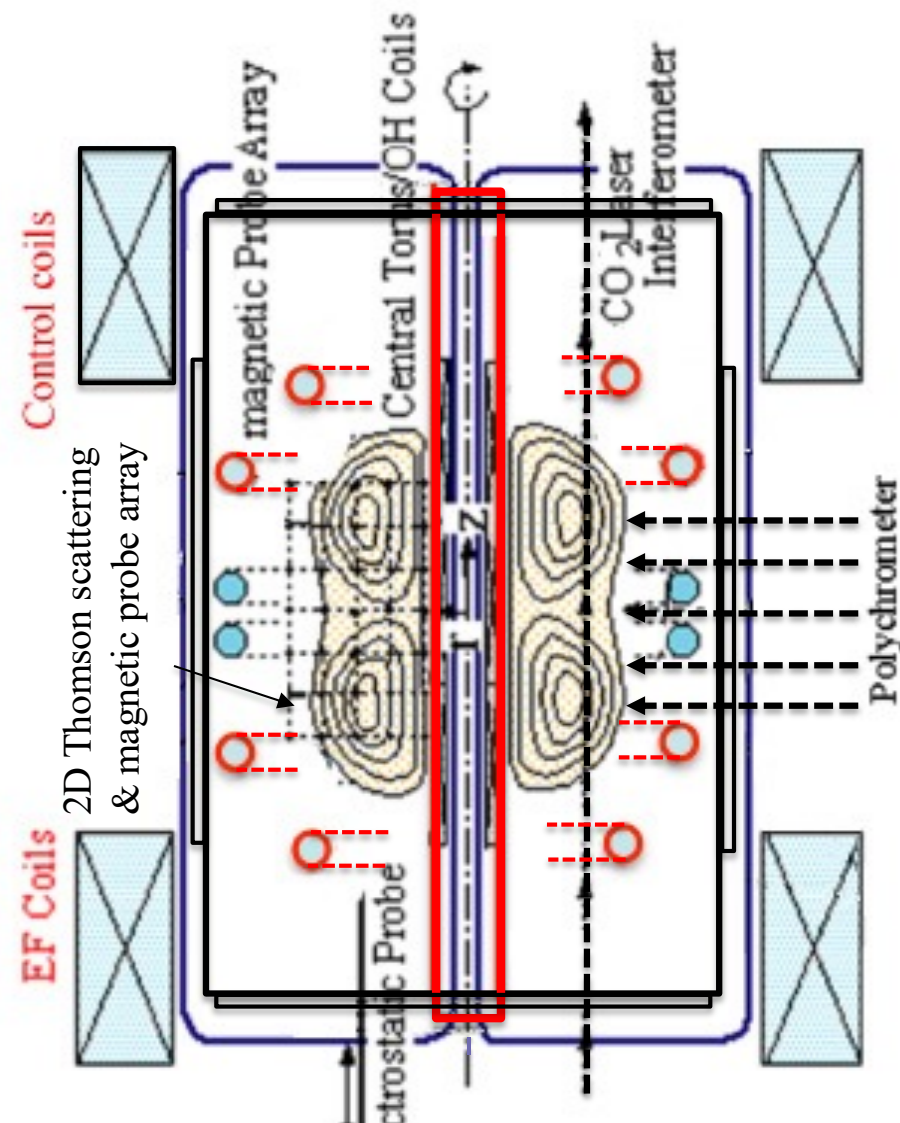
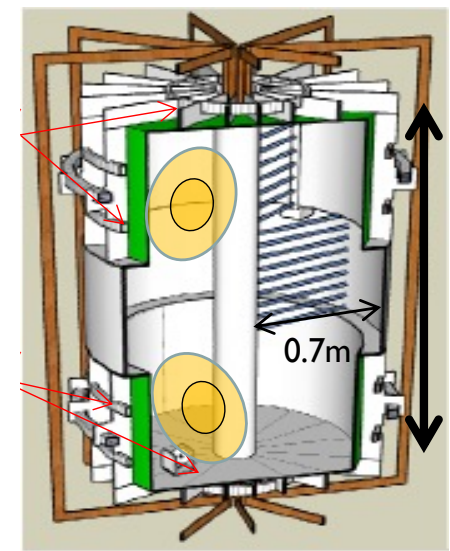
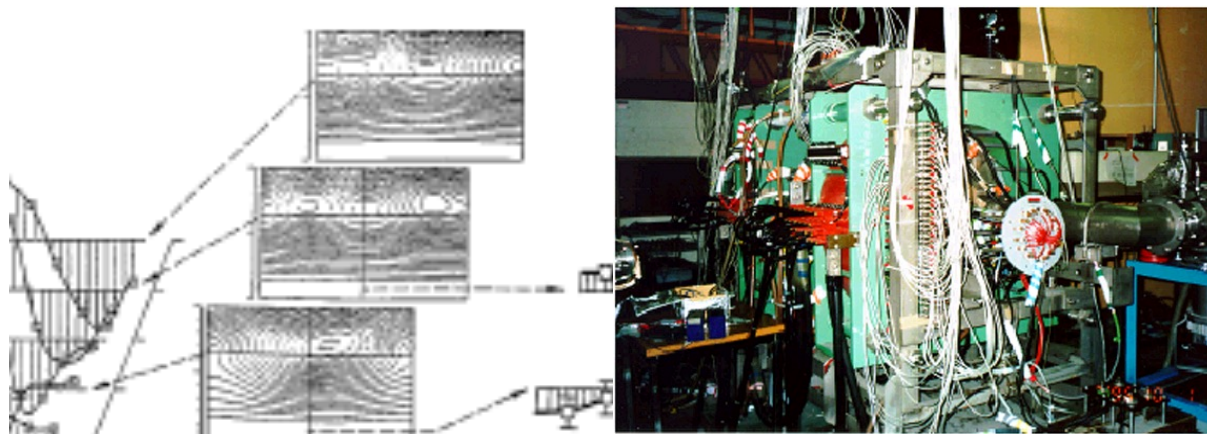
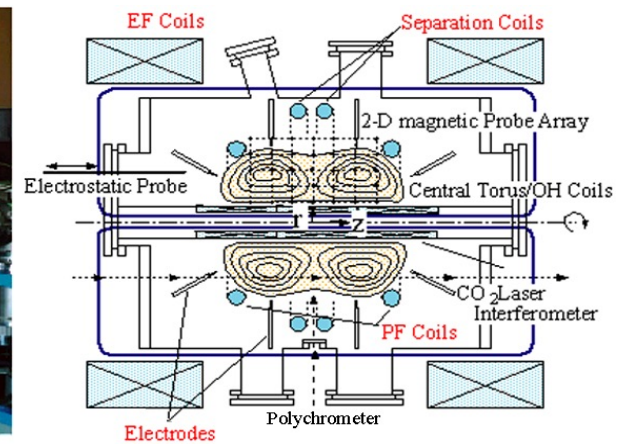
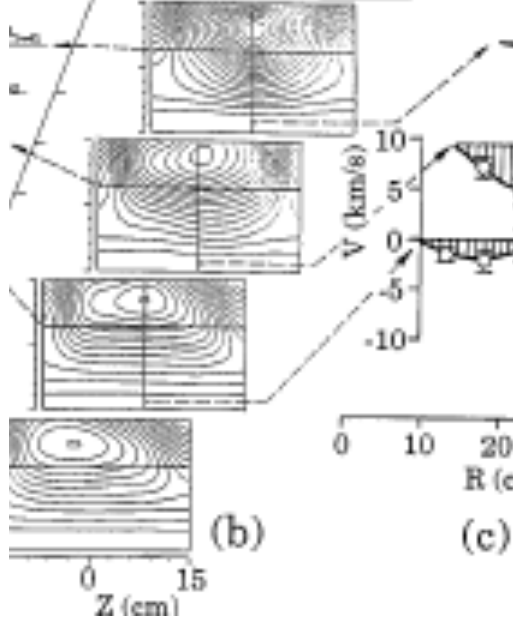
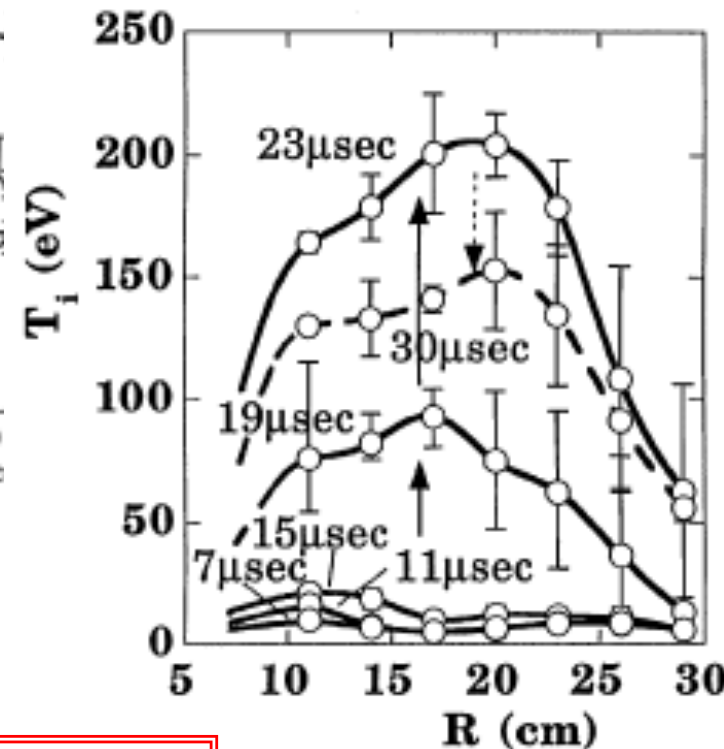


