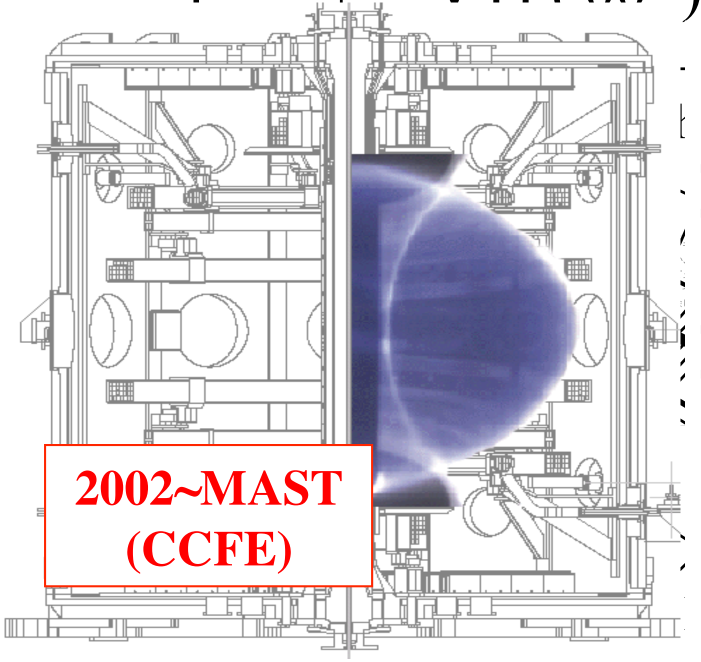




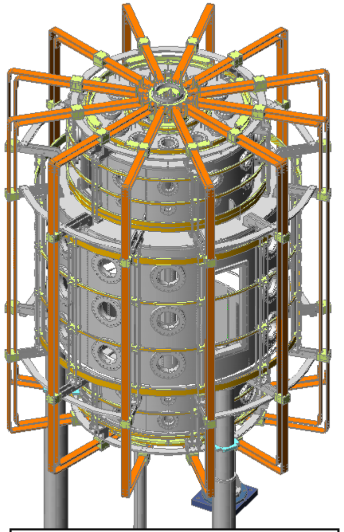
Internal Coil

TS-3('90~), TS-4('00~), SSX, MRX('95~)

Swift-FRC ('01~), SPRIT



2002~MAST
(CCFE)



2011~?
VEST (SNU)

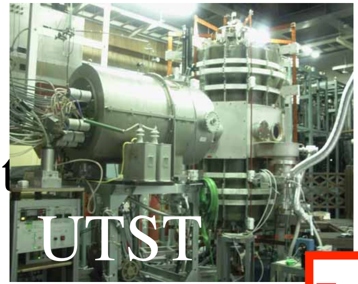
2004~ UTST
(U.Tokyo)

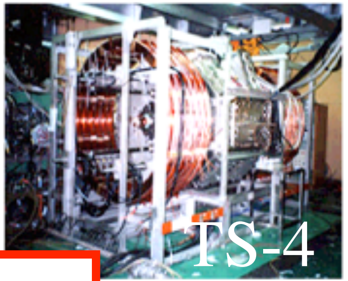
('96~)

Flux

US-J Joint Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas (CMSO)

1) International COE of Magnetic Reconnection and Magnetic Self-Organization including beam dynamics
2) Collaboration of US NSF and Japan JSPS COE Project
3) Interdisciplinary COE among lab., observation, theory
4) Borderless exchange/ education of young scientists

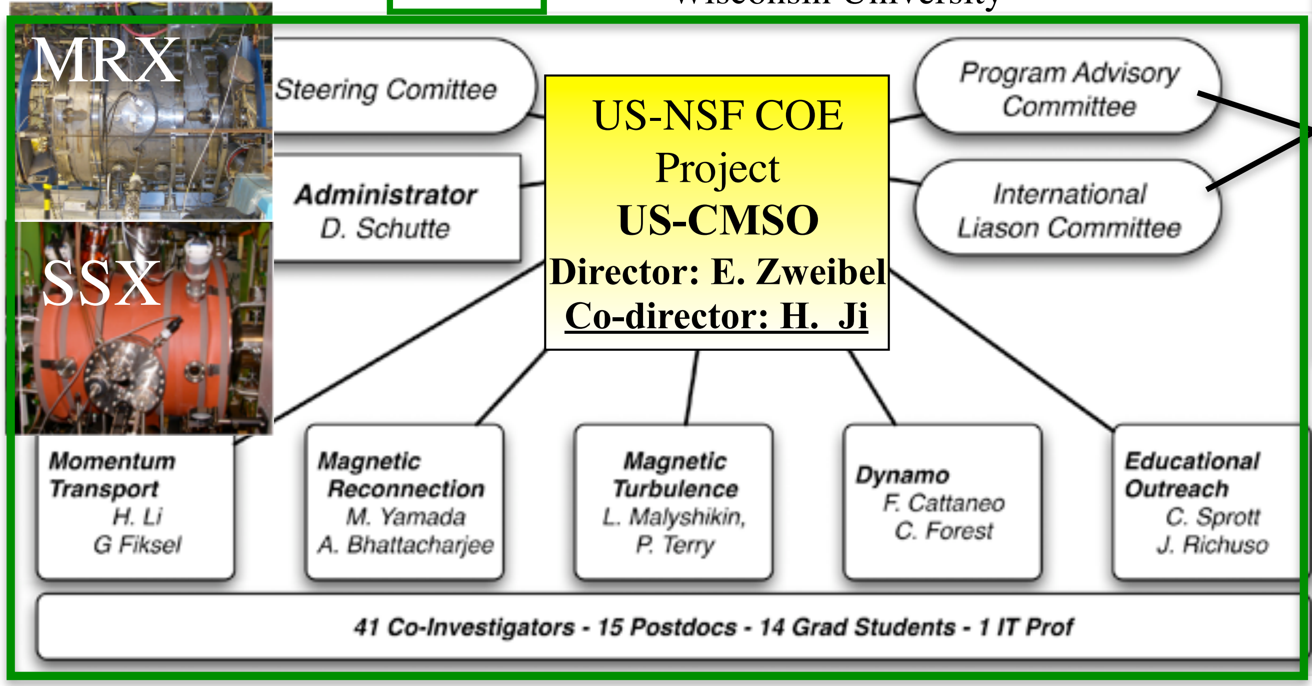




COE: Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas (CMSO)

US

Core：Princeton Univrsity
Wisconsin University



Steering Comittee

Program Advisory Committee

US-NSF COE Project
US-CMSO
Director: E. Zweibel
Co-director: H. Ji

Administrator
D. Schutte

International Liason Committee

Momentum Transport
H. Li
G Fiksel

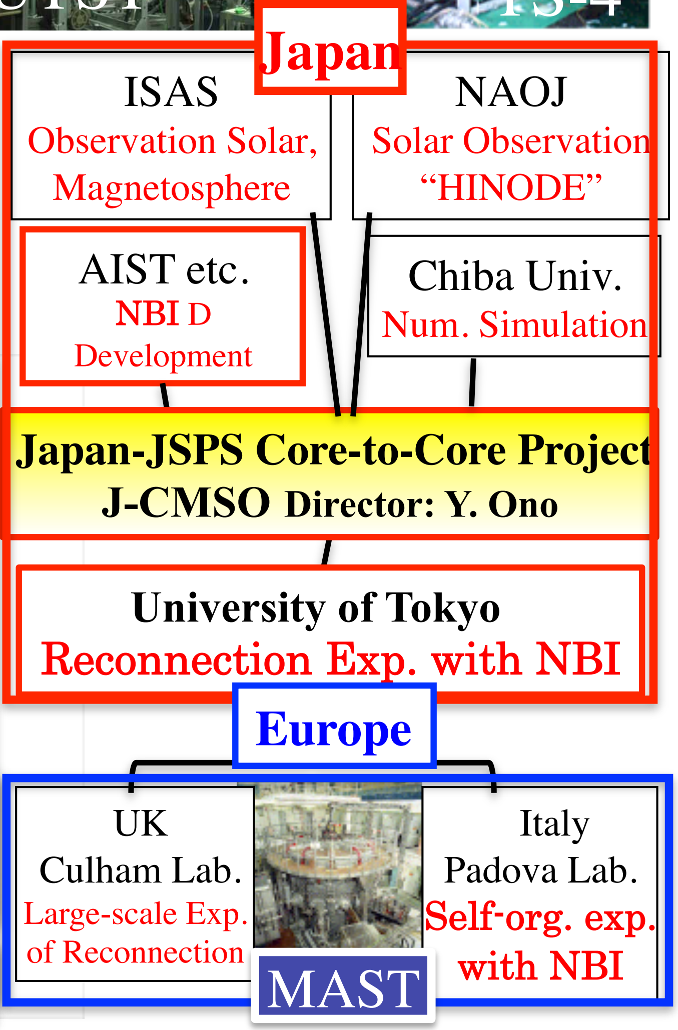
Magnetic Reconnection
M. Yamada
A. Bhattacharjee

Magnetic Turbulence
L. Malyshikin,
P. Terry

Dynamo
F. Cattaneo
C. Forest

Educational Outreach
C. Sprott
J. Richuso

41 Co-Investigators - 15 Postdocs - 14 Grad Students - 1 IT Prof



Japan

ISAS
Observation Solar, Magnetosphere

NAOJ
Solar Observation "HINODE"

AIST etc.
NBI D Development

Chiba Univ.
Num. Simulation

Japan-JSPS Core-to-Core Project
J-CMSO Director: Y. Ono

University of Tokyo
Reconnection Exp. with NBI

Europe

UK
Culham Lab.
Large-scale Exp. of Reconnection

Italy
Padova Lab.
Self-org. exp. with NBI

Contents

● Mechanism for reconnection heating?

2-D T_e measurement by electrostatic probe

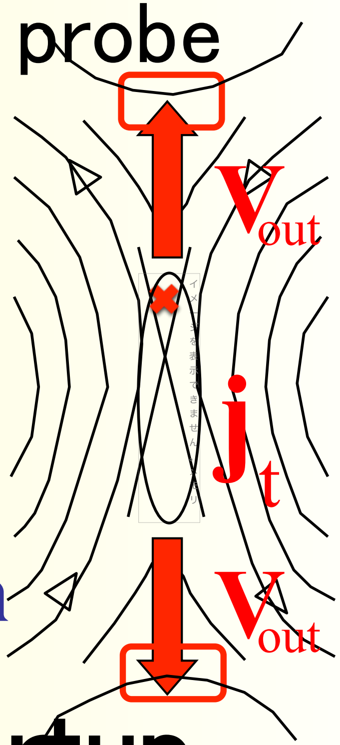
Sheet current heating of T_e

2-D Doppler T_i measurement

Outflow heating of T_i

1-D T_i, V_i probe, CO2 Interferometer

Fast shock in the downsteam area



●Application to high-ß ST startup

Scaling study of reconnection heating

High-beta ST formation in TS, UTST, MAST

TS-3 Spherical Torus Merging Device

The first merging ST device since 1985

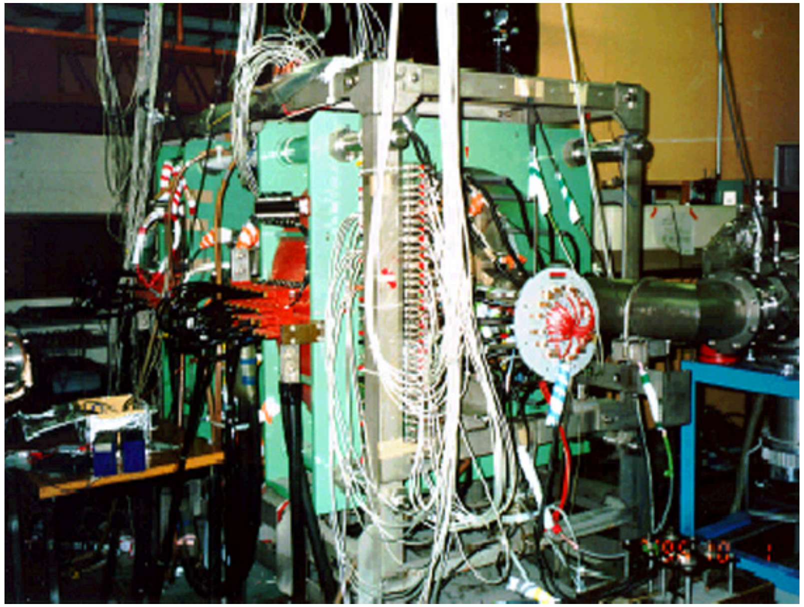
U. Tokyo, Nihon-U, Osaka-U., NAOJ, ISAS

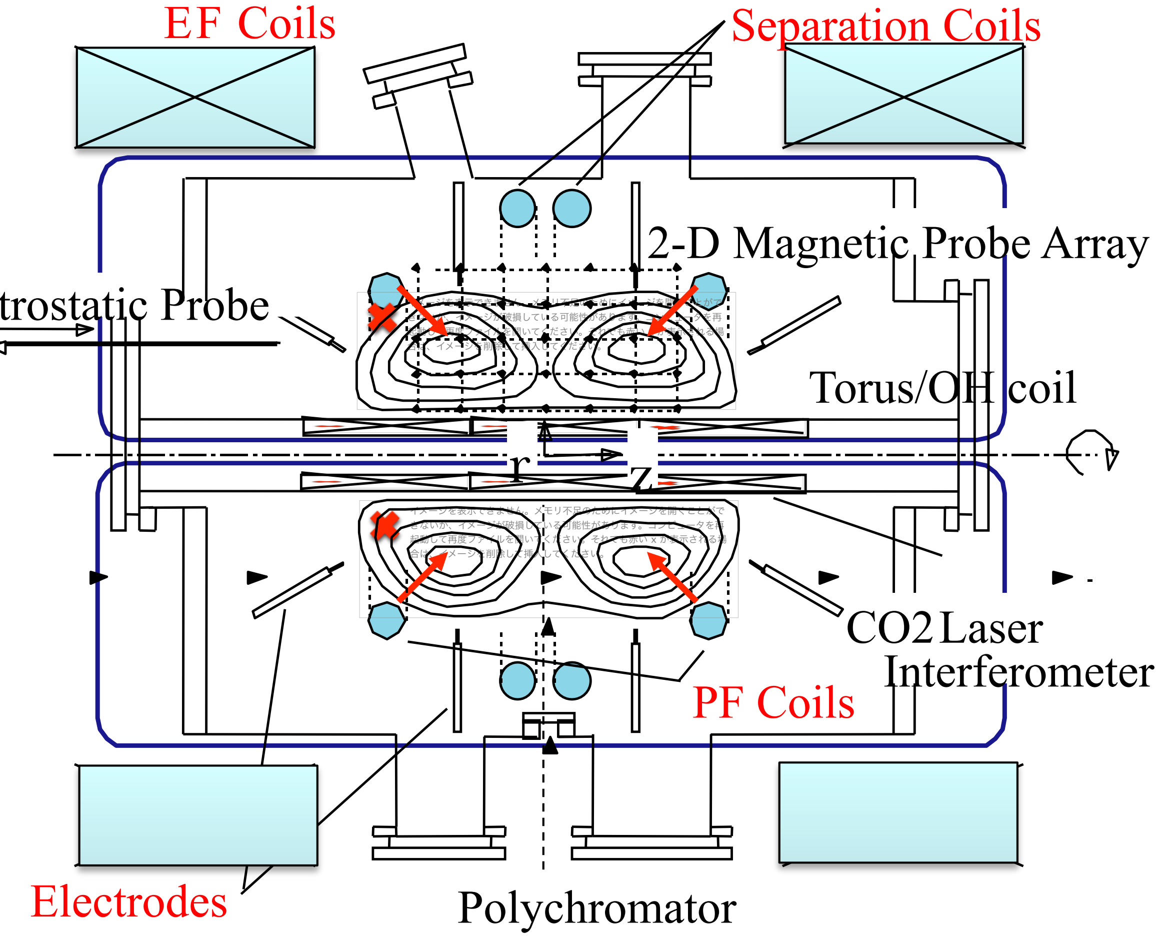
R=0.15-0.22m , R/a=1.6

B_0~.5kG, Ti=10-100eV ,

T_e=10-30eV ,

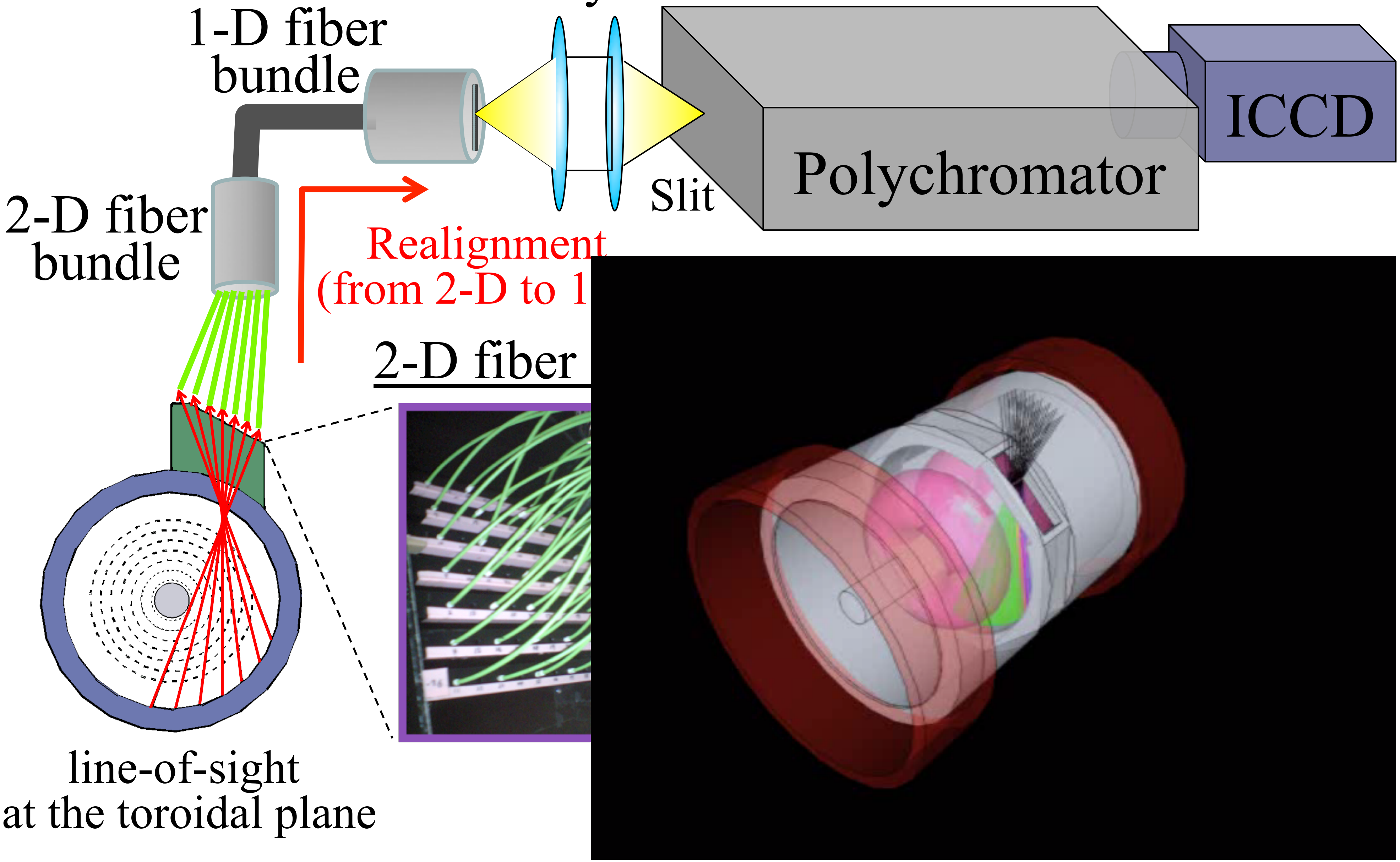
n_e=0.5-1.×$10^{20}m^{-3}$





2-D Doppler Measurement System

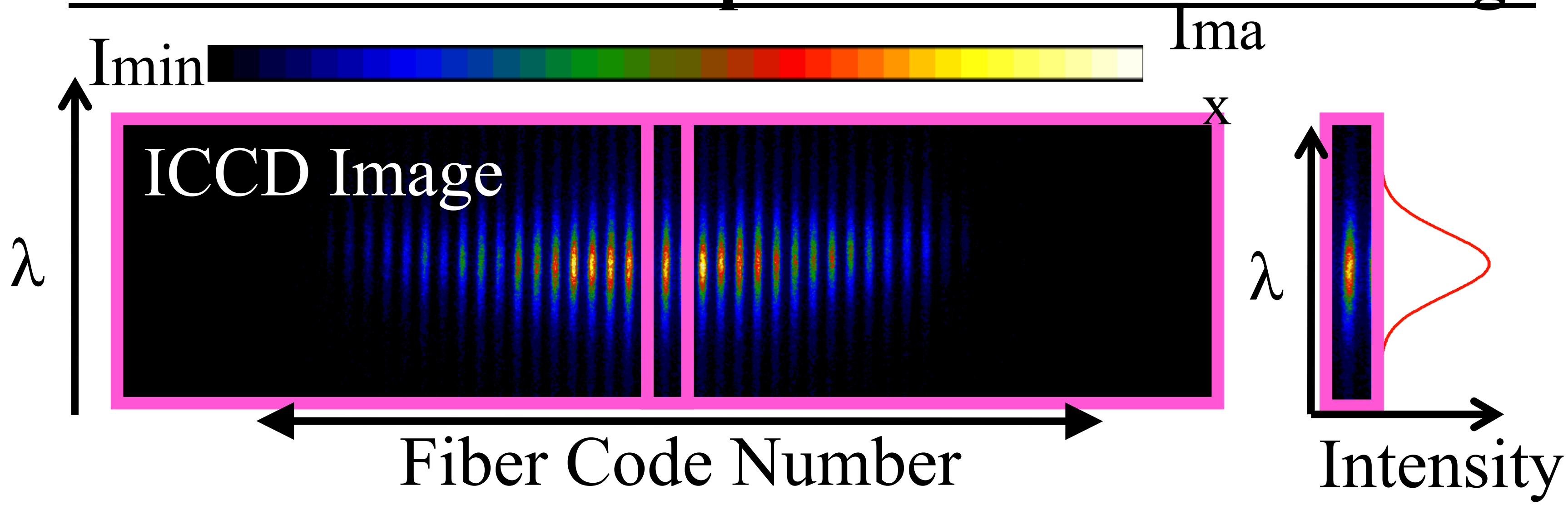
2011 RSI by Tanabe et al.

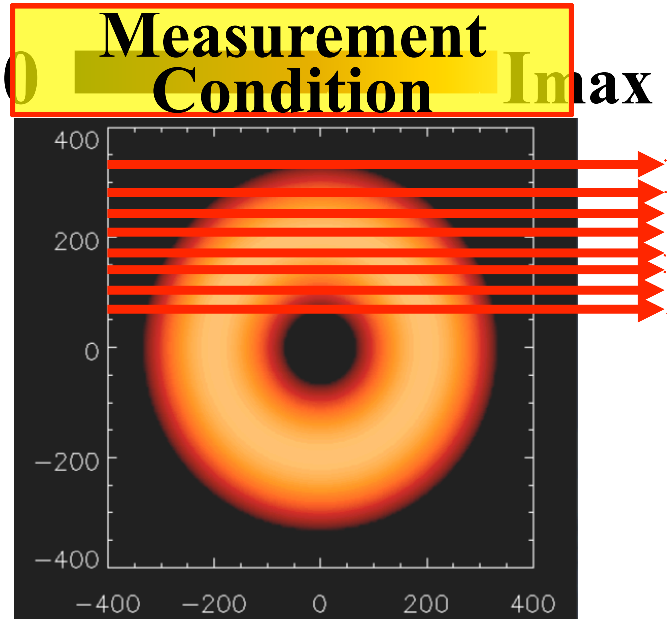


line-of-sight
at the toroidal plane

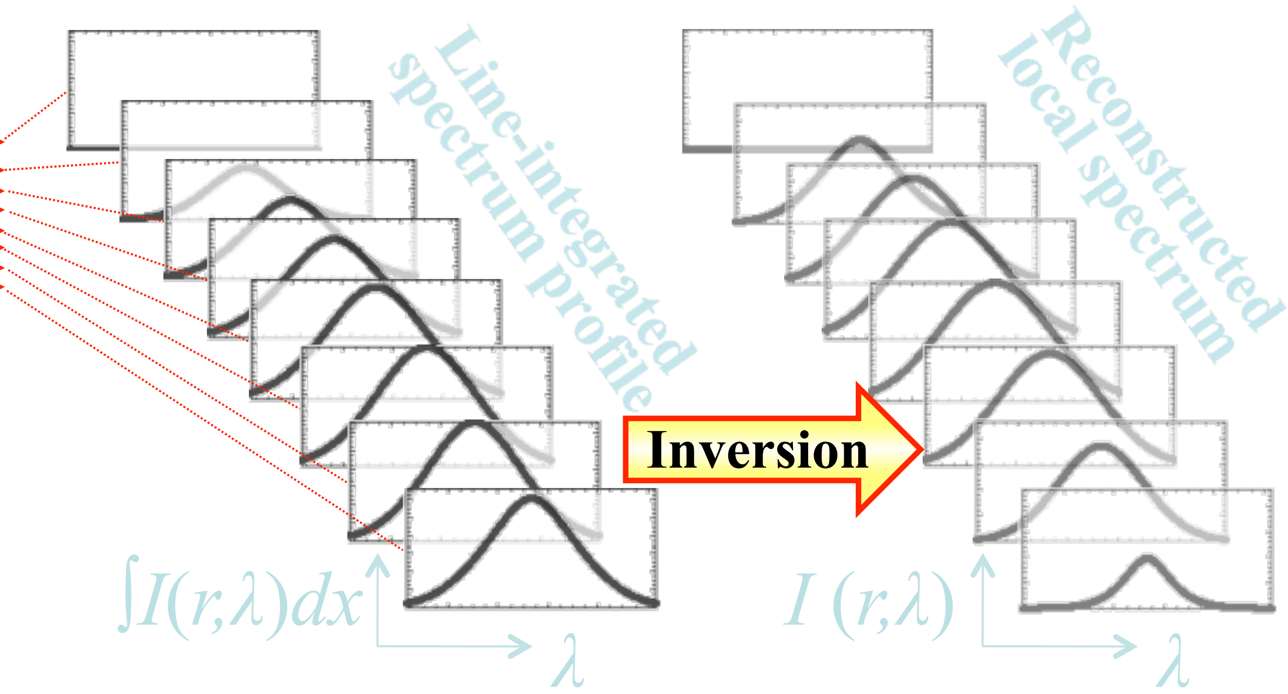
ICCD Image Reconstruction to measure 2-D T_i Profile

1. Extract each code spectrum from ICCD Image





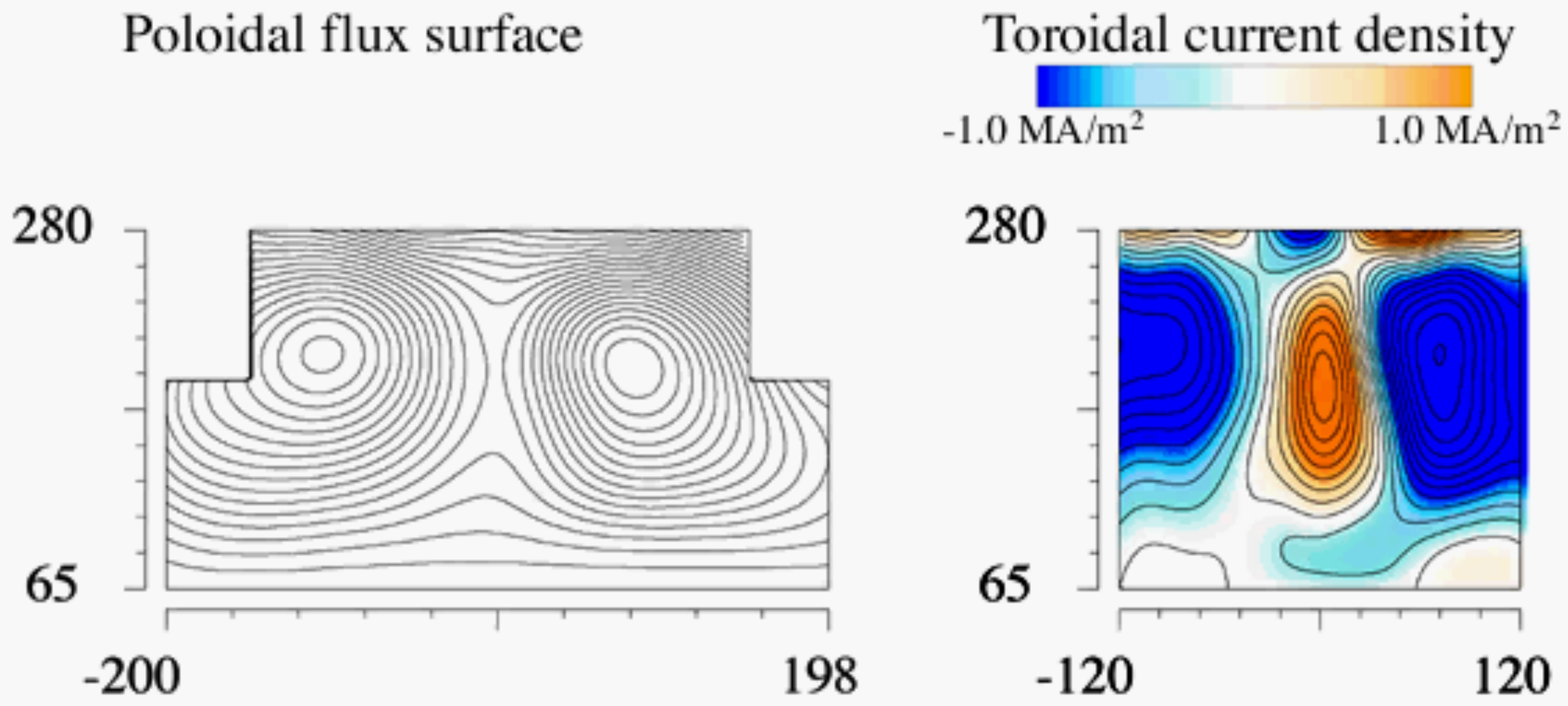
imitated emission profile



Merging of two STs produced by PF coil induction

High power heating of merging supresses paramag. B_t of ST, increasing ß quickly / significantly.

(contour spacing 0.5[mWb])



Poloidal flux surface

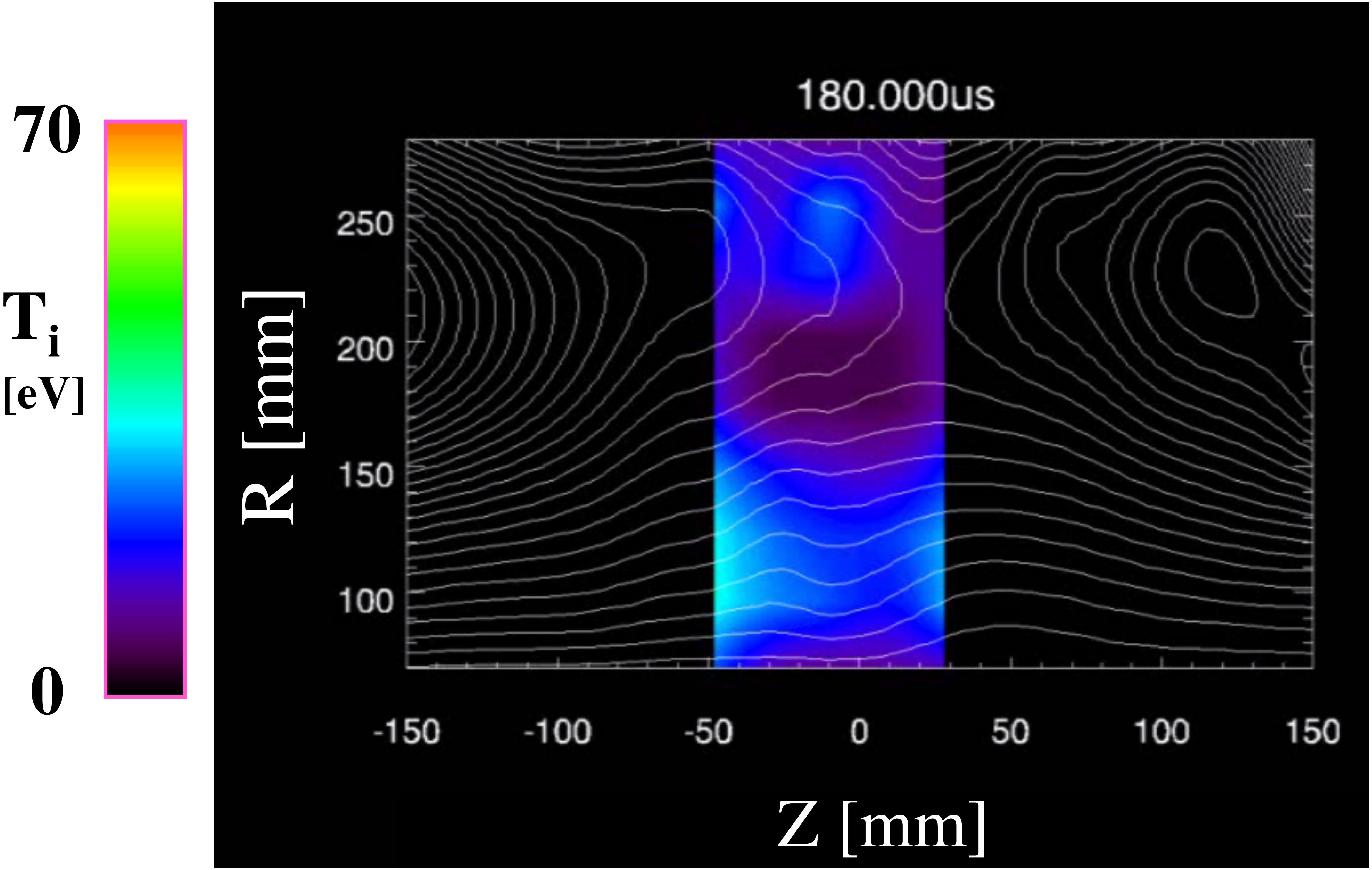
Toroidal current density

Large external force (Ipf=20kA)

Sheet ejection

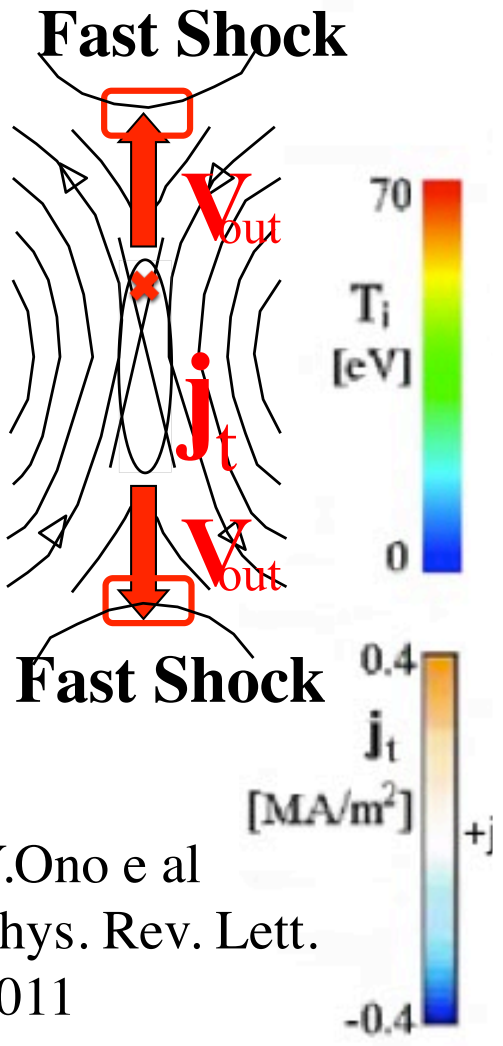
Time 42.0 [μsec]

Measured 2-D Ti Profile during Counter Helicity Merging of Two Spheromaks



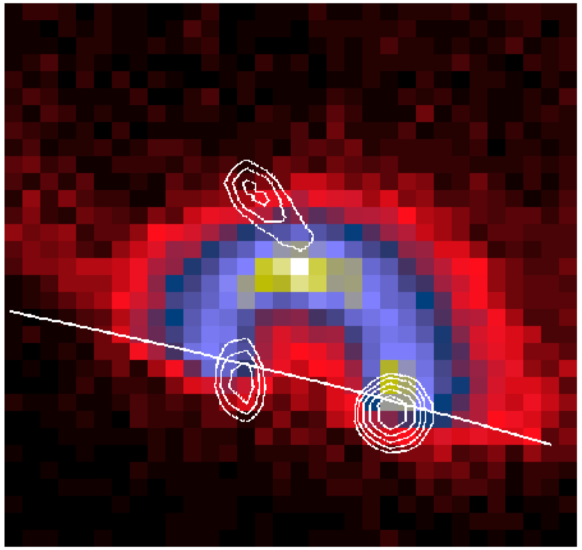
First 2-D measurement of Ti

Clear evidence of ion heating by outflow!