Merging Formation of High-Beta Spherical Tokamak with Absolute Minimum-B in TS-6 merging experiment

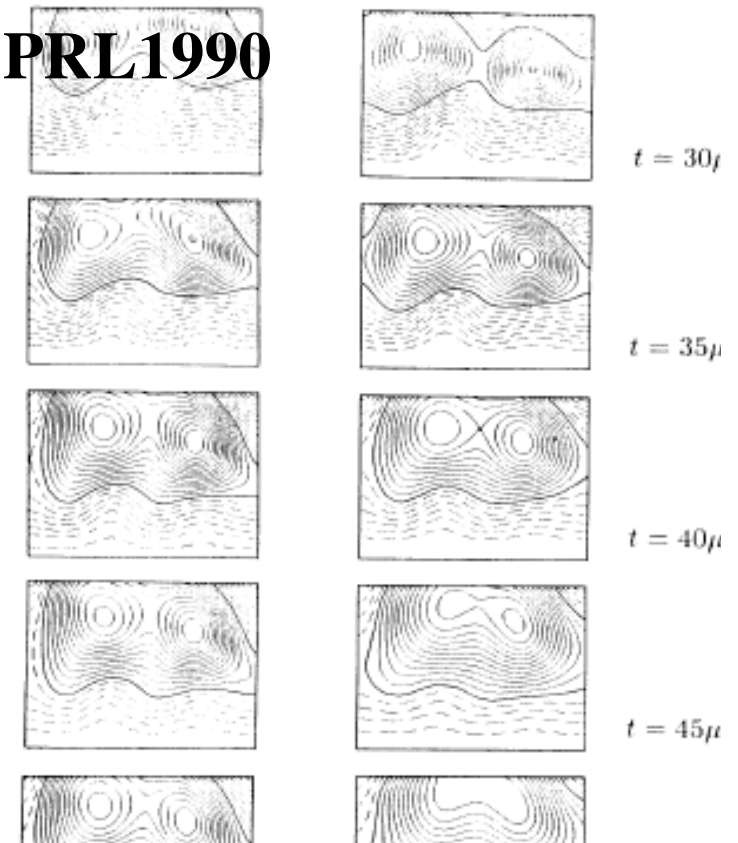
Y. Ono, S. Takada, H. Tanaka, M. Akimitsu, R. Someya, S. Kamiya, T. Ahmadi, K. Doi, Y. Cai, J. Kim, H. Tanabe, R. Horiuchi, S. Usama, C. Z. Cheng **Univ. Tokyo, ISTW, Nov. 3**



The TS-3 merging startup was first demonstrated in 1986.