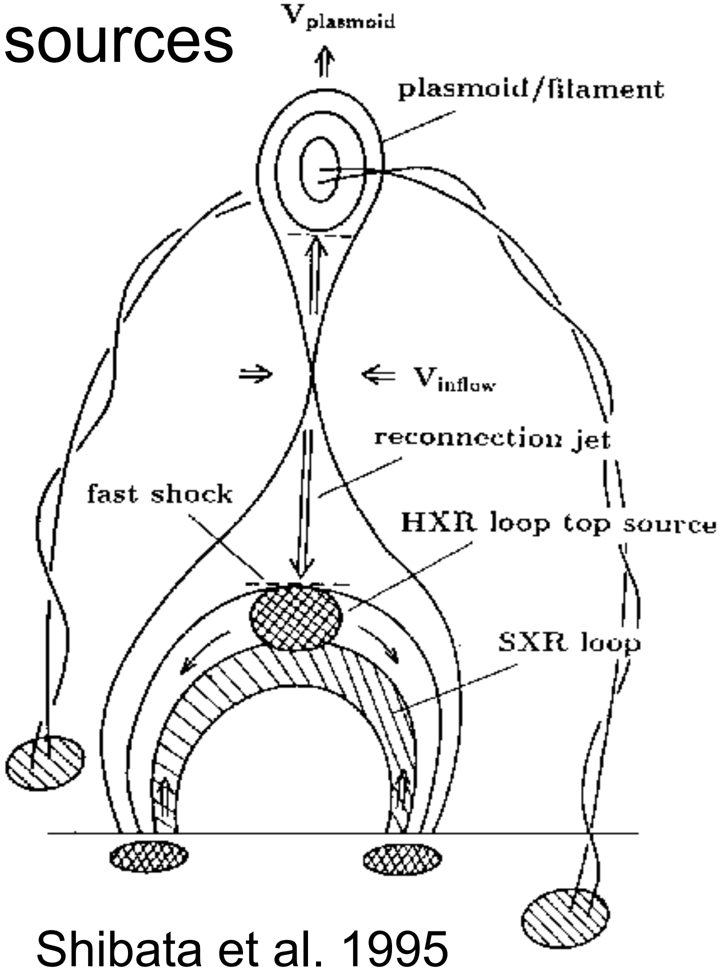


Y.Ono e al
Phys. Rev. Lett.
2011

Loop top hard X-ray sources



Masuda et al. 1994

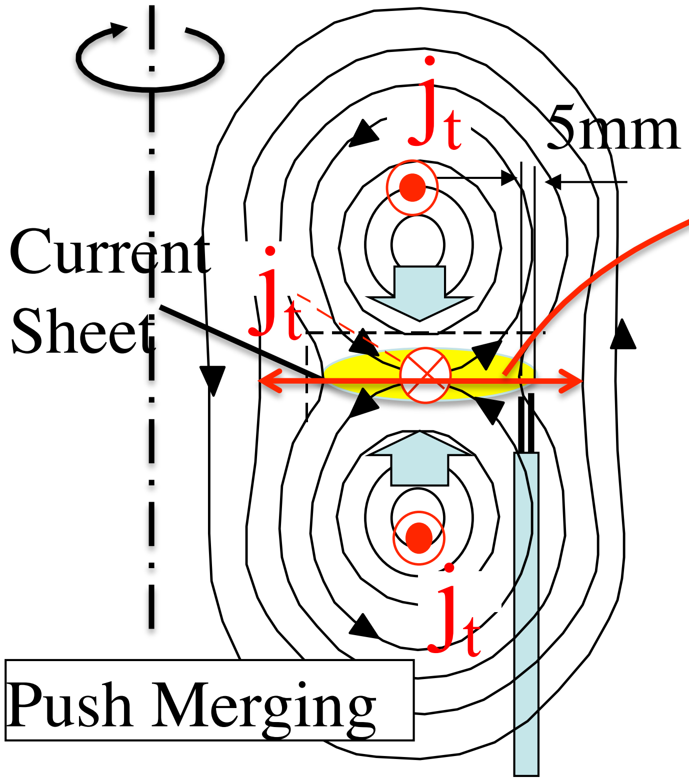


Shibata et al. 1995

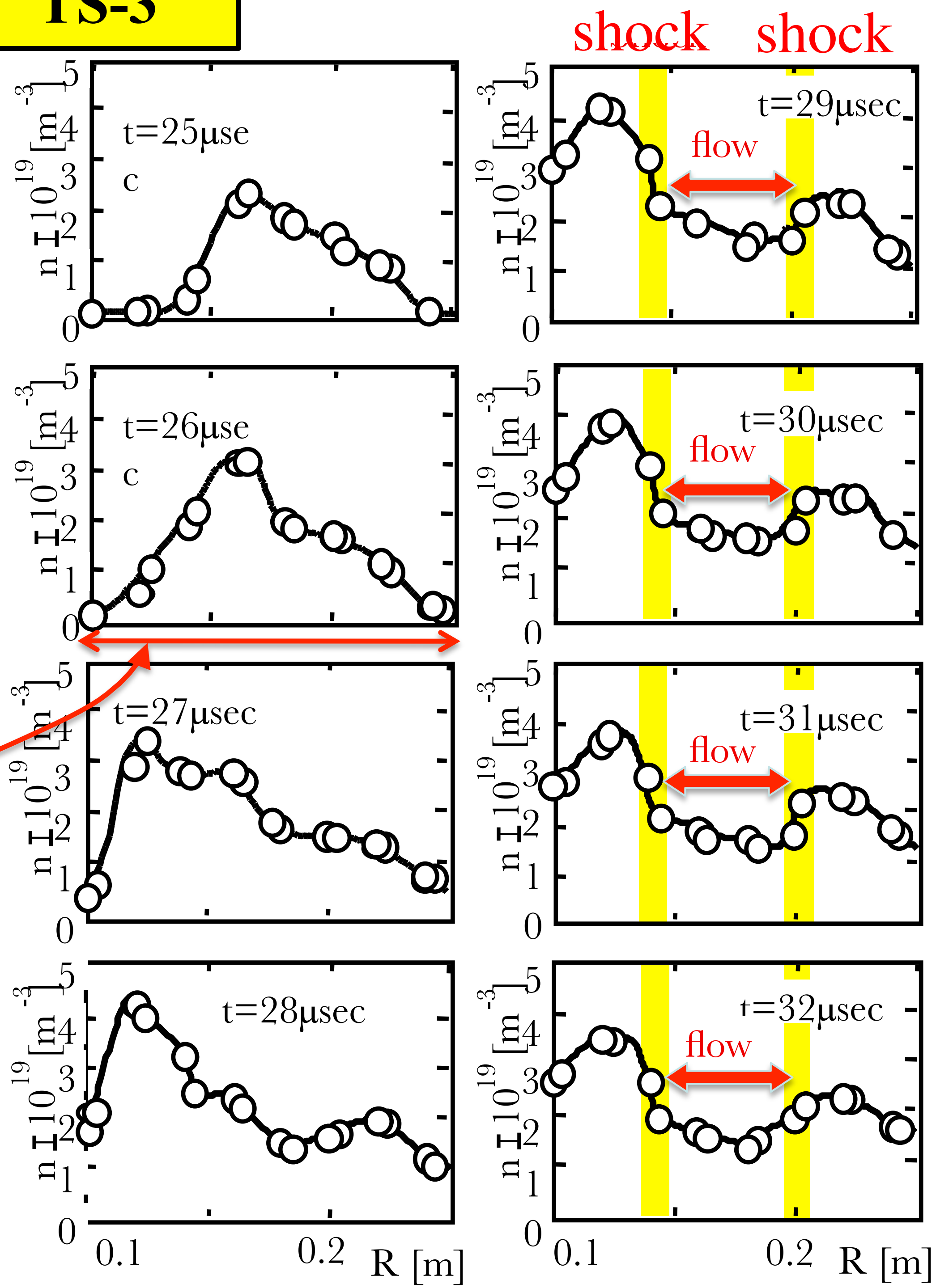
30μs 35μs 60μs

Evidence of Fast Shock

High resolution n_e measurement by pair double probes

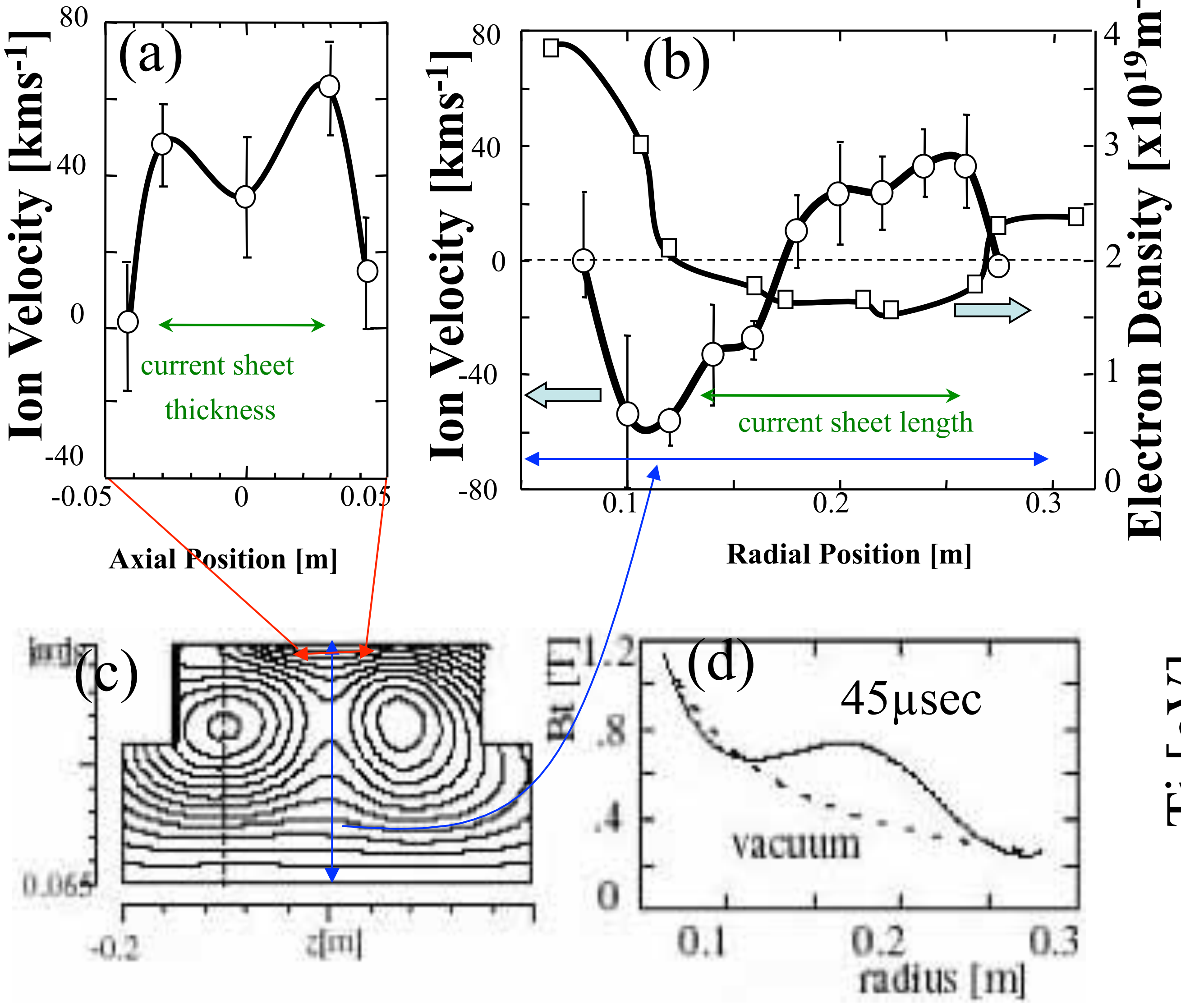


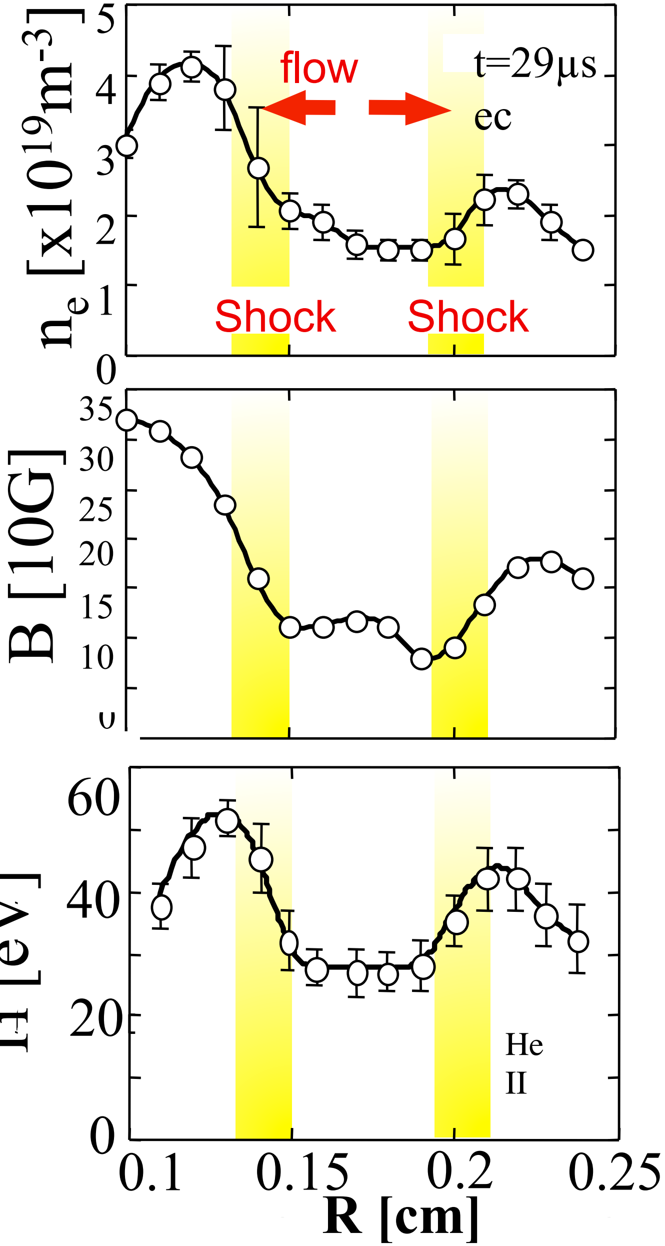
TS-3



At down-stream, hot T_i spot, steep increase in n_e and dumping of Ion flow are observed, indicating formation of fast shock .

$$n_1/n_2=B_1/B_2=v_1/v_2,$$
$$n_1/B_1=n_2/B_2$$

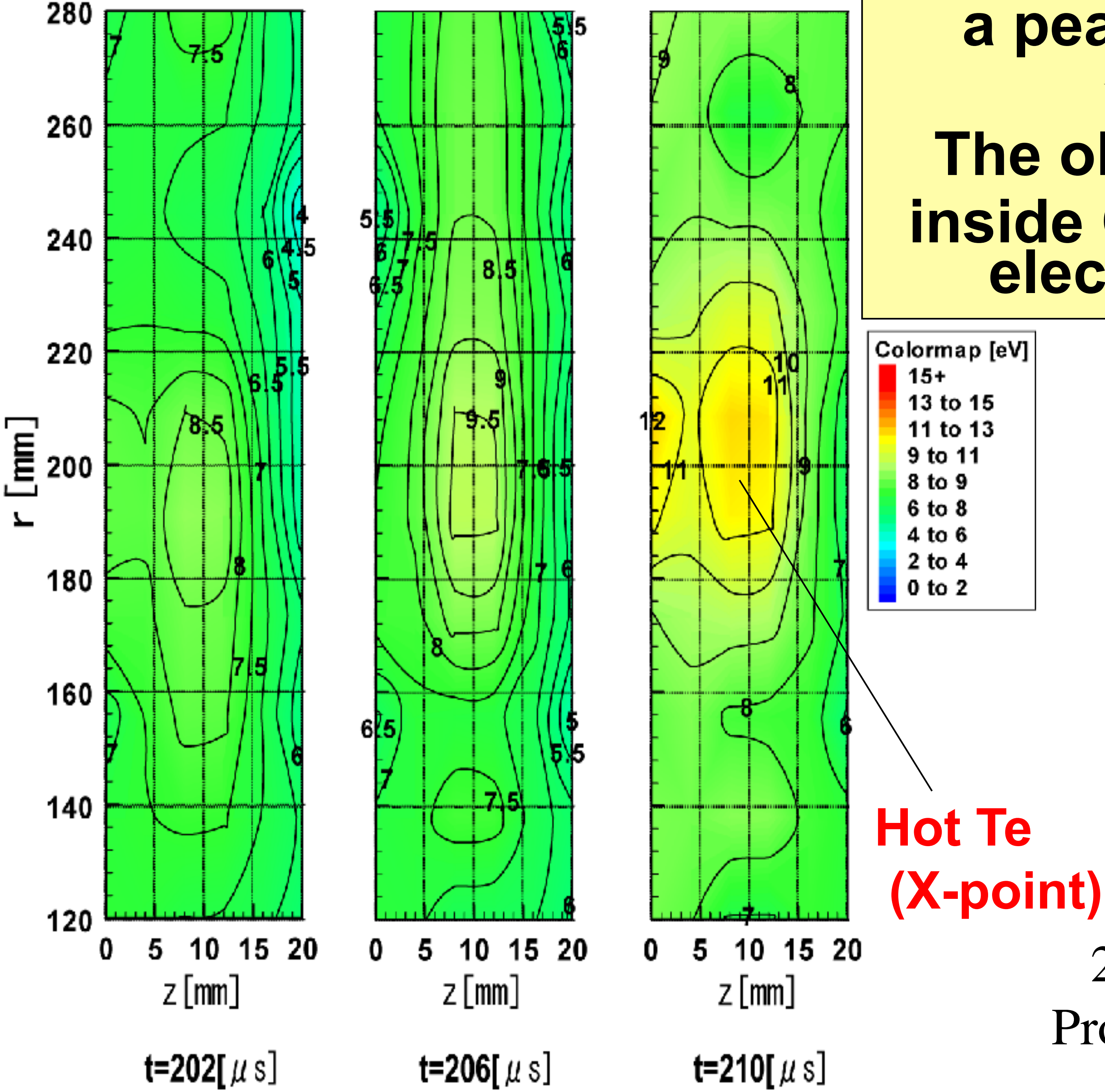


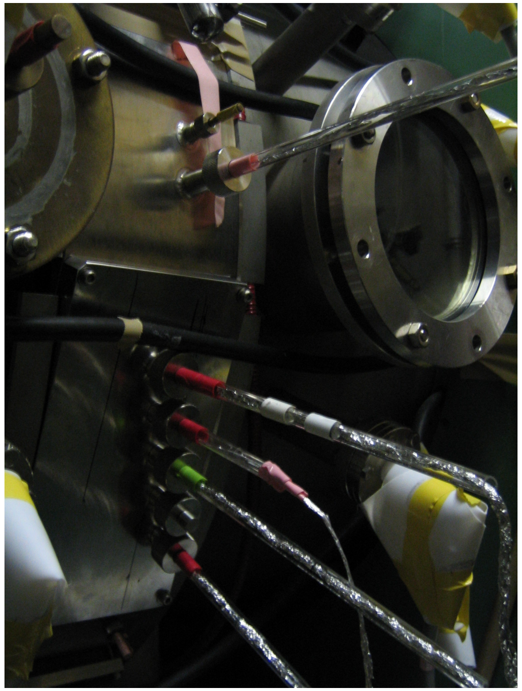


Te Profile

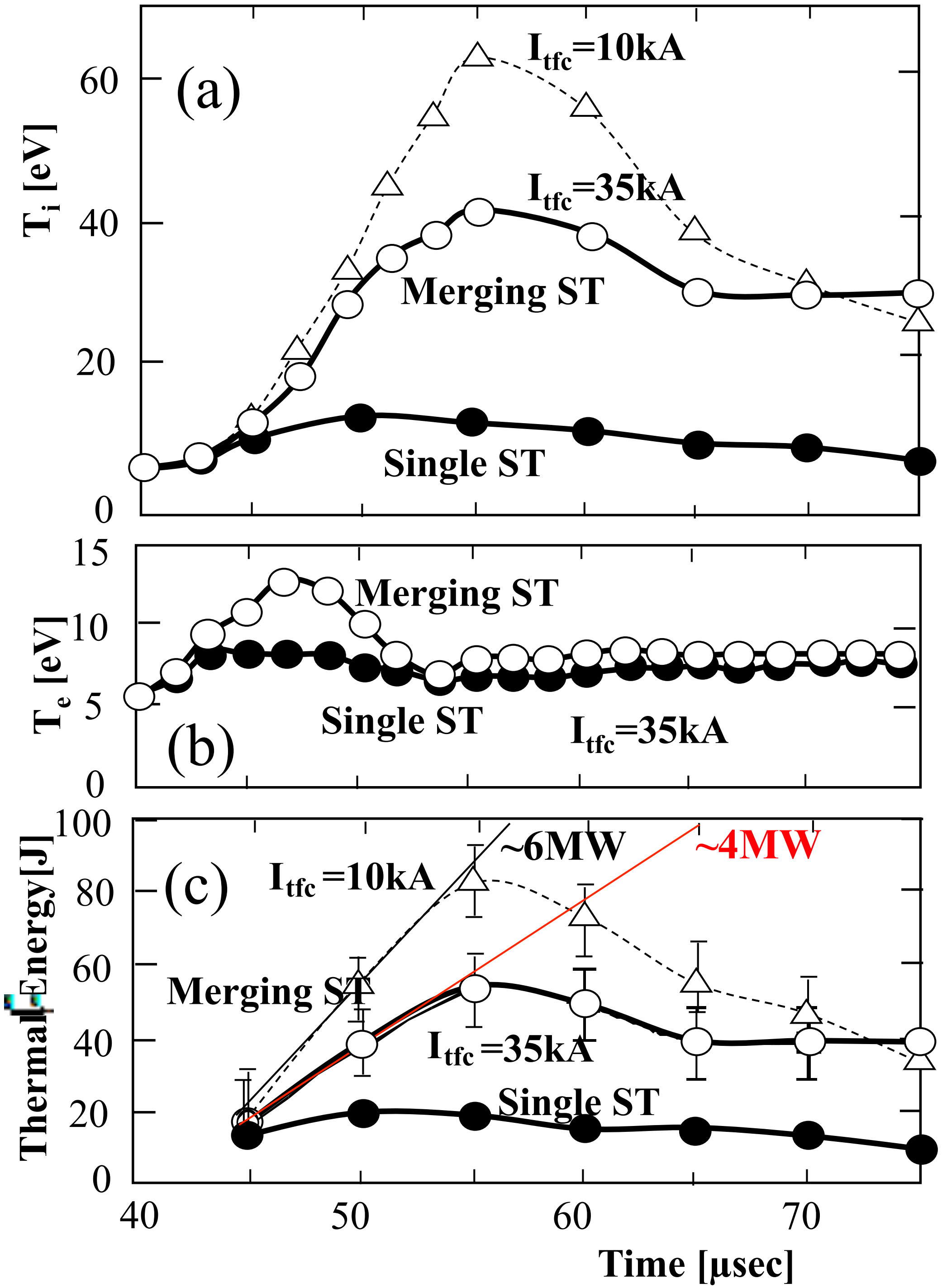
The current sheet has a peaked T_e profile。

The ohmic heating inside CS causes its electron heating.

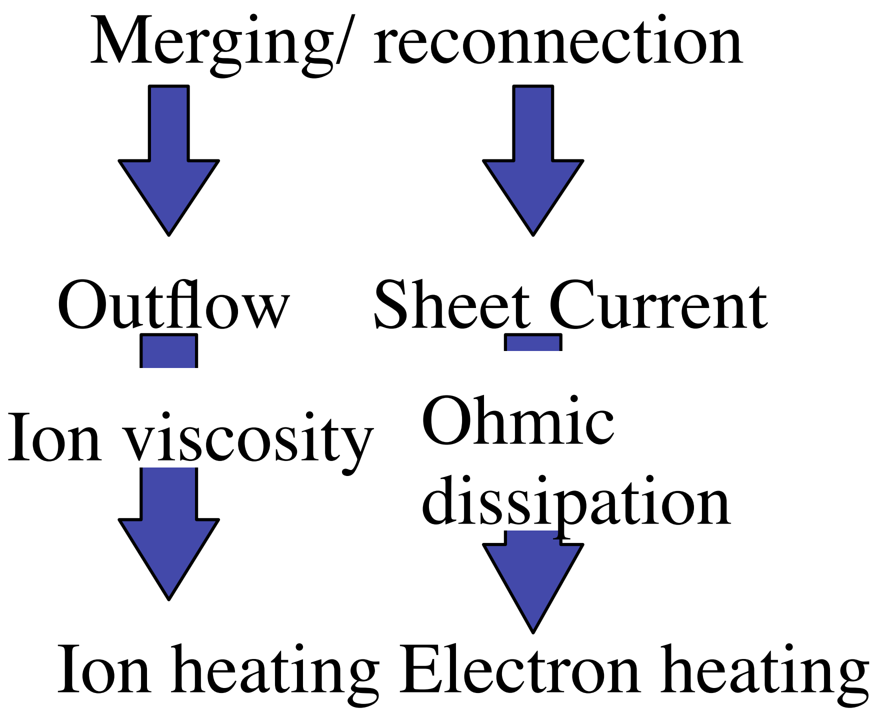




2-D Electrostatic
Probe measurements



Heating power of ST merging is as high as 10MW for half kG STs



Merging/ reconnection

Outflow

Ion viscosity

Ion heating

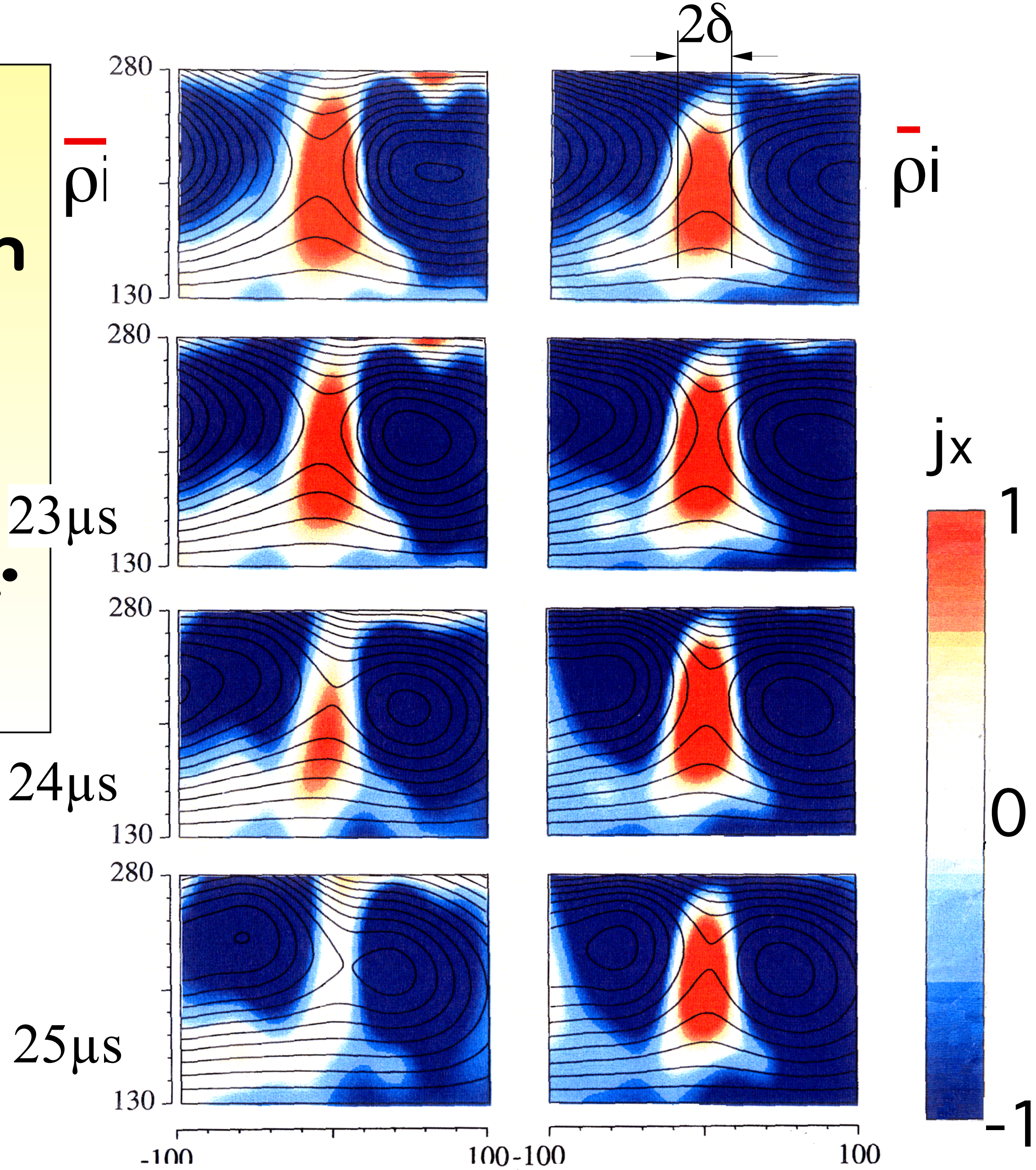
Sheet Current

Ohmic dissipation

Electron heating

The ion heating power and energy decreases with B_t

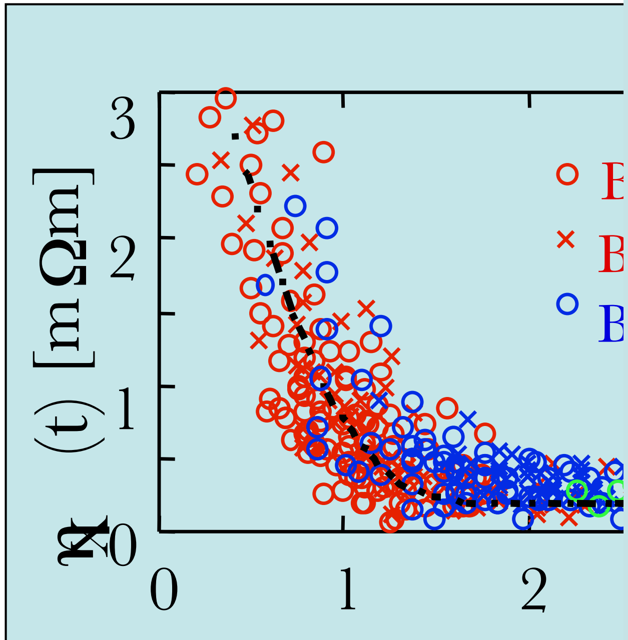
The reconnection (outflow) speed increases with ρ_i and inversely with B_z.



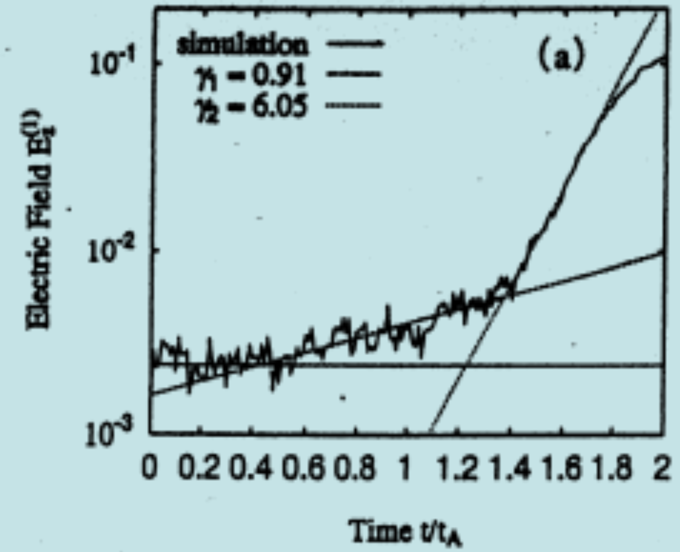
(a) $B_t \approx B_{//}$ (b) $B_t \approx 3B_{//}$

2-D contours of flux-surfaces and jt for reconnections with $Bz \approx B_{//}$ and $Bz \approx 3B_{//}$.

1) Plasmoid Eje
Transition to inter
reconnection in
averaged rec. sp



Large



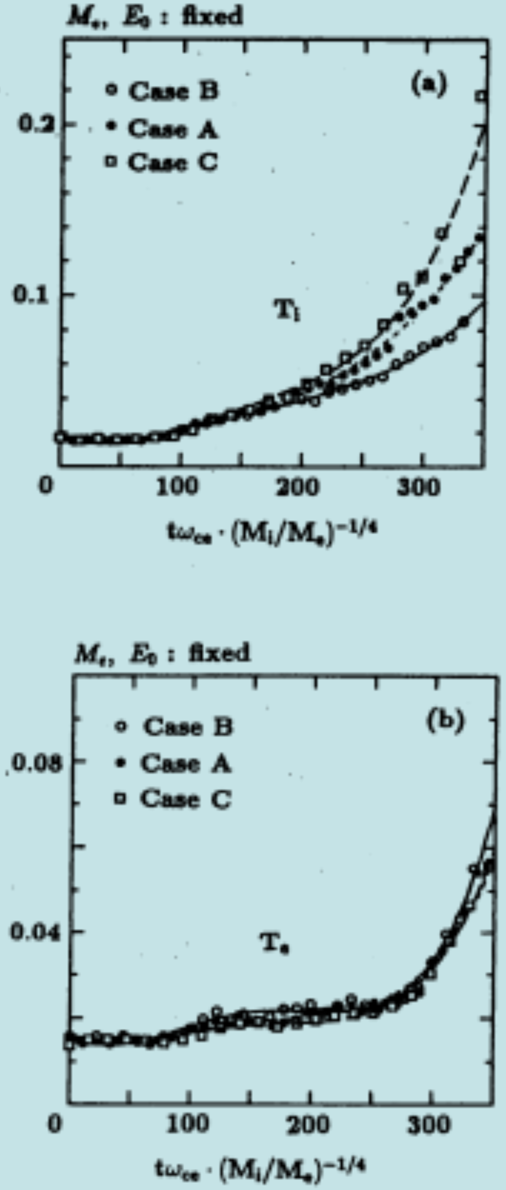
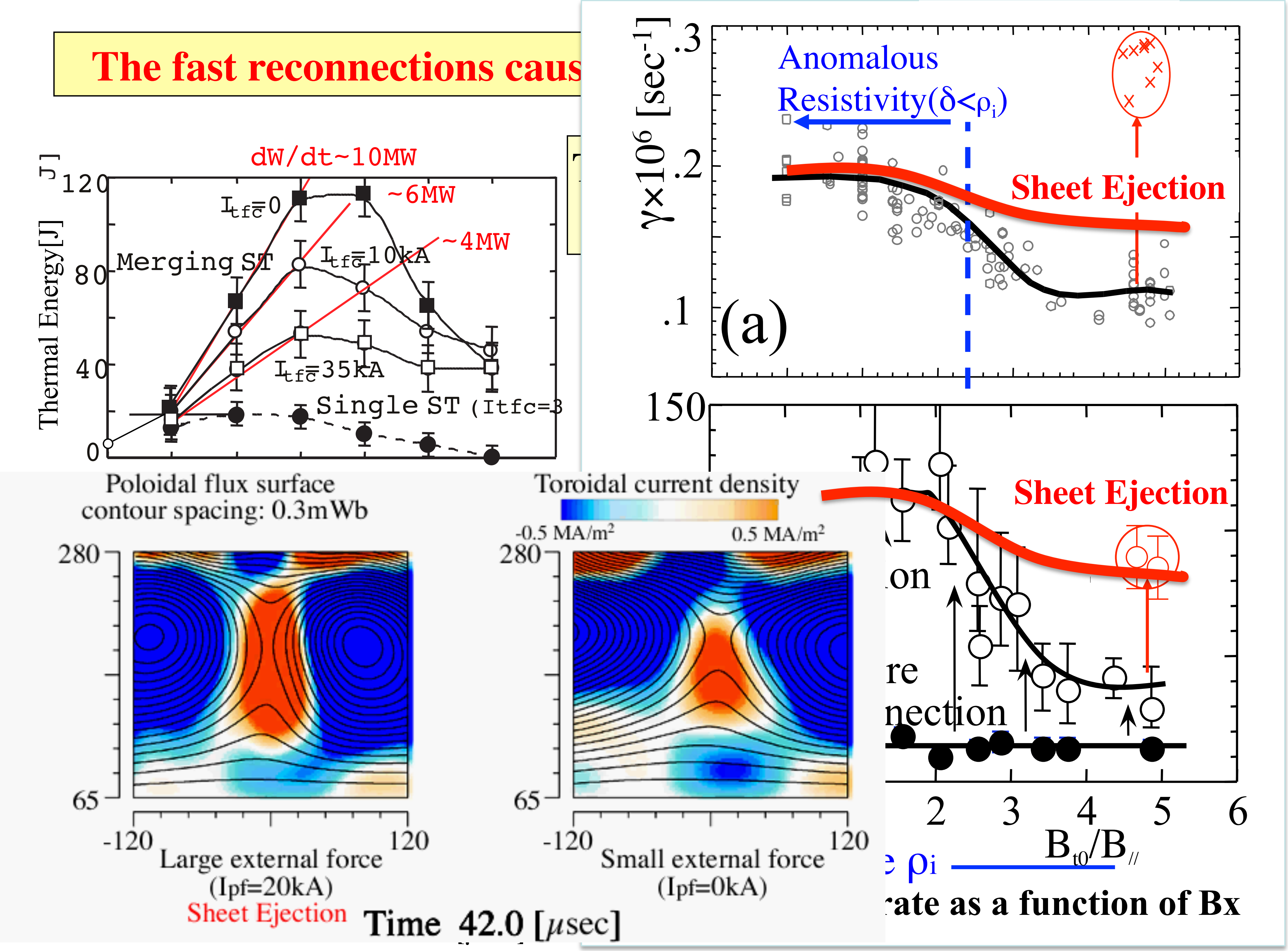


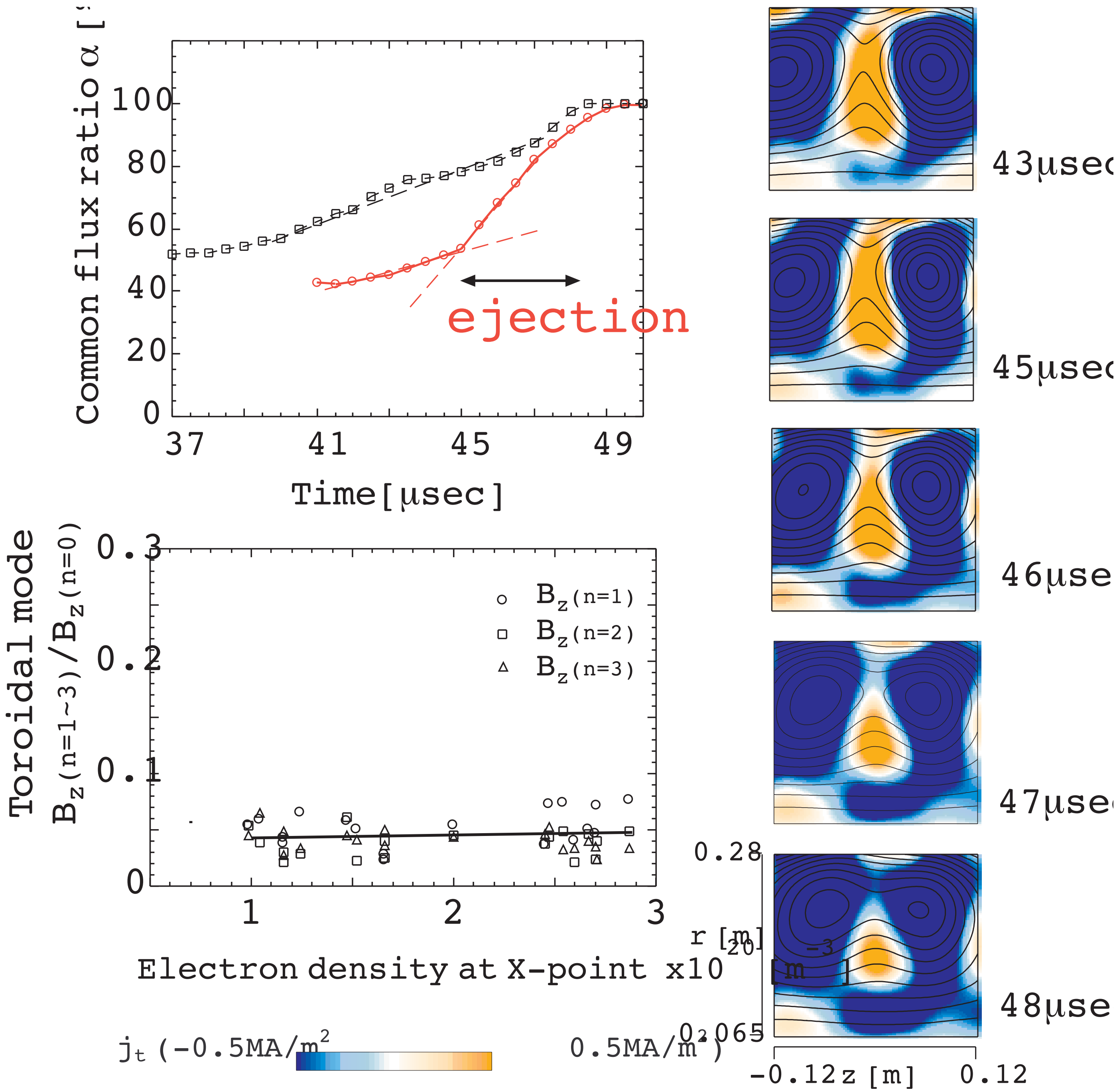
FIG. 10. Temporal evolutions of (a) the ion temperature and (b) the electron temperature at the reconnection point for the same cases as Fig. 8, where an open circle, a closed circle, and an open square correspond to the simulation results for case B, case A, and case C, respectively.