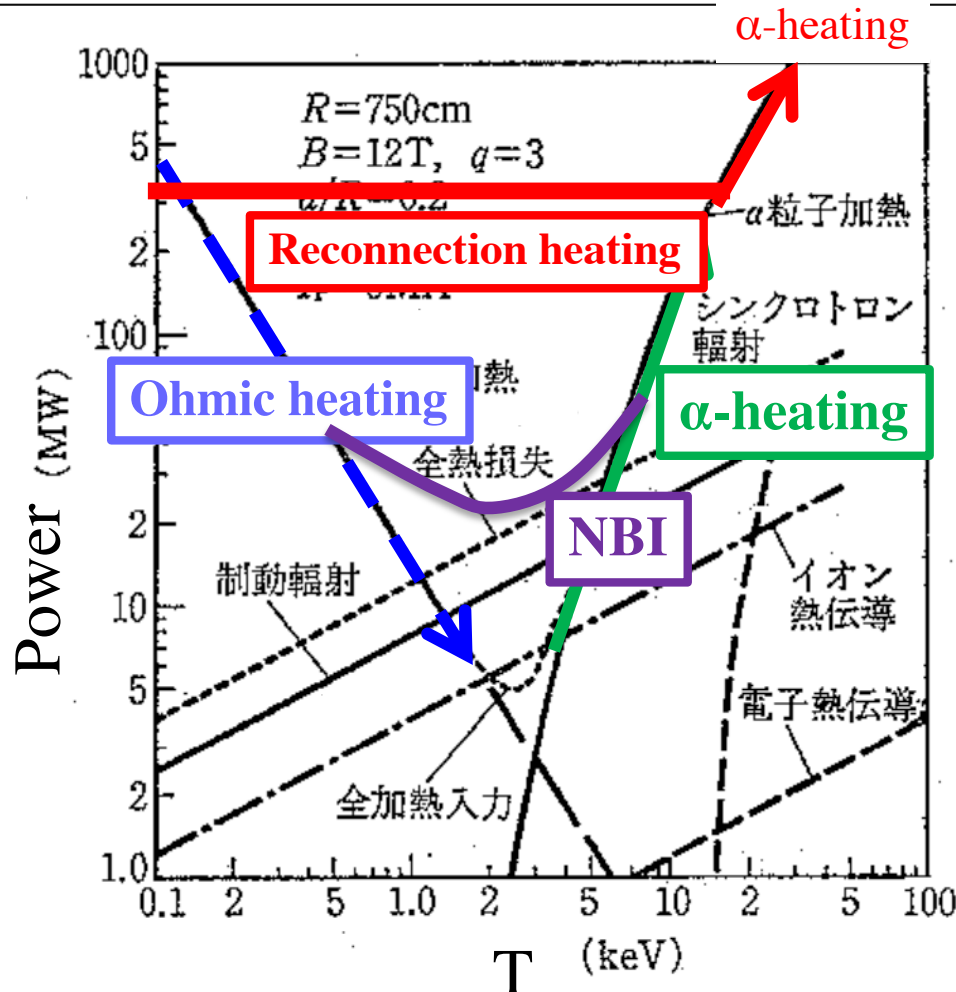
PRL1990



PRL1996

TS-3

The high-power reconnection heating can heat ions over 10keV without using NBI / RF heating



Ohmic heating

$$P_{OH} \propto \eta I^2 \propto T_e^{-3/2}$$

α -heating P_α starts increasing over several keV

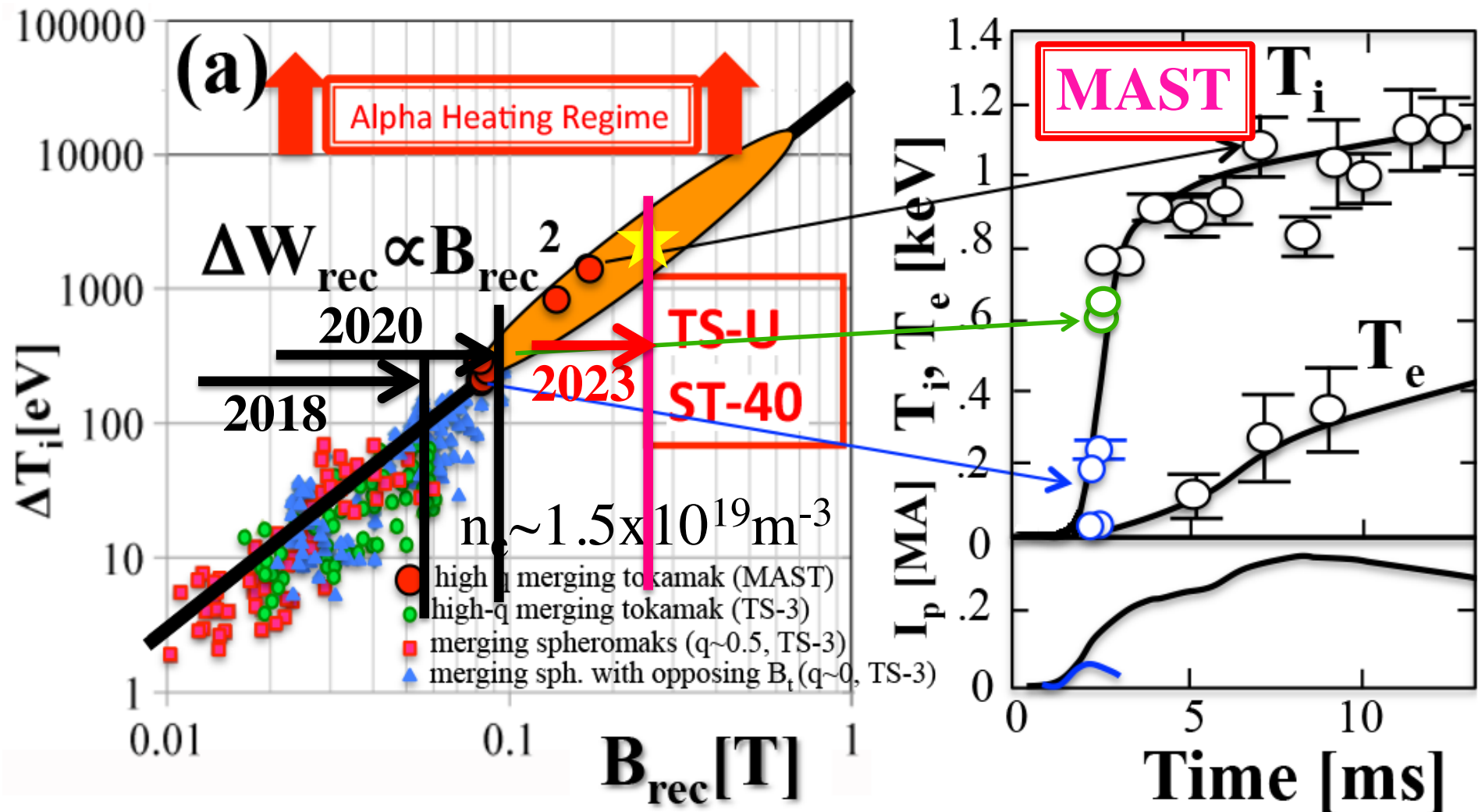
Need

- 1) NBI (Neural Beam Injection)
- 2) RF Heating

Reconnection heating: MW power has no temperature dependence

$P_{rec} = 40\%$ of poloidal magnetic energy / reconnection time

B_{rec}^2 -scaling for the major outflow heating of ions



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

$$\text{Sweet-Parker Model: } V_{\text{outflow}} \sim V_{pA} \propto B_p / n^{1/2}$$

MHD Steady-State model predicts the outflow $\sim V_{alf}$
Two fluid model needs the scaling of electrostatic potential Φ

Assumptions: 2D ,Steady-state

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

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

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

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

Mass
conservation:

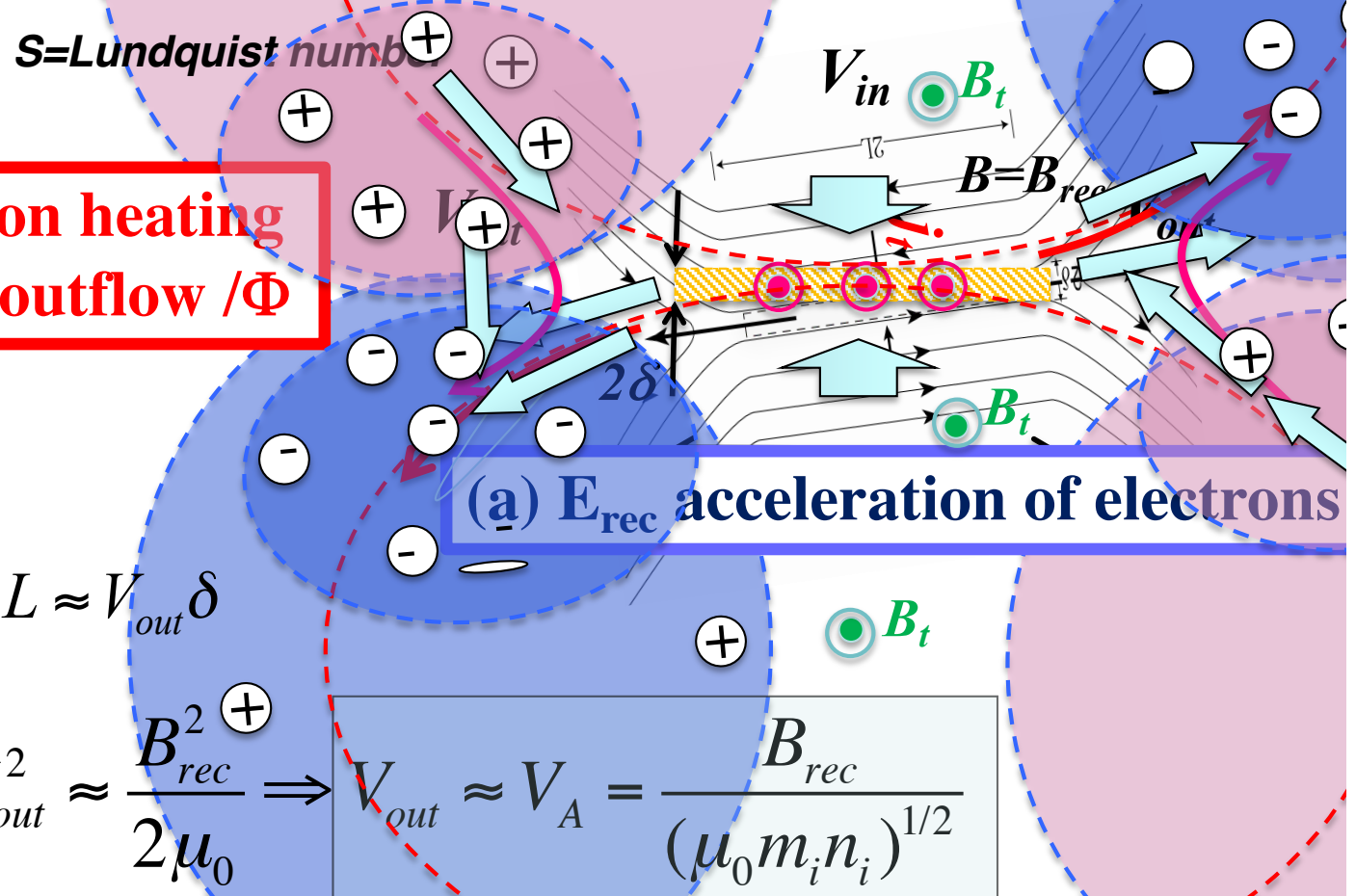
$$\text{Pressure balance: } \frac{1}{2} m_i n_i V_{out}^2 \approx \frac{B_{rec}^2}{2\mu_0} \Rightarrow V_{out} \approx V_A = \frac{B_{rec}}{(\mu_0 m_i n_i)^{1/2}}$$

(b) Formation of potential well and hil

$S = \text{Lundquist number}$

**(c) Ion heating
by outflow $\propto \Phi$**

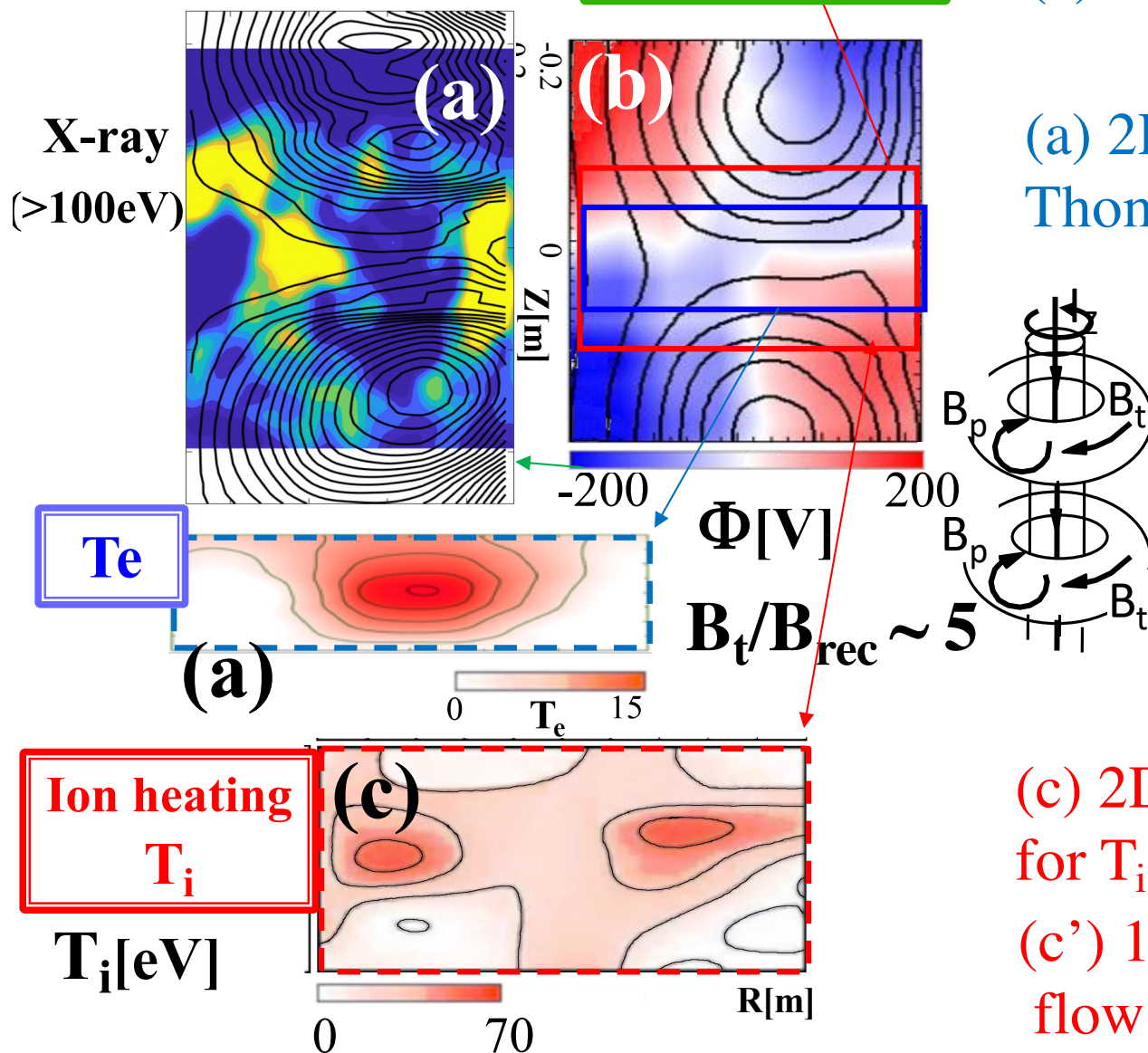
(a) E_{rec} acceleration of electrons



2D imaging diagnostics for TS-3U : (a) T_i , (b) T_e , (c) electrostatic potential Φ and poloidal flux, (d) soft-X-ray emission ($>100\text{eV}$)

Electron acceleration

Potential Φ



(a) 2D Soft X-ray Emission for High Energy Electron

(a) 2D Electrostatic Probe / Thomson Scattering for 2D T_e

(b) 2D electrostatic probe for electrostatic potential Φ (Tanaka UP11.122) Global!!