Horiuchi, Sato, Phys. Plasmas 1 (11), 3597, (1994).

The fast reconnections caus



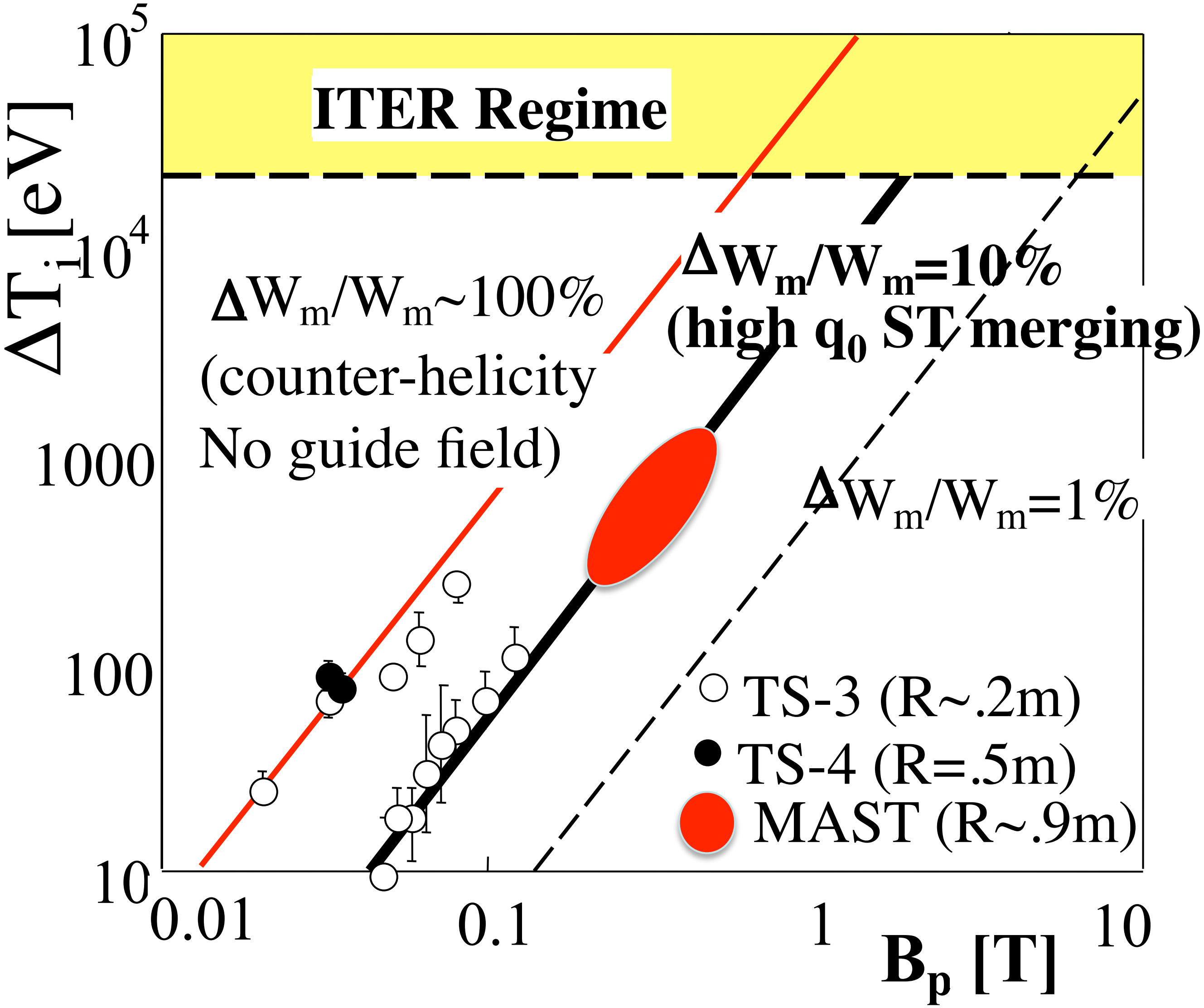
Toroidal symmetry of plasma was maintained during the sheet ejection.



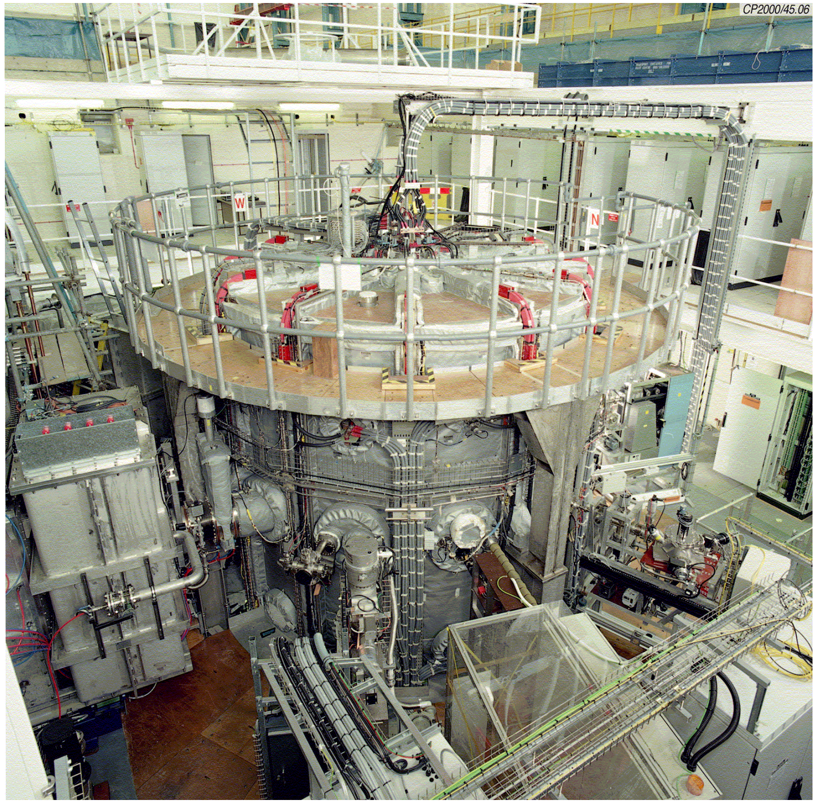
The B^2-scaling holds true for the merging/ reconnection heating with arbitrary guide field B_t.

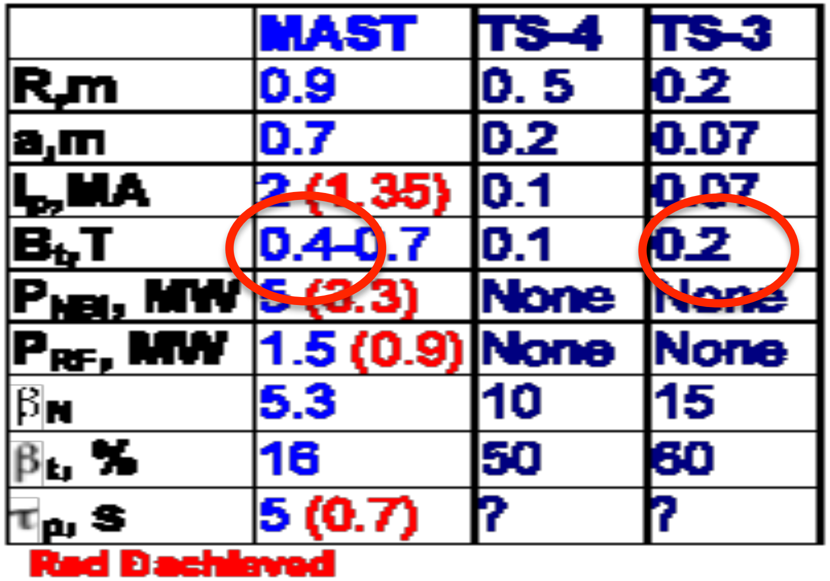
$\Delta W_i =$
$= \alpha\beta\int B^2/2\mu_o dv$
$\sim 0.8\beta W_m$
where $\beta \sim 0.5$ (FRC)
-0.1 (high-q ST).

An additional complete merging will increased ΔW_i by another 5-10%.



TS-3,TS-4 and MAST Parameters





	MAST	TS-4	TS-3
R,m	0.9	0. 5	0.2
a,m	0.7	0.2	0.07
I_p,MA	2 (1.35)	0.1	0.07
B_t,T	0.4-0.7	0.1	0.2
P_{NBI}, MW	5 (3.3)	None	None
P_{RF}, MW	1.5 (0.9)	None	None
β_N	5.3	10	15
β_t, %	16	50	60
τ_p, s	5 (0.7)	?	?

Rad Dachieved

Formation methods used:

- merging-compression (Reconnection Startup)
- direct induction (Center Solenoid Startup)

Pre-ionisation methods and tools used:

- ECR pre-ionisation
- EBW current formation
- NBI pre-ionisation
- UV lamp, TS laser, hot filaments
- combination of these

From MAST data (UKAEA, Gryaznevich)

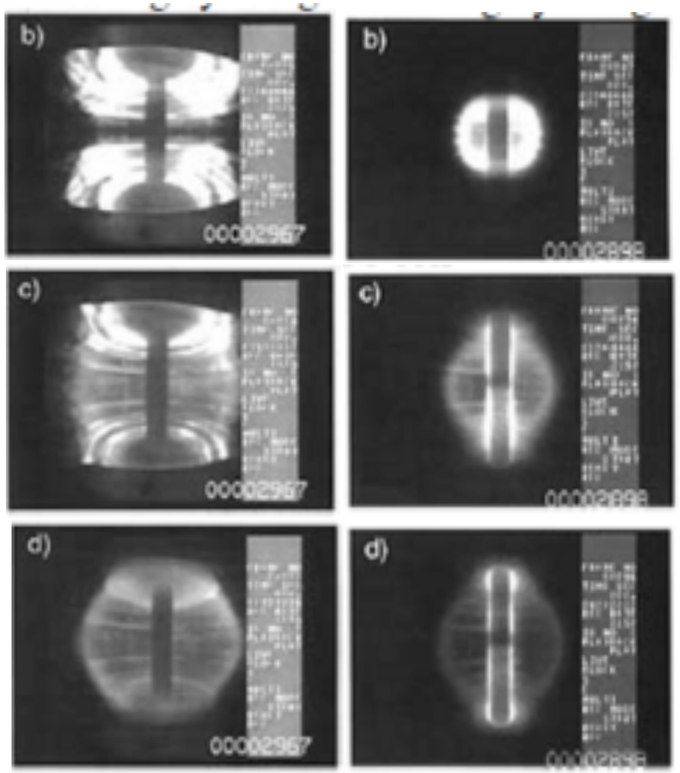
MAST

T. Yamada et al 29-1-1

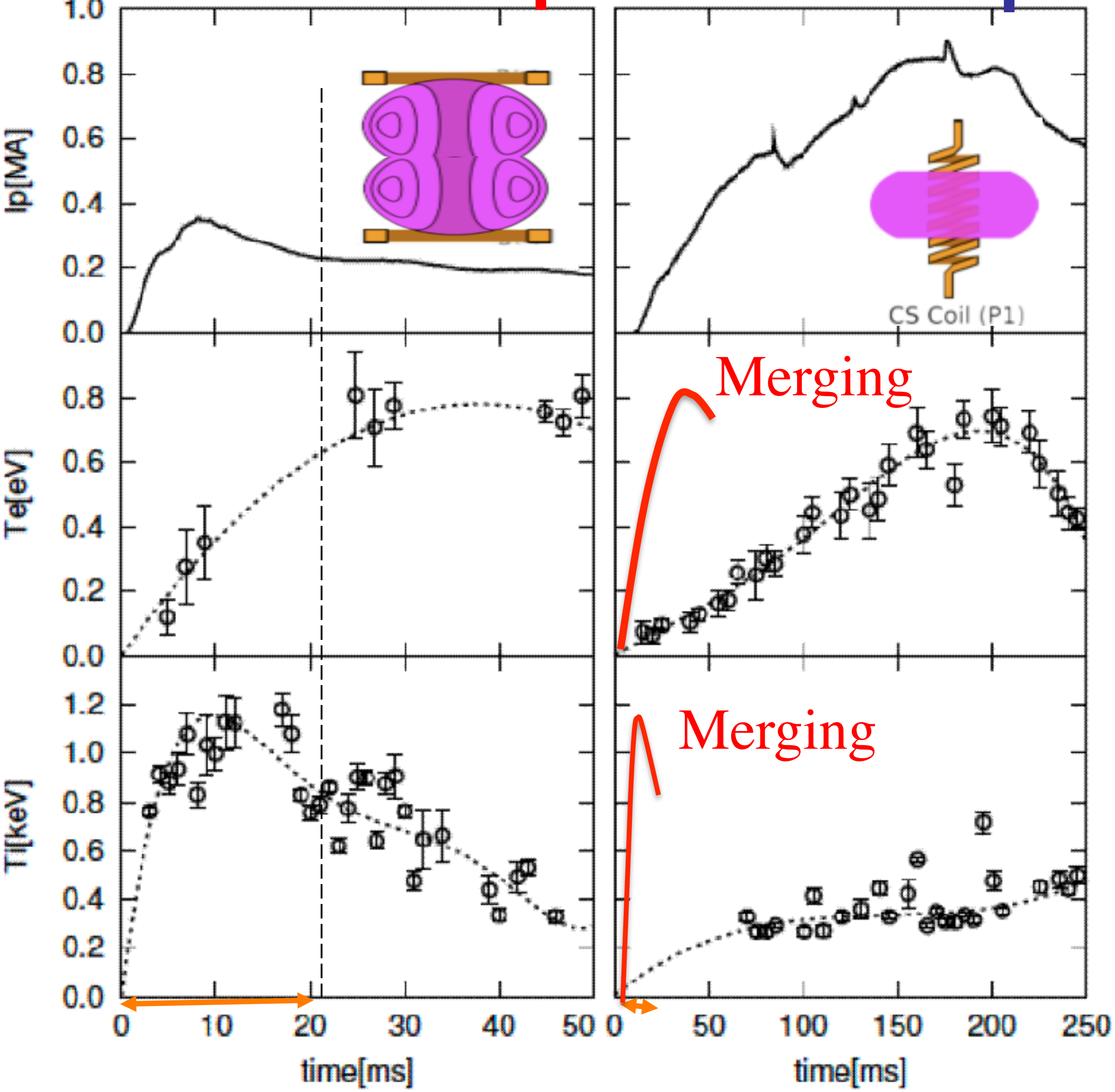
MAST-TS Collaboration

The reconnection start-up heats ions and electrons much faster than the conventional CS startup.

Rec. startup **CS startup**



Rec. startup **CS startup**



Comparison with Troyon Scaling

TS-3, 4

ST

merging :$\beta_N < 10$

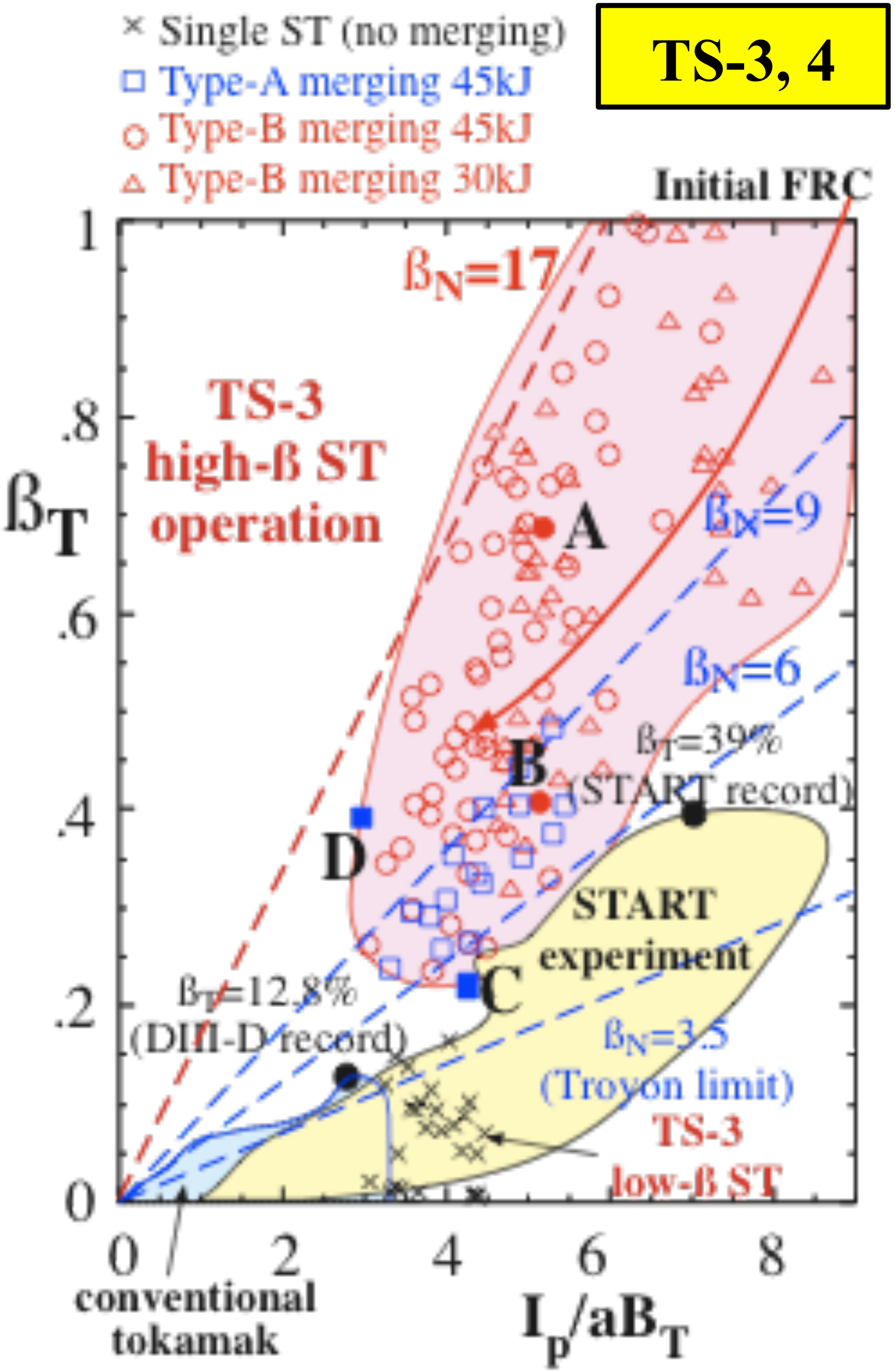
C: 1st stable

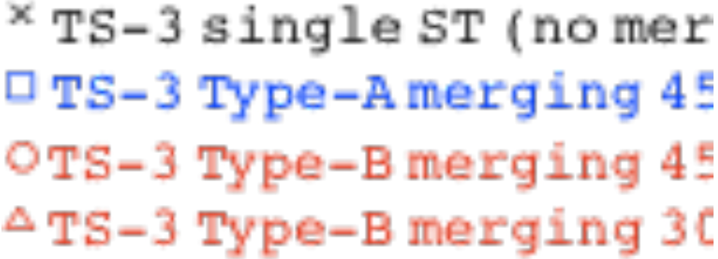
D: unstable

FRC tarns: $\beta_N < 20$

A: 2nd stable

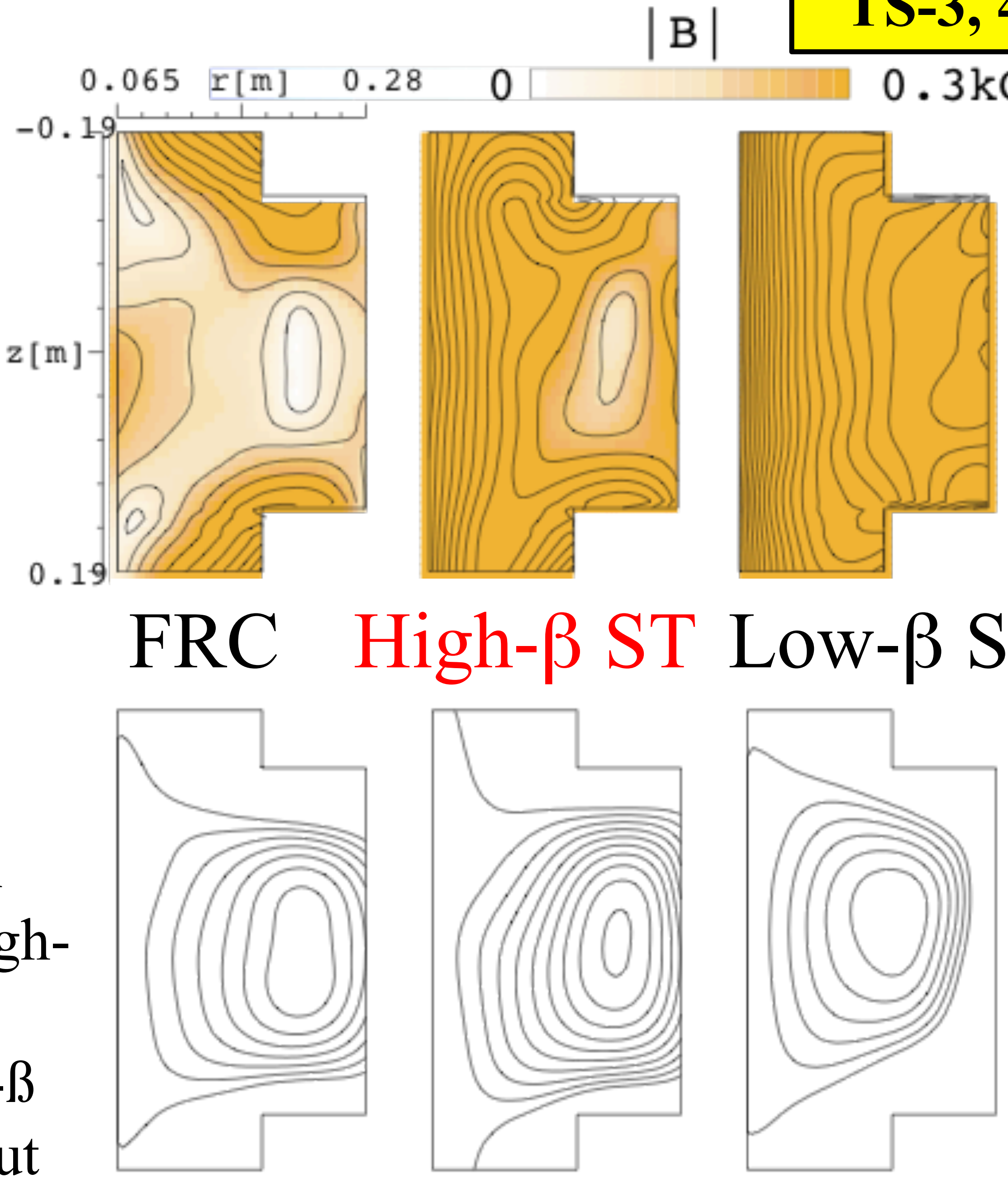
B: unstable




× TS-3 single ST (no mer
□ TS-3 Type-A merging 45
○ TS-3 Type-B merging 45
△ TS-3 Type-B merging 3

TS-3, 4

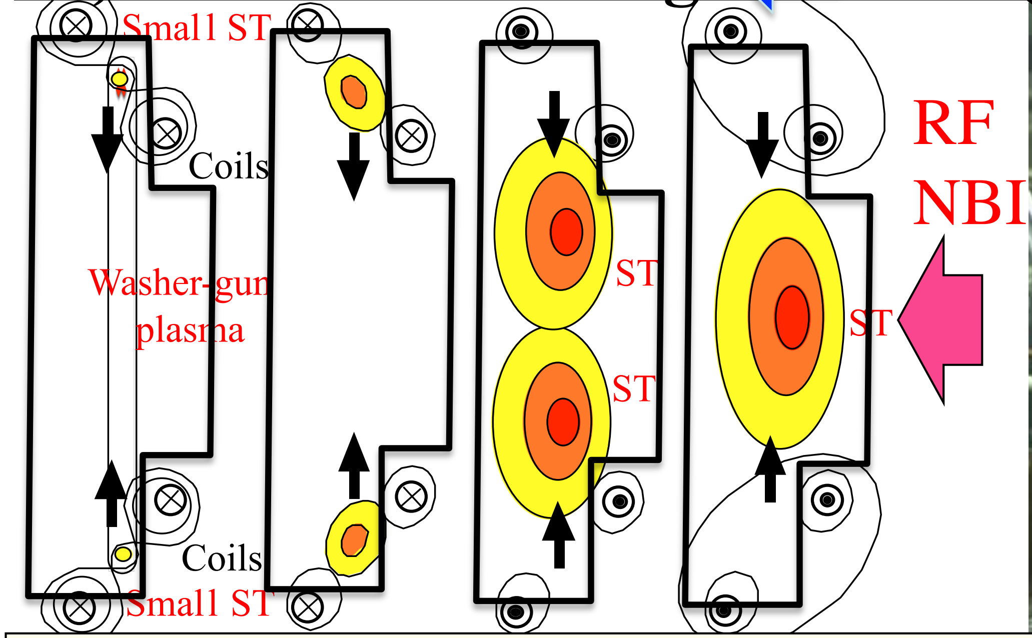
The ultra-high-β ST produced from an FRC has an **absolute-min-B** configuration.

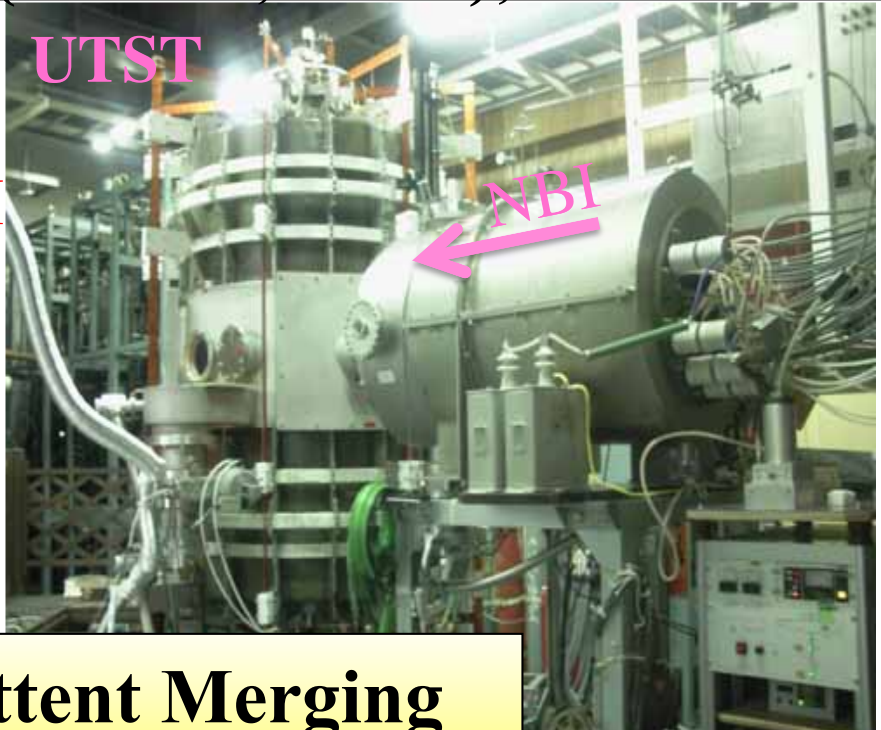


|B| and poloidal flux contours of FRC, high-ß ST (transformed from FRC) and low-ß ST (produced without merging)

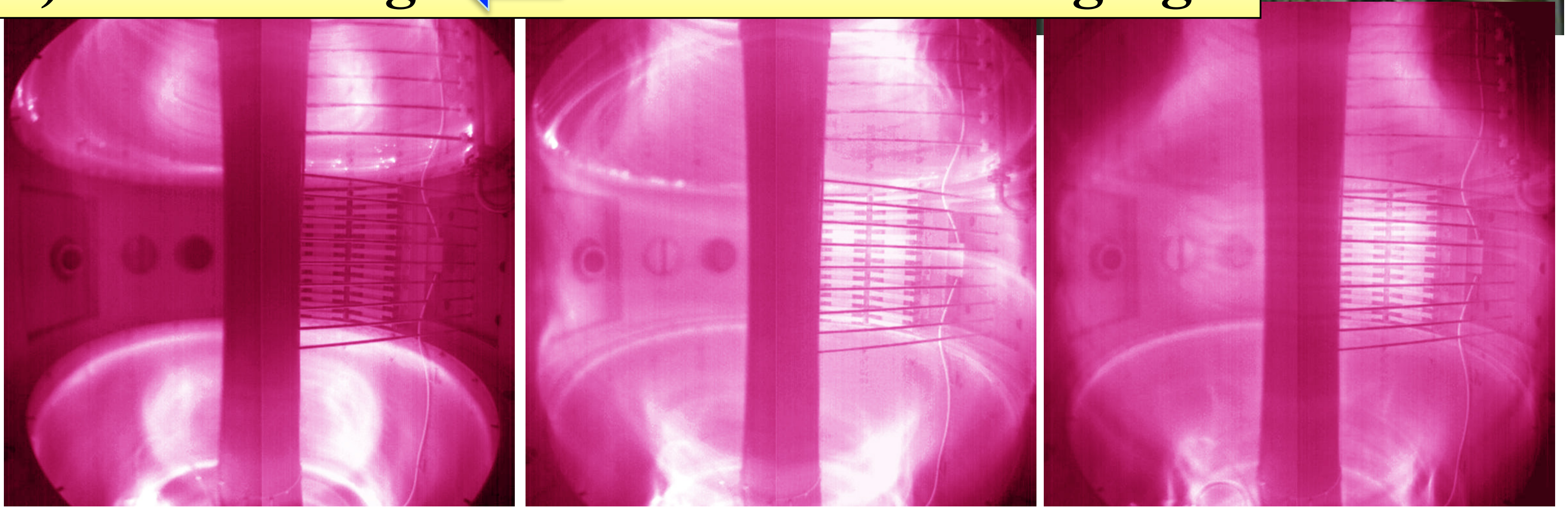
High-ß ST Sustainment

2) Electron Heating ← NBI(0.7MW, 25kV), HHFW



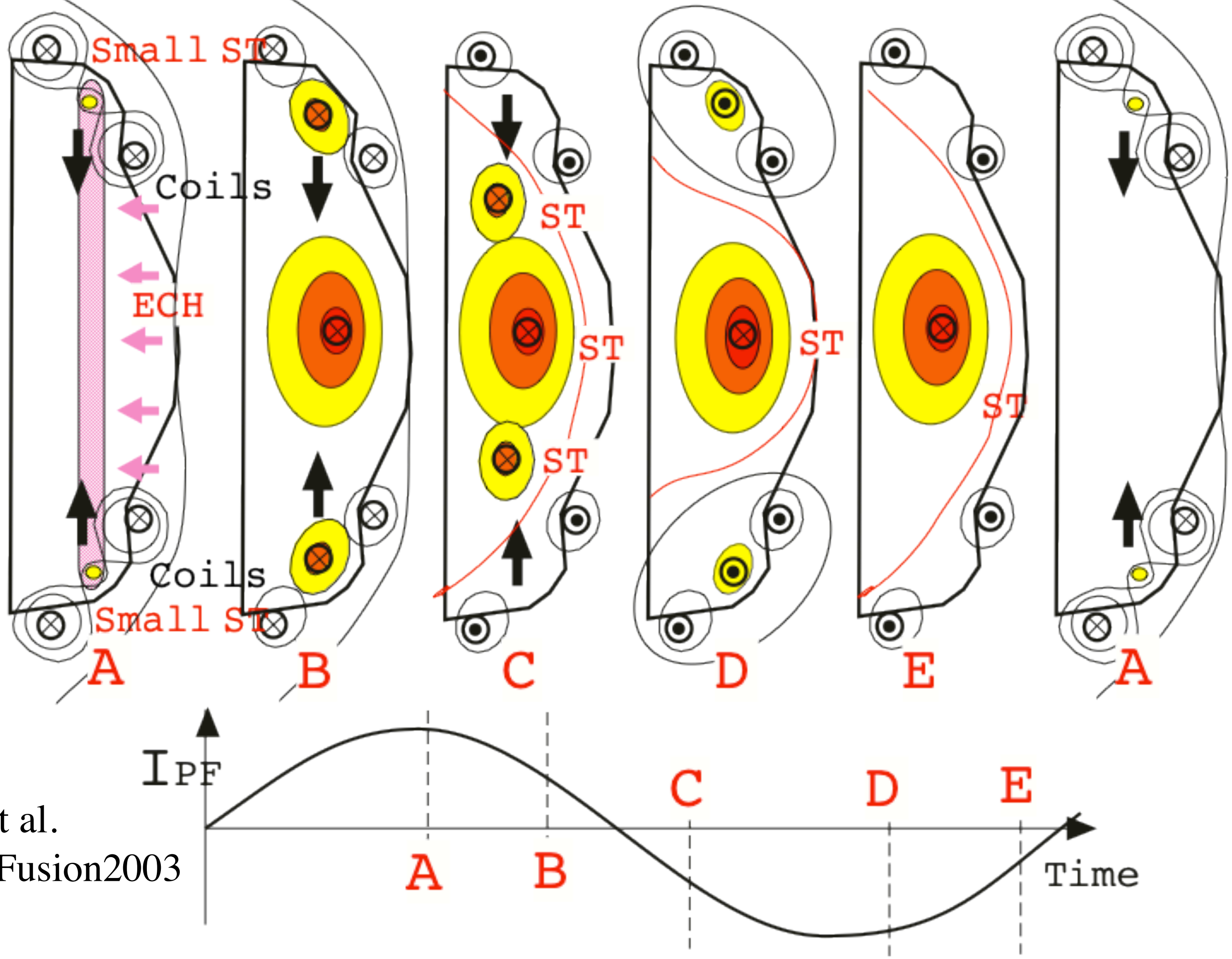


1) Ion Heating ← Intermittent Merging



1) Ion Heating ← Intermittent Merging

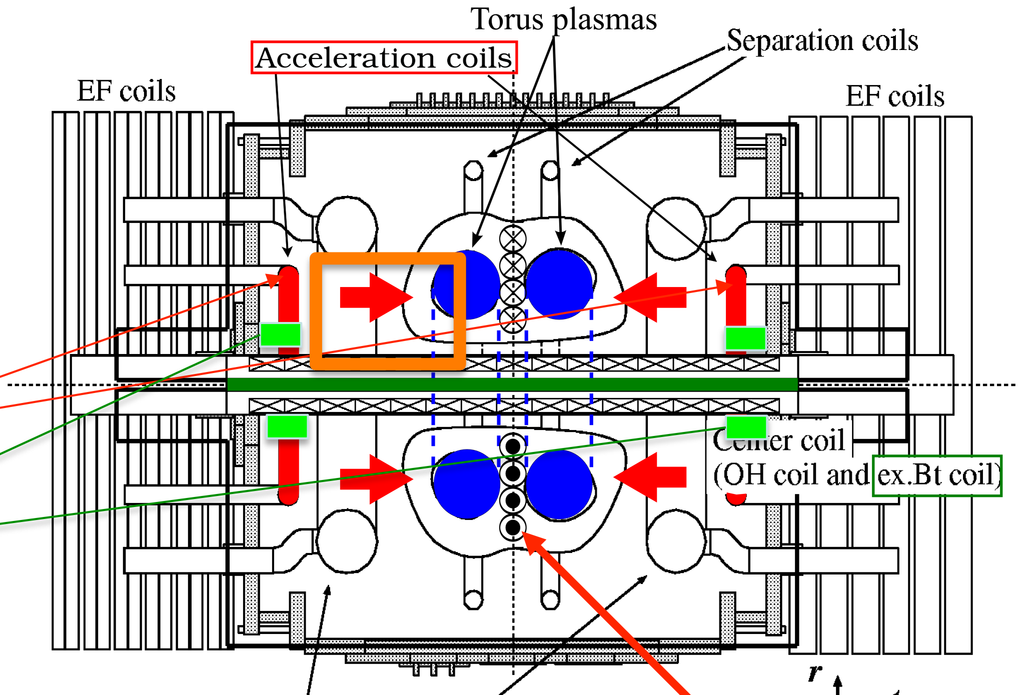
Intermittent merging is useful for ion heating/ current-drive because of the rectifying effect of ST formation.