(b) 2D Magnetic Probes for magnetic field

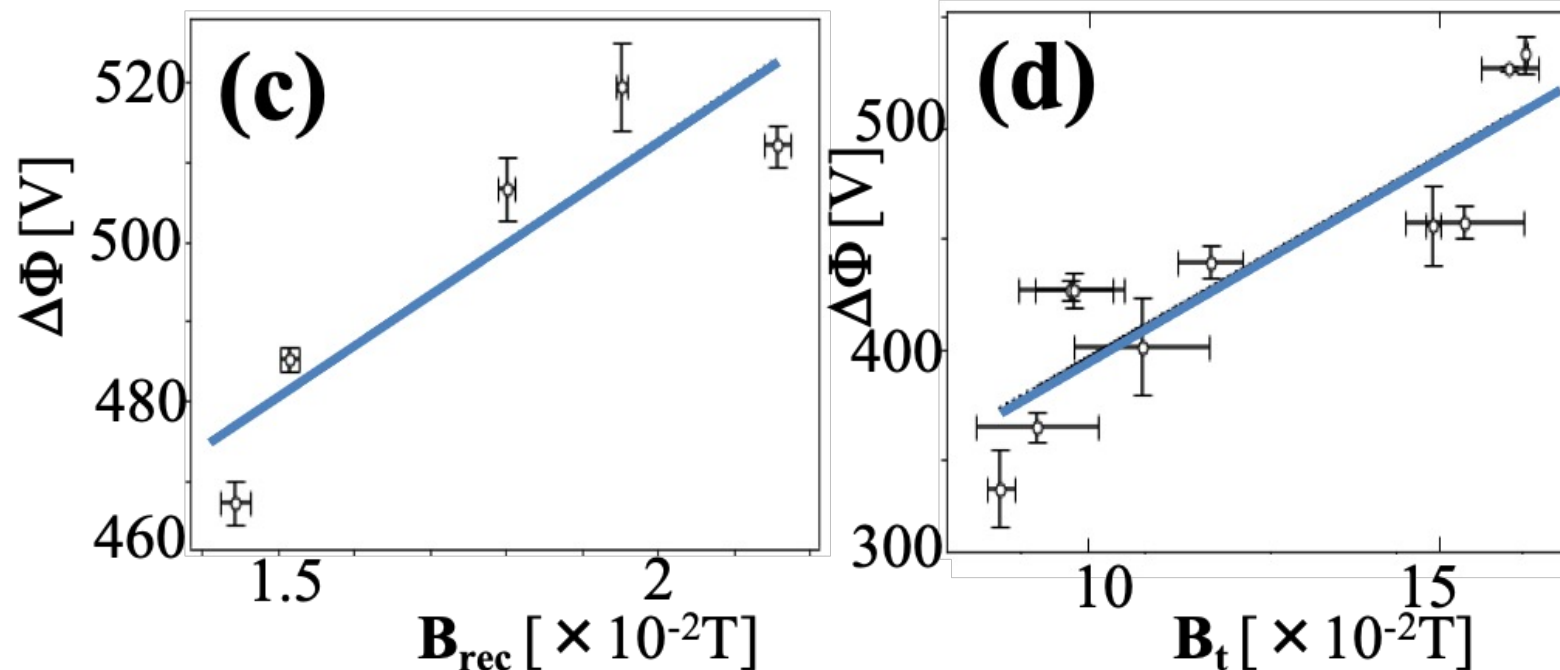
(c) 2D Doppler tomography for T_i (Tanabe UP11.121)

(c') 1D Doppler probe for ion flow (Someya UP11.123)

The electrostatic potential gap $\Delta\Phi$ increase proportionally with B_{rec} and B_t , indicating $v_{out} \propto B_{rec}$ and $\Delta T_i \propto B_{rec}^2$ when we compress sheet to q_i .

$$V_{out} = |E_{rec} \times B| / B^2 \sim E_p / B_t \sim C B_{rec} \quad \Rightarrow \quad T_i \propto m_i V_{out}^2 \propto B_{rec}^2 / n_i$$

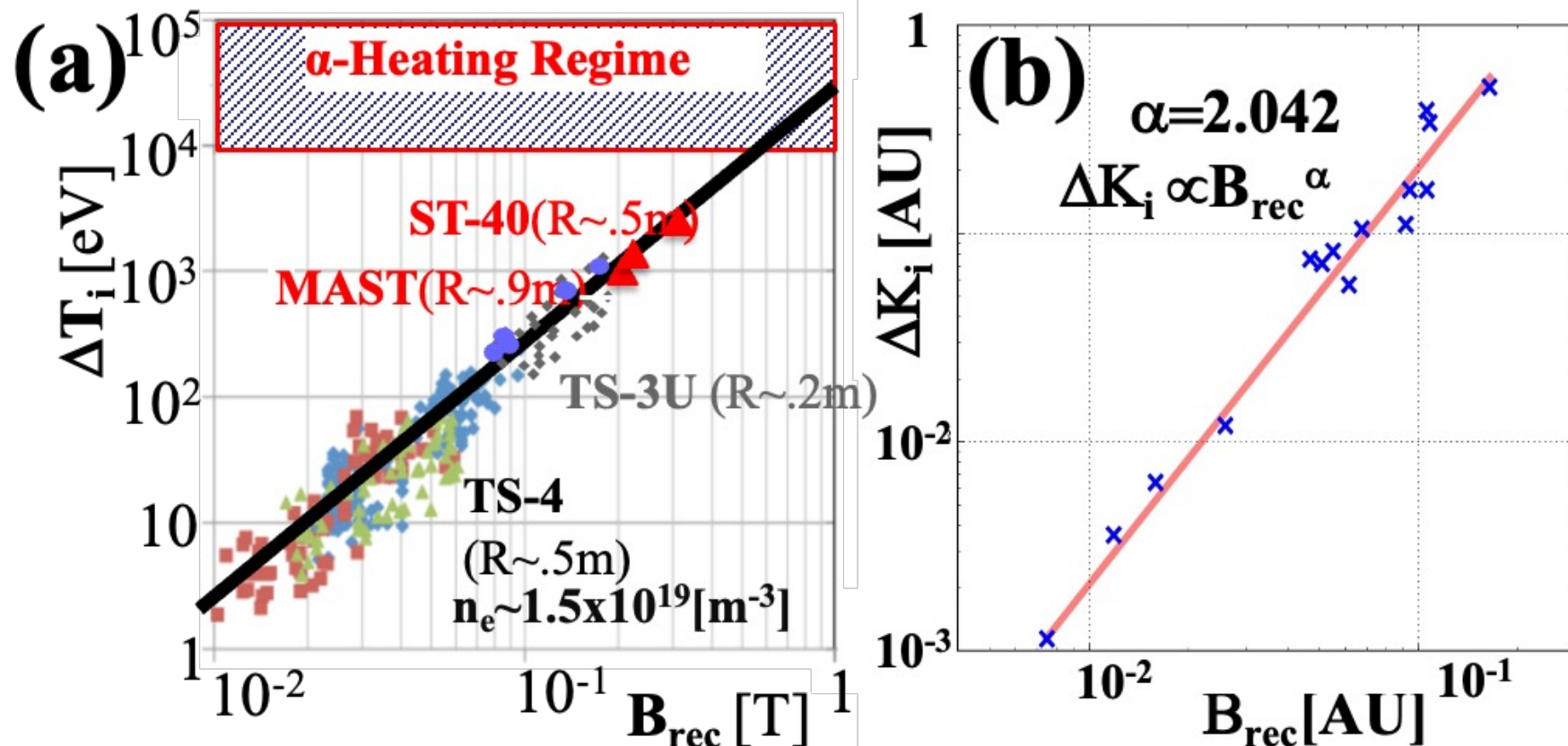
$$E_p = \Delta\Phi / L \sim C B_t B_{rec}$$