Y. Ono et al.
Nuclear Fusion2003

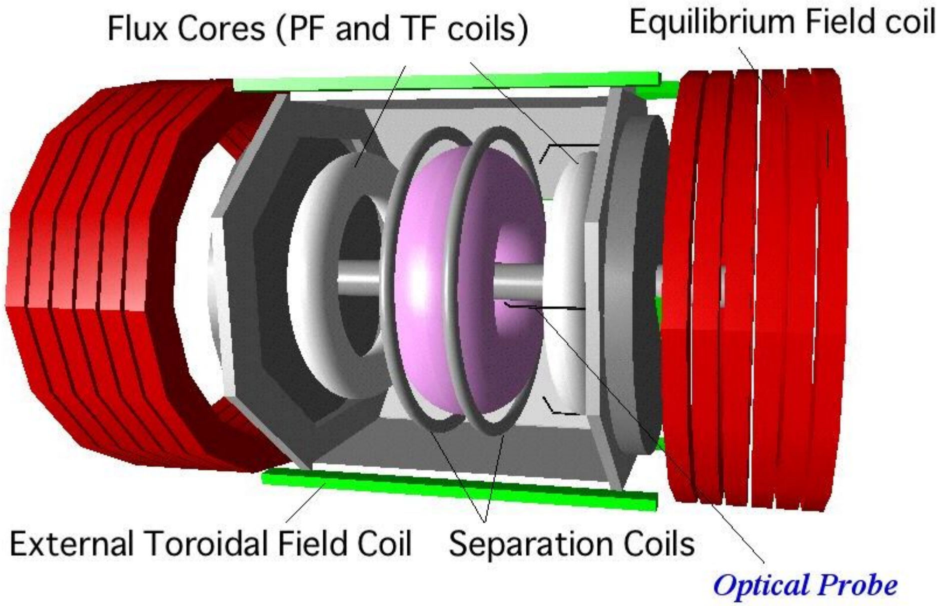
TS-4

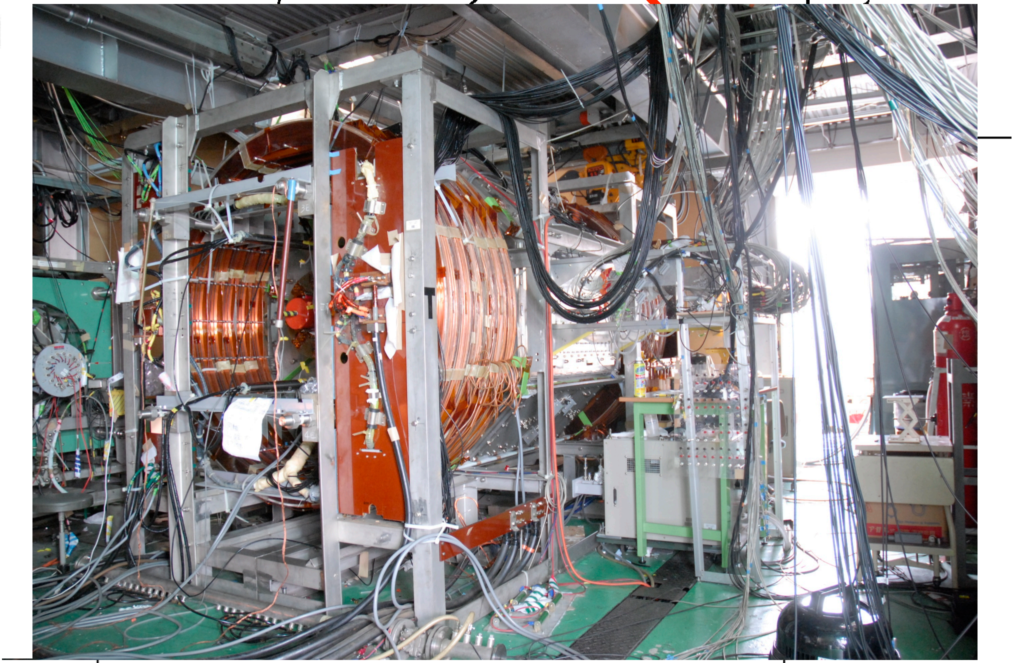
TS-4 Torus Plasma Merging Device



PF#5,6 Coils

PF#7,8 Coils



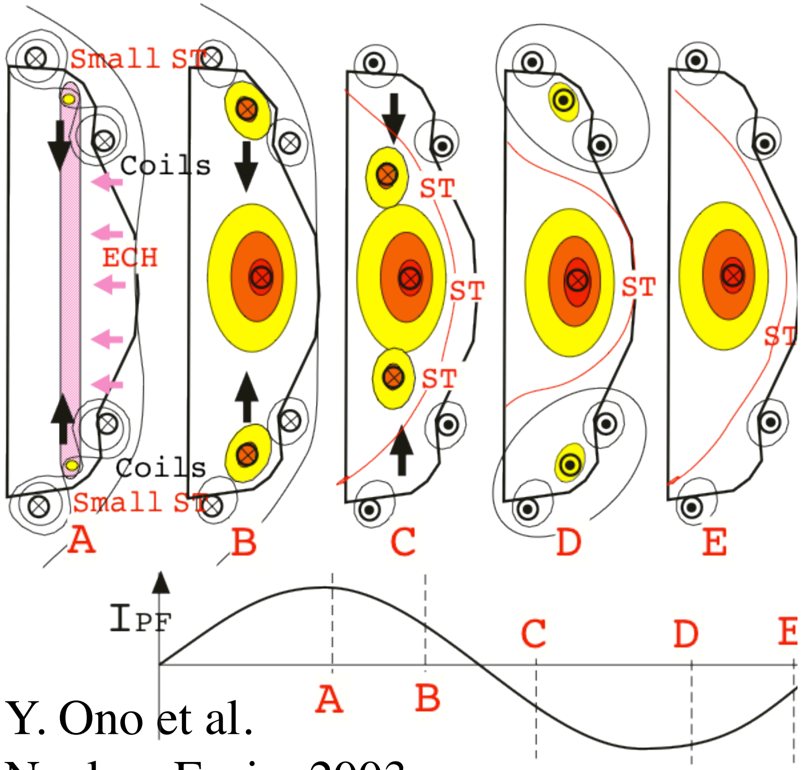


Probe 1 2 3 4 5 6 7 8 9 $r = 0$

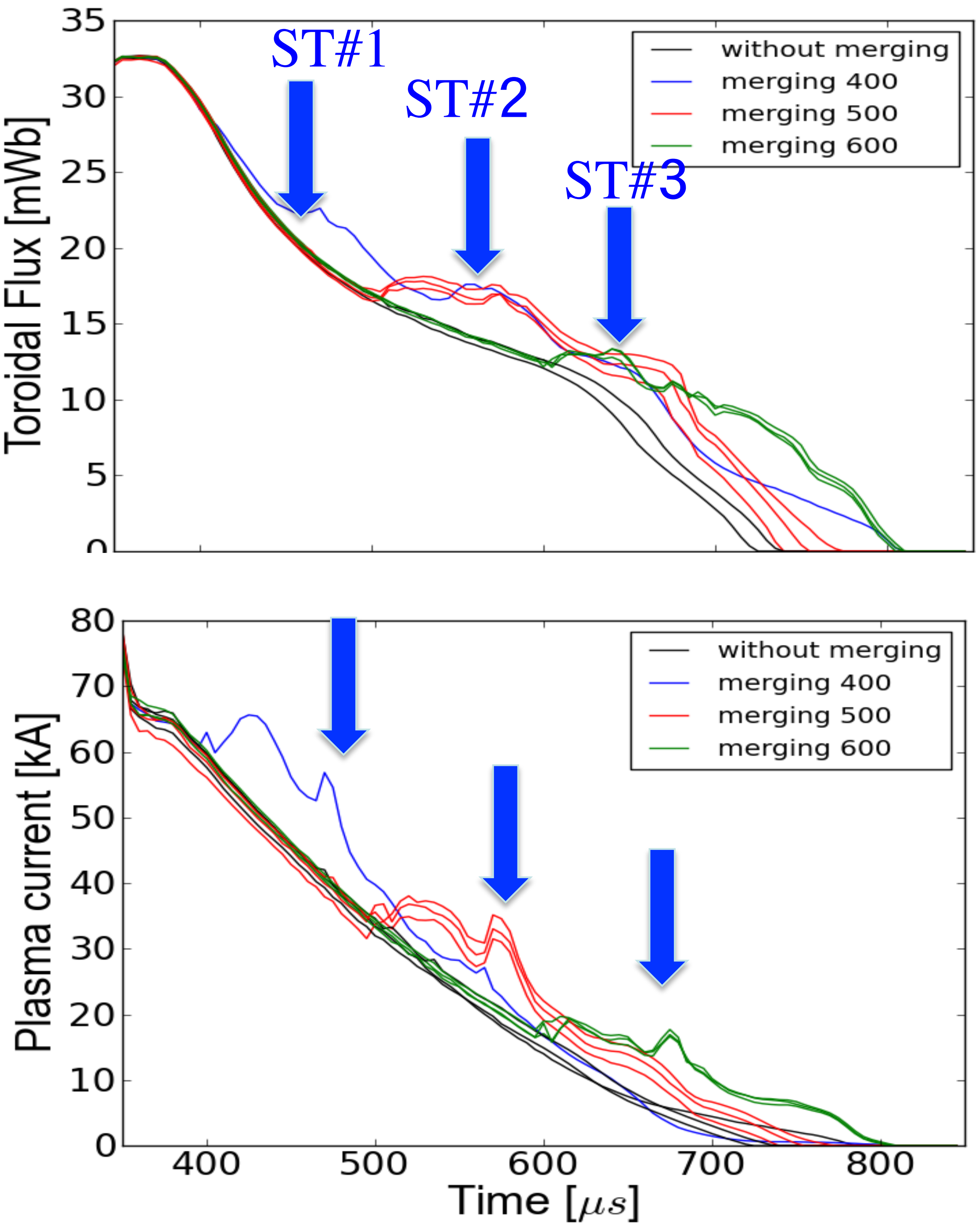
$z = 0$

1) Ion Heating
← Intermittent Merging

The intermittent ST merging increases both of toroidal flux and toroidal current.

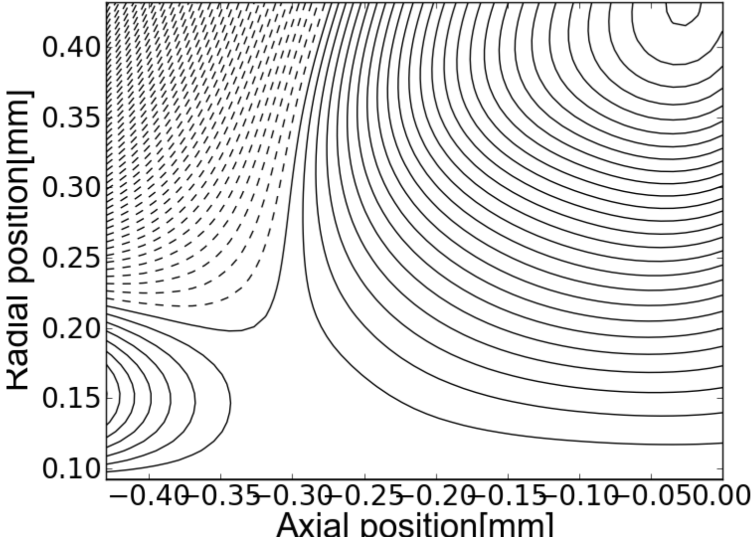


Y. Ono et al.
Nuclear Fusion2003

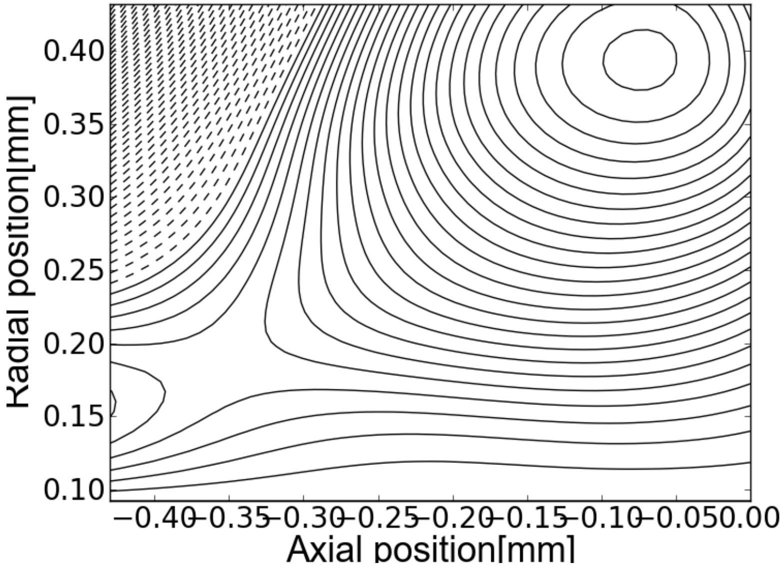


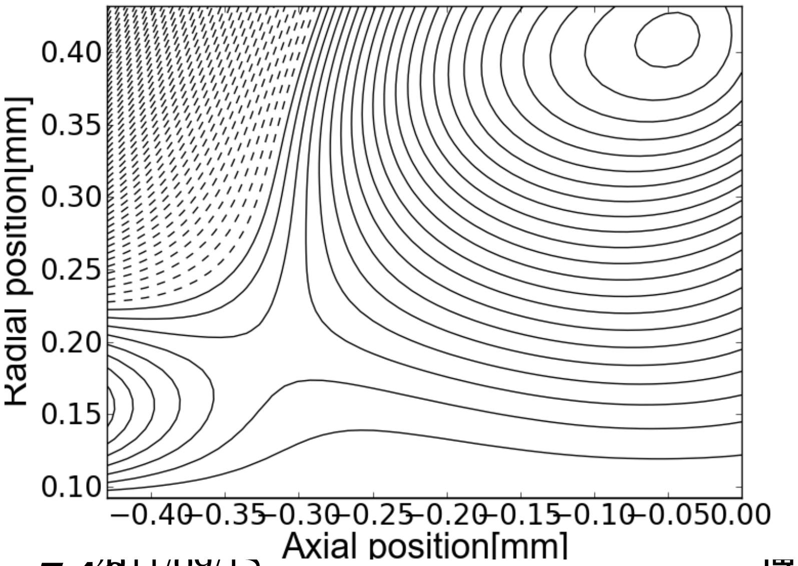
Intermittent Merging for Ion Heating/ Current Drive

520µs

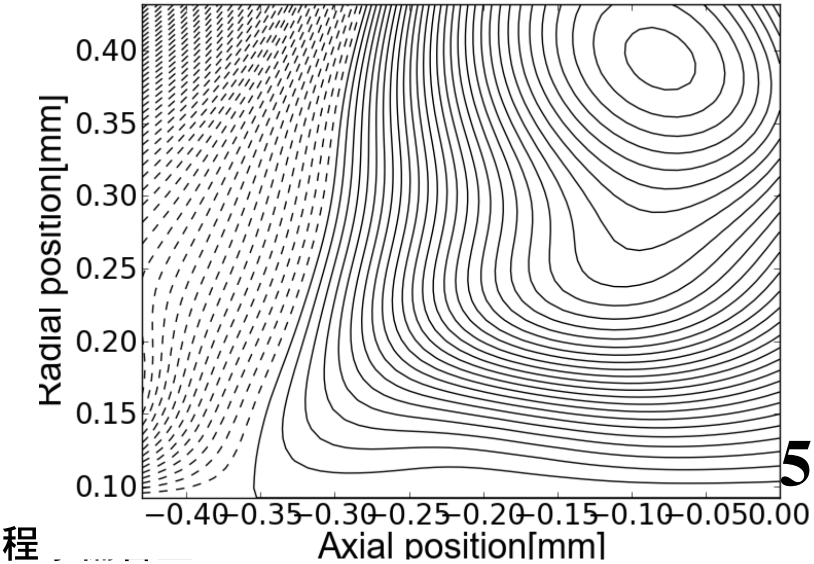


560µs





540µs



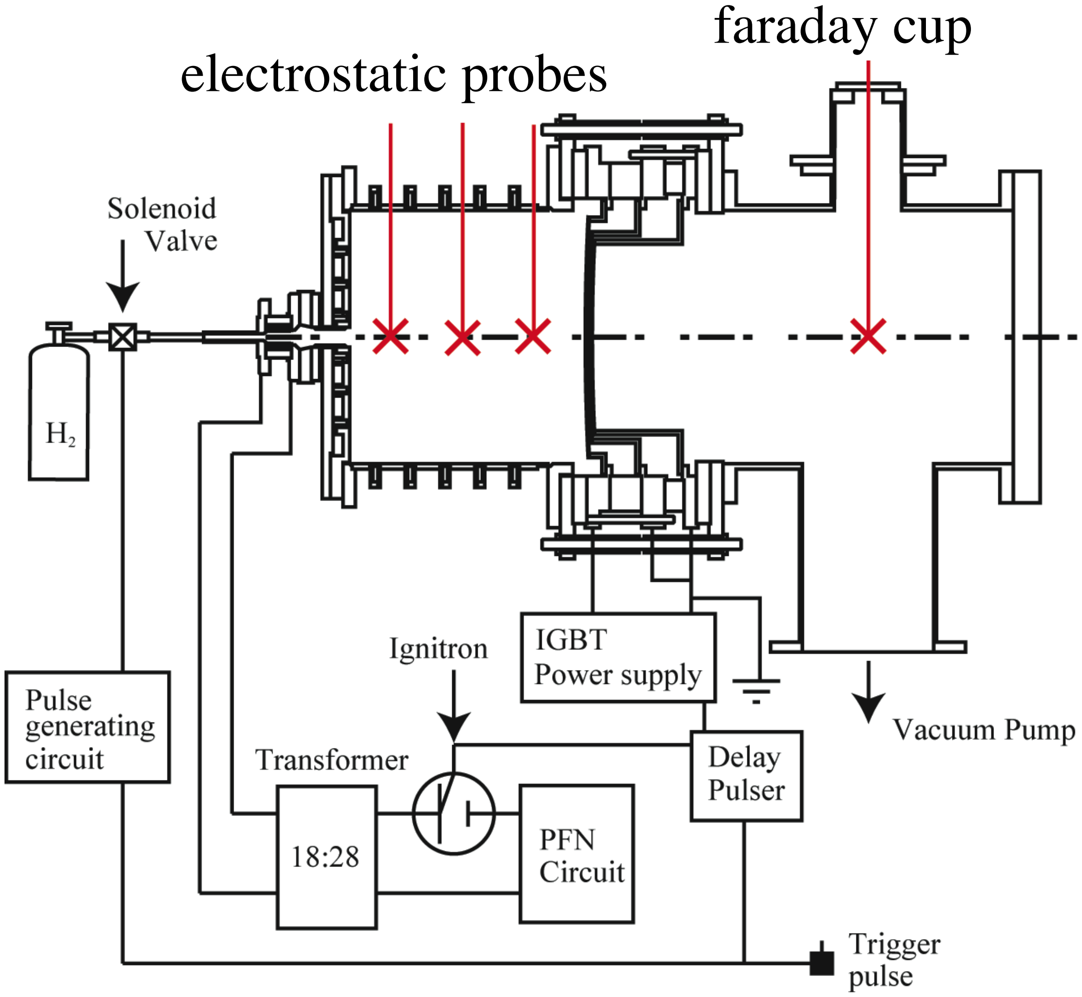
580µs

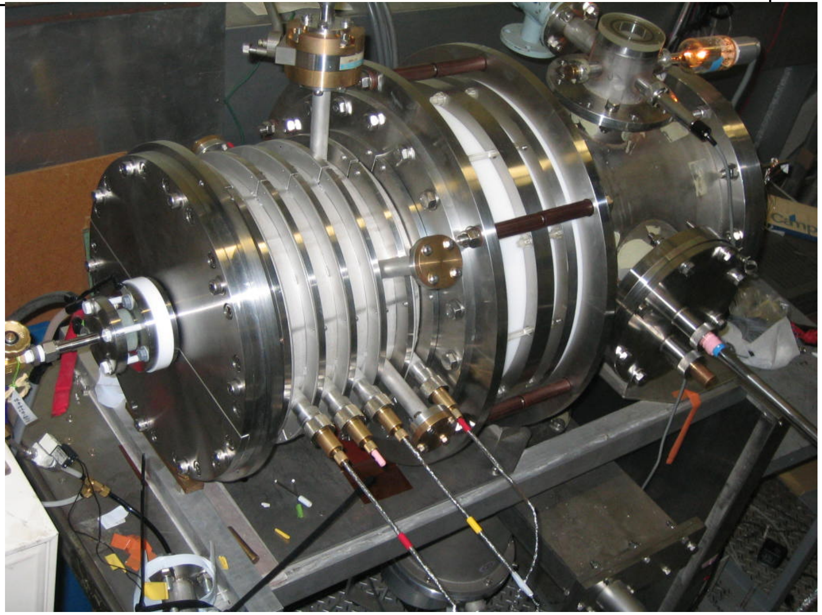
2) Electron Heating ⬅ Intermittent Merging

Development of Washer-Gun Type NBI

1)Maintenance-free、2)Low-Cost、3)Air-Cool

Collaboration with Nihon Univ., Osaka Univ.(T. Asai)





measurement points for

1. electrostatic probes

z=59, 143, 224mm, r=arbitrarily

2. faraday cup

from 340mm after

Acceleration Electrodes (f=2000mm

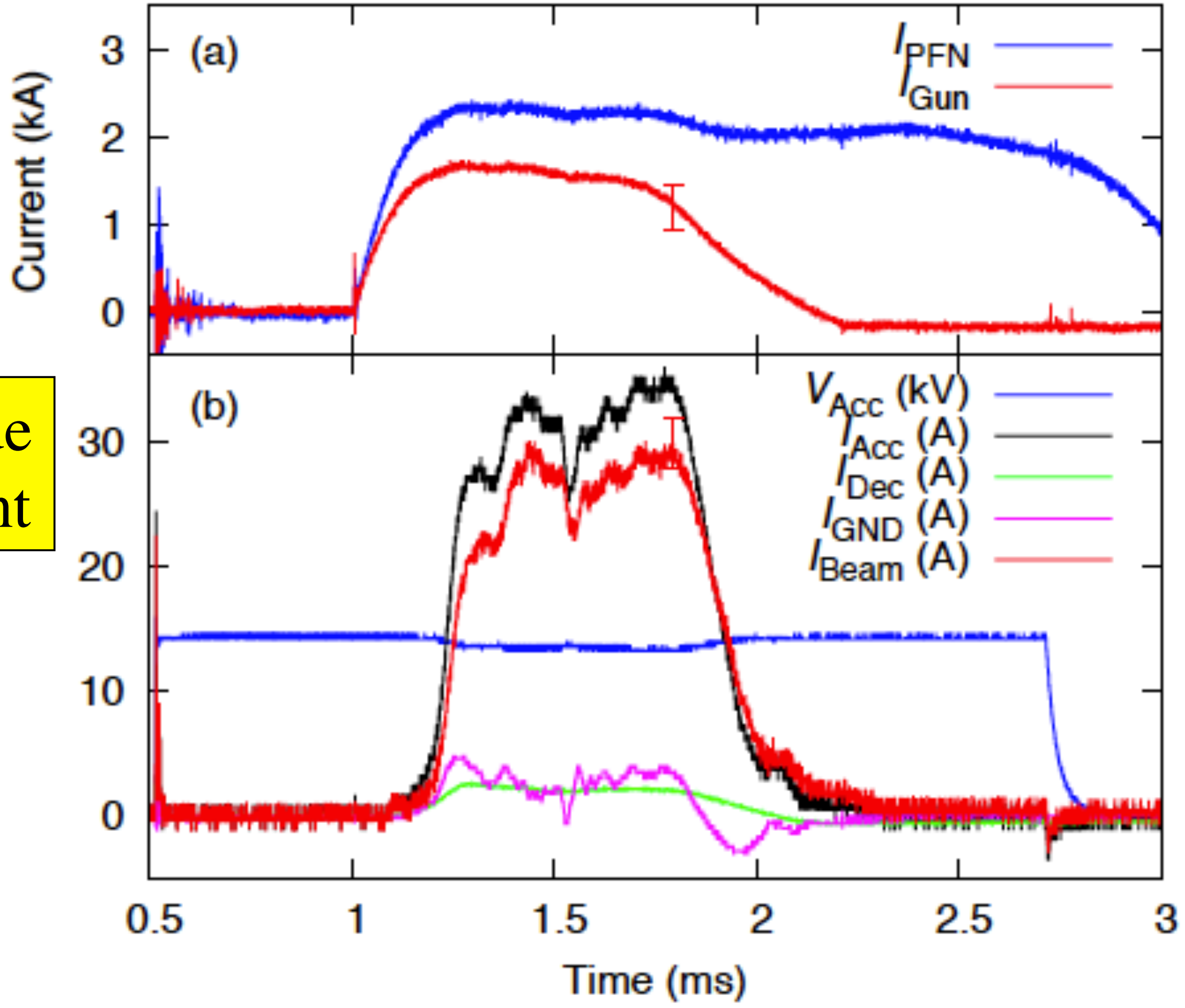
Development of Washer-Gun Type NBI

1) Maintenance-free, 2) Low-Cost, 3) Air-Cool

Collaboration with Nihon Univ., Osaka Univ.(T. Asai)

Gun Current

Electrode Current



Beam Power

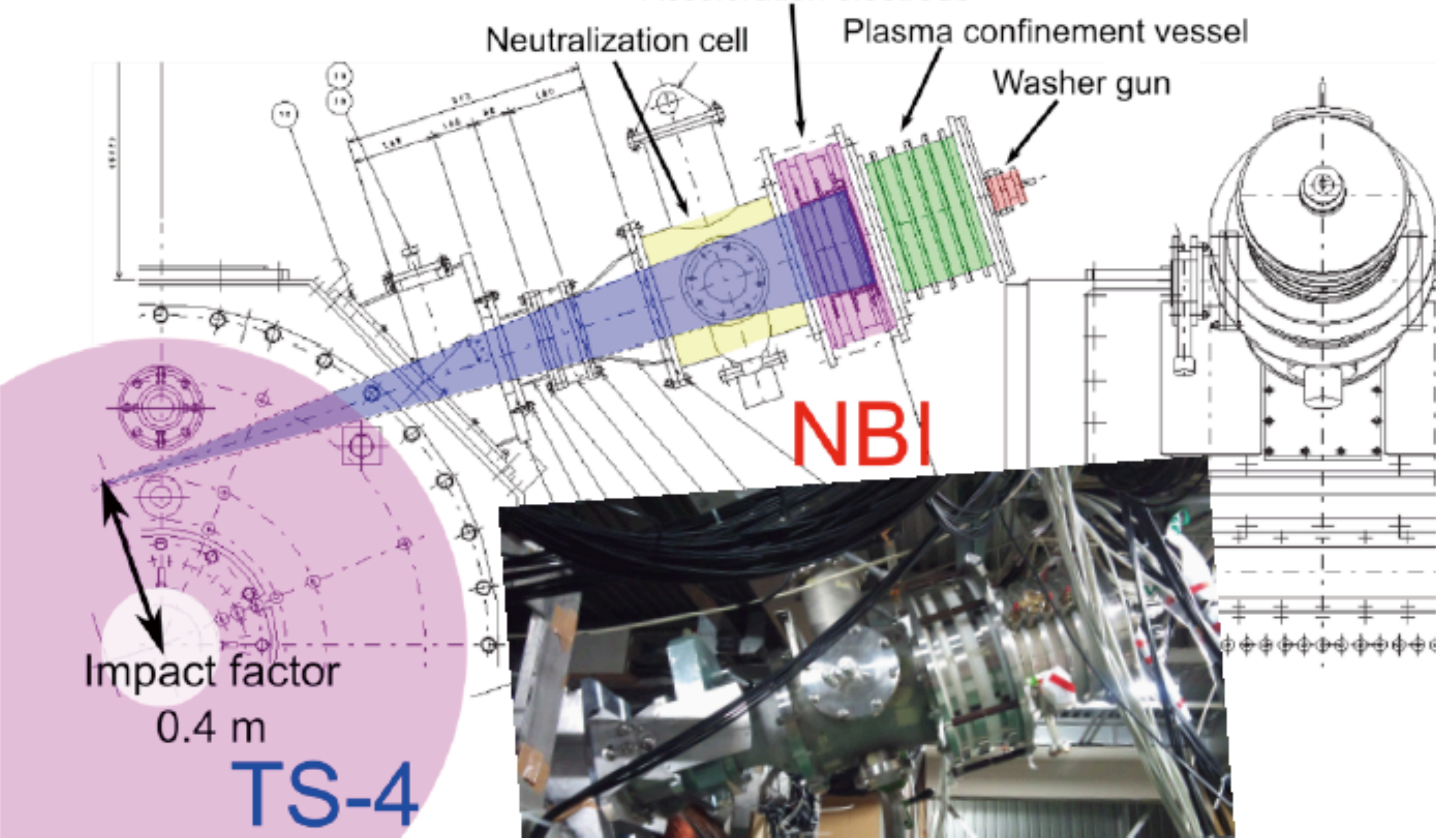
P =15kVx30A

=0.45MW

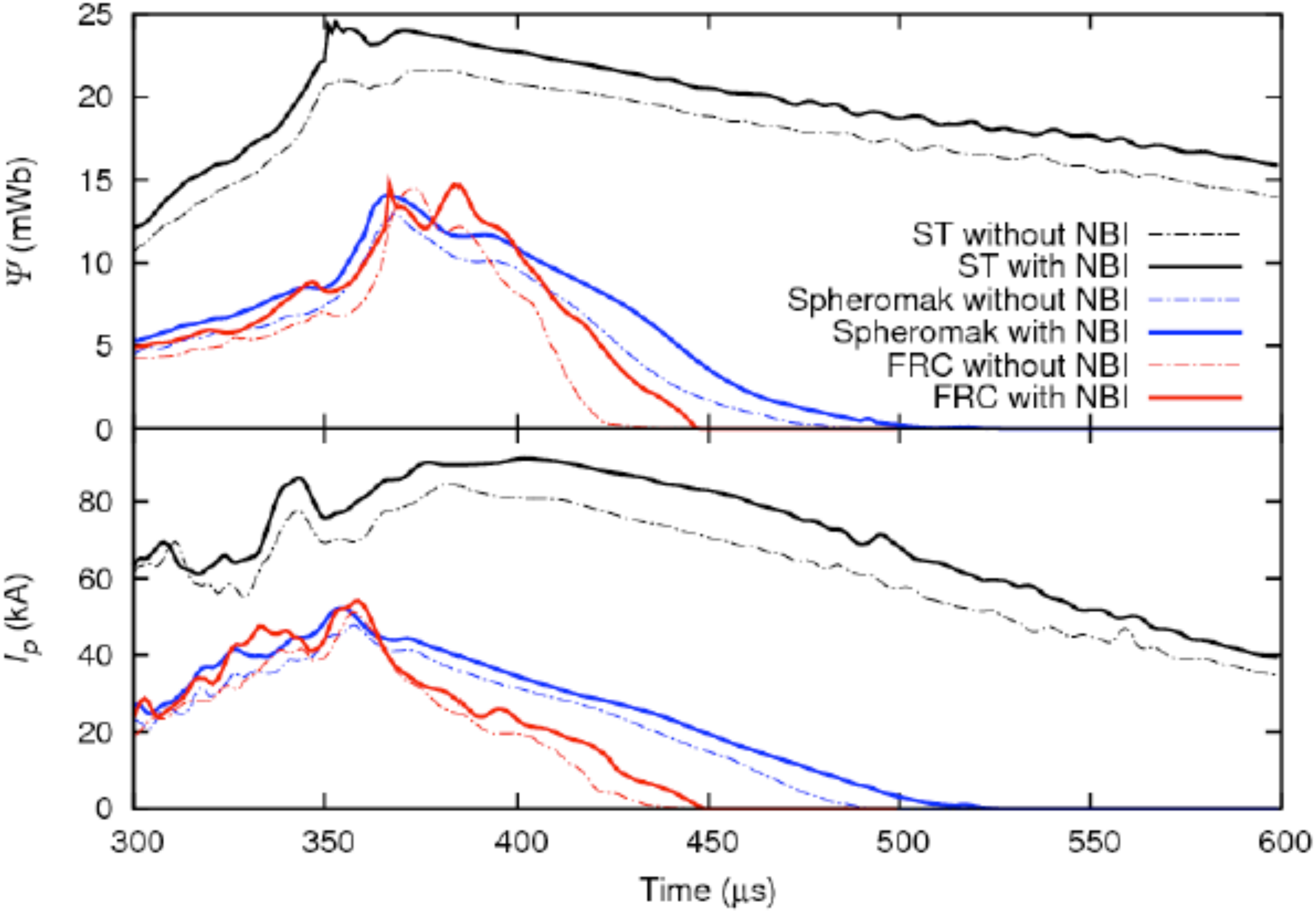
Development of Washer-Gun Type NBI

1) Maintenance-free, 2) Low-Cost, 3) Air-Cool

Collaboration with Nihon Univ., Osaka Univ.(T. Asai)

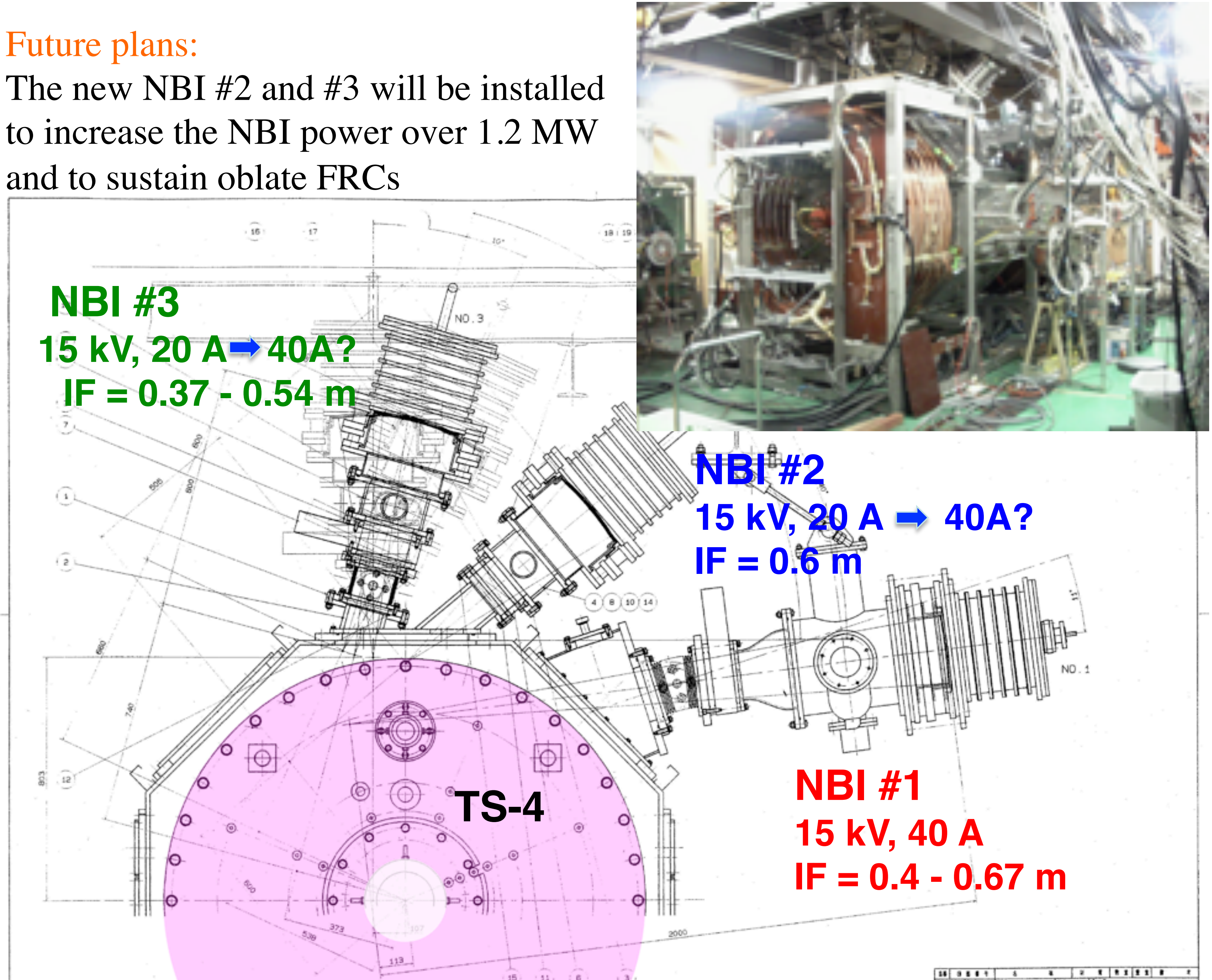


Initial Results of Neutral Beam Injection into High-beta (30%) ST , Spheromak & FRC in TS-4 (15kV, 40A)



Future plans:

The new NBI #2 and #3 will be installed to increase the NBI power over 1.2 MW and to sustain oblate FRCs



NBI #3
15 kV, 20 A ➡ 40A?
IF = 0.37 - 0.54 m

NBI #2
15 kV, 20 A ➡ 40A?
IF = 0.6 m

NBI #1
15 kV, 40 A
IF = 0.4 - 0.67 m

TS-4

CONCLUSIONS

2-D visible light tomography system for T_i and T_e.

2-Dscan of electrostatic probes for T_e

1) Direct observation of outflow heating of ions significantly higher than electron heating.
2) Ohmic heating of electrons inside the current sheet.
3) Formation of fast shock for outflow dumping.
4) T_e peaks at X-point while Ti does at downstream
5) T_i increases with inversely with B_z.
6) Ion heating energy & T_i increase with B^2.

High power reconnection heating for ST experiment

Reconnection heating in MAST tokamak experiment
up to T_i=1.2keV, T_i=0.8keV.

Successful Double-Null ext.-coil startup in UTST