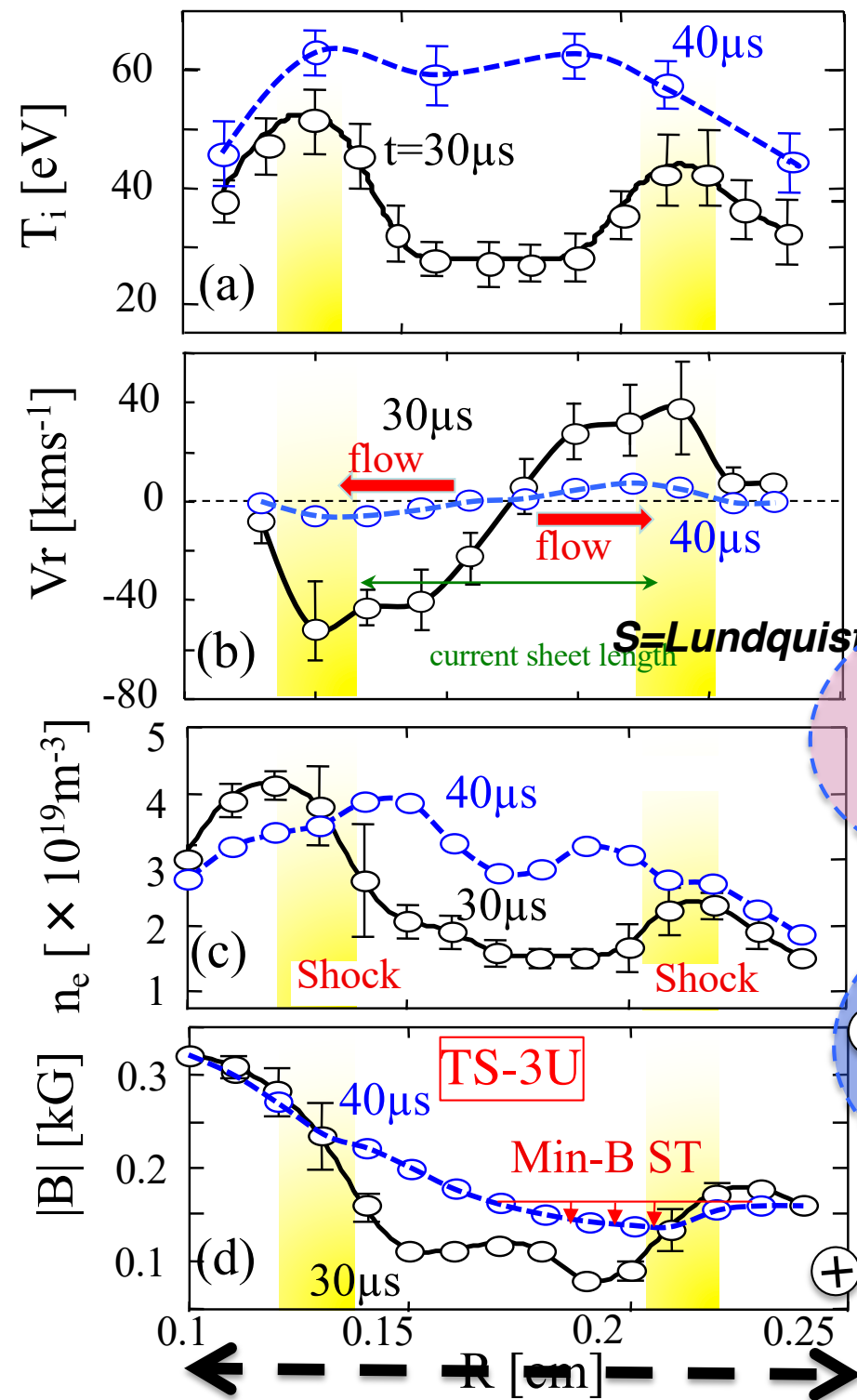
Dependence of the electro potential gap $\Delta\Phi$ in the downstream of reconnection on the reconnecting magnetic field B_{rec} and (d) that on the toroidal (guide) magnetic field B_t in TS-3U merging experiment.

A series of our merging experiments and PIC simulations indicates
 $n_i \Delta T_i \propto B_{\text{rec}}^2$ (and $\Delta T_i \propto B_{\text{rec}}^2$ under $n_i \sim \text{const.}$)

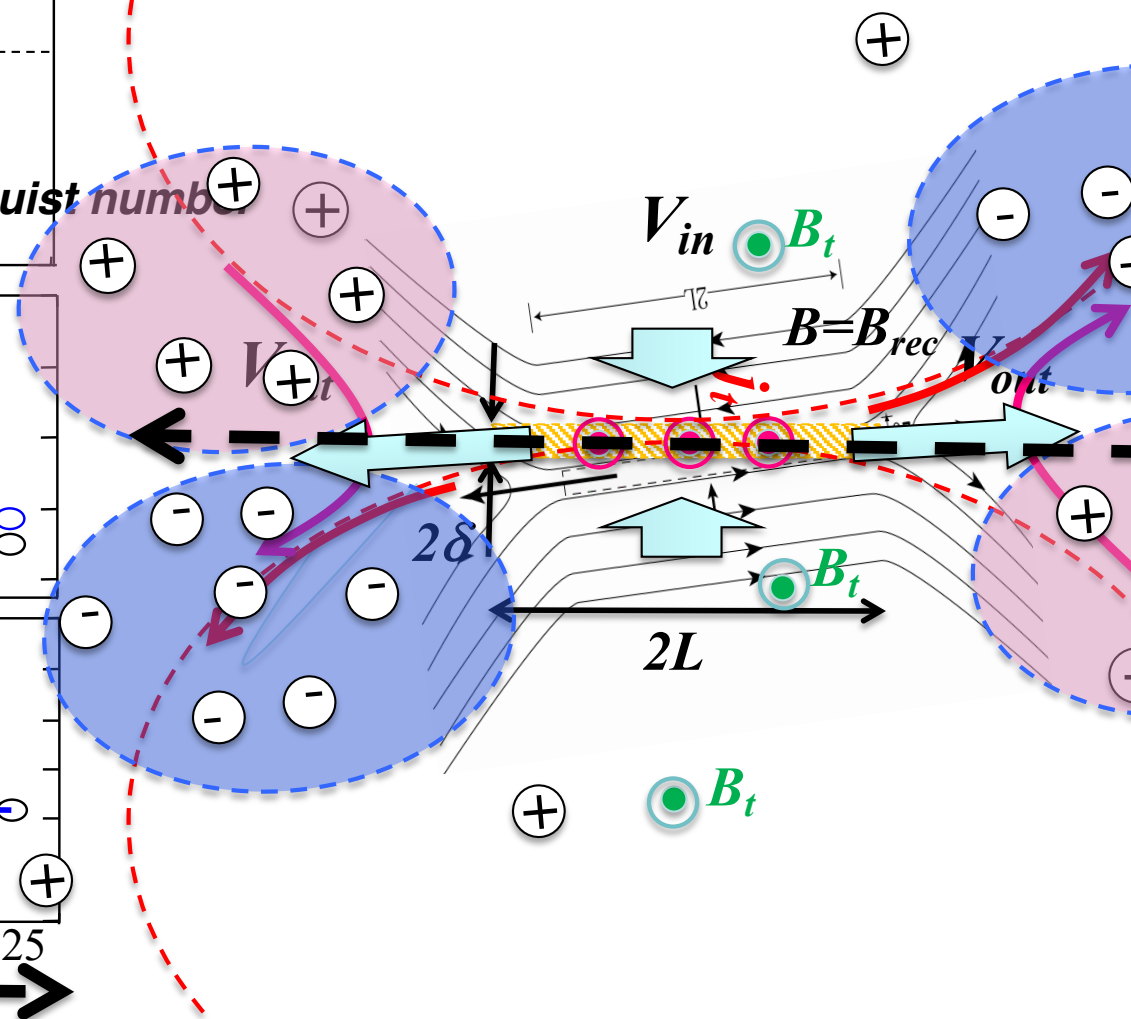
How can we explain its physics? What condition is needed?



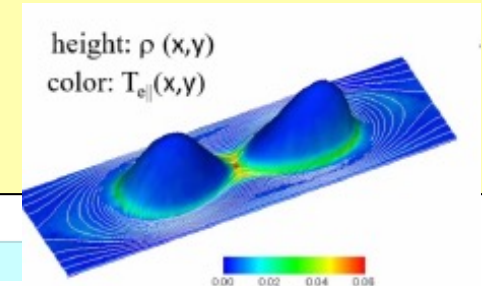
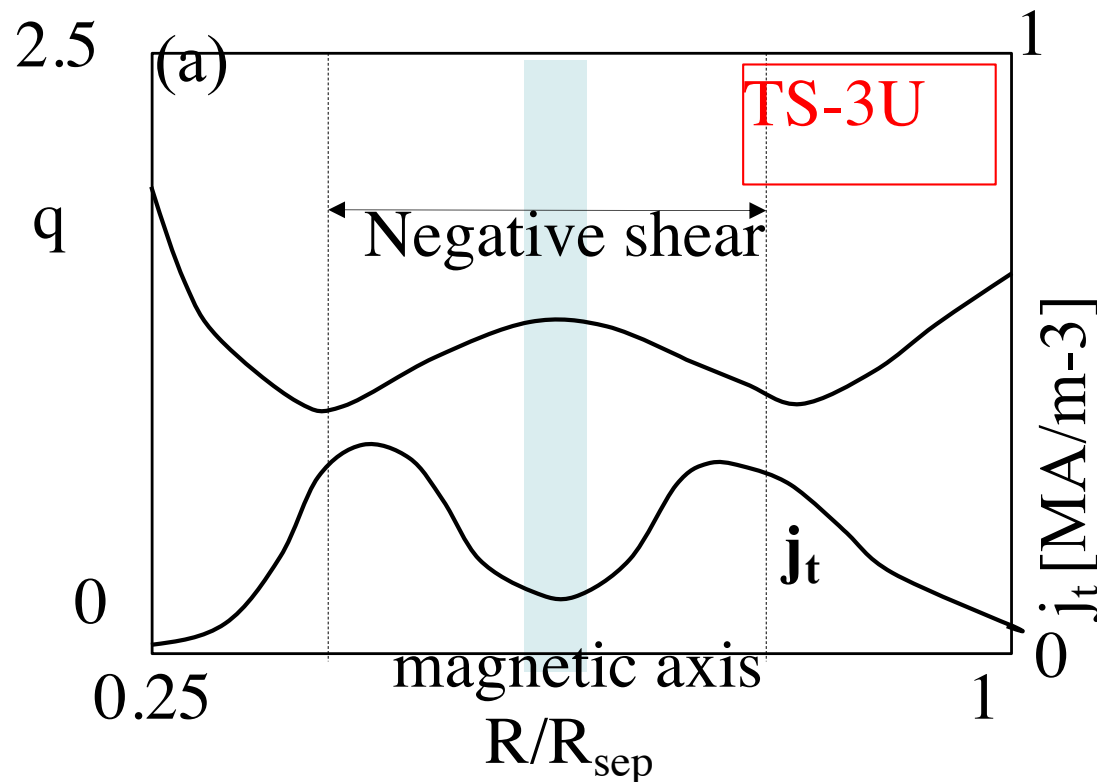
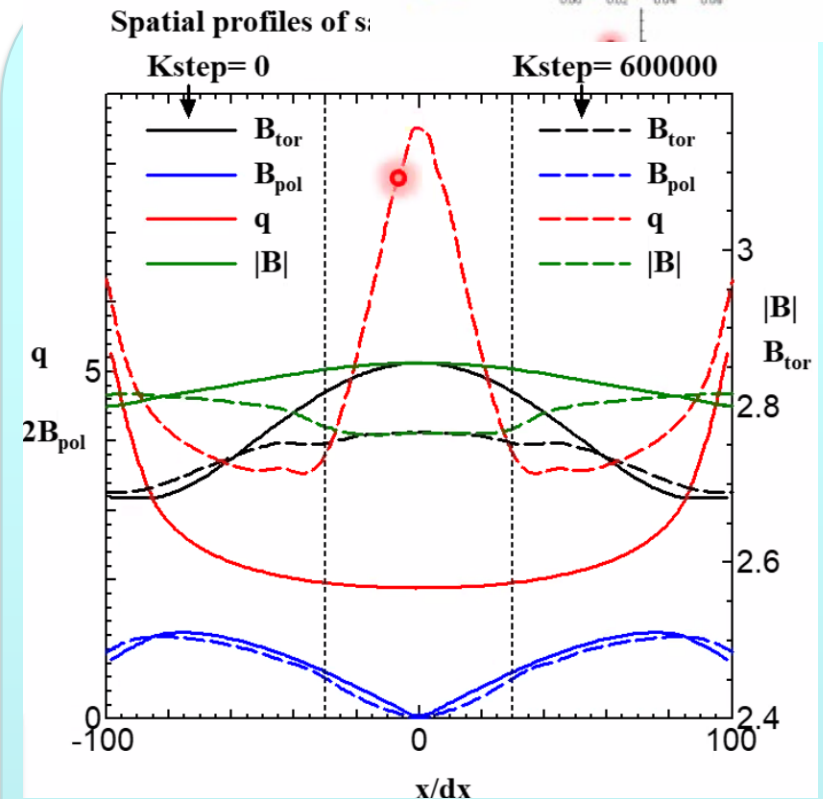
Dependence of ion temperature increment ΔT_i on reconnecting magnetic field B_{rec} of merging tokamak plasmas under constant electron density $n_e \sim 1.5 \times 10^{19} \text{ m}^{-3}$, (b) Dependence of ion kinetic/ thermal energy— increment ΔK_i on reconnecting magnetic field B_{rec} in 2D PIC simulation of slab model reconnection whose guide field is $B_t \sim 4B_{\text{rec}}$.



The ST merging forms
Broad and hollow Ti profile,
Forming absolute minimum-B



The ST merging/reconnection produce hollow T_i and j_t profiles in the new ST, forming reversed-shear profile both in TS-6 experiment and PIC simulation



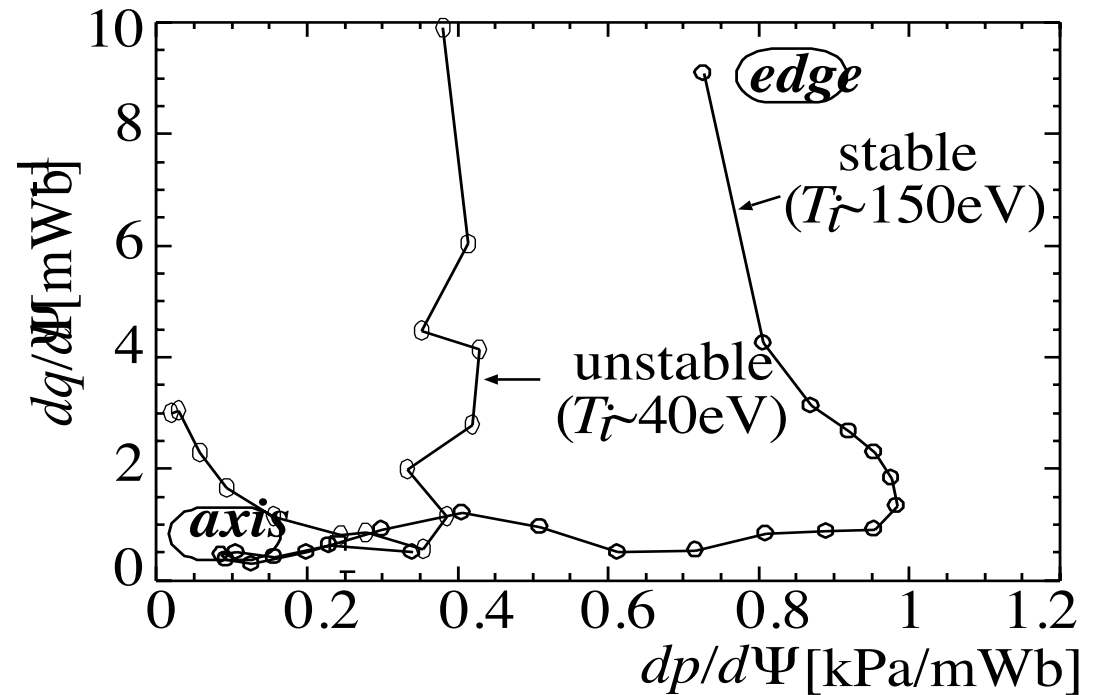
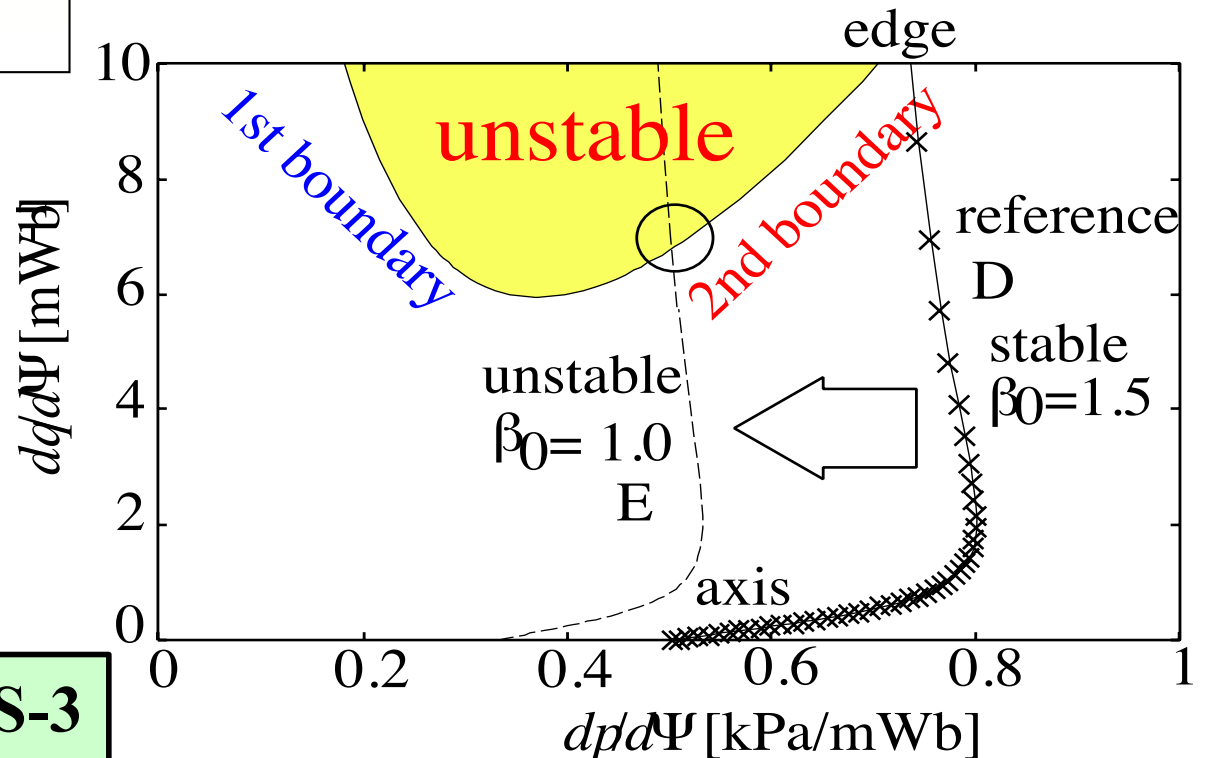
PIC Simulation by Horiuchi
(NIFS, AAPPS-DPP2022)

If hollow current profile,
high pressure grad. and
 high shear at the edge
 $\Rightarrow$ **2nd Stable Regime**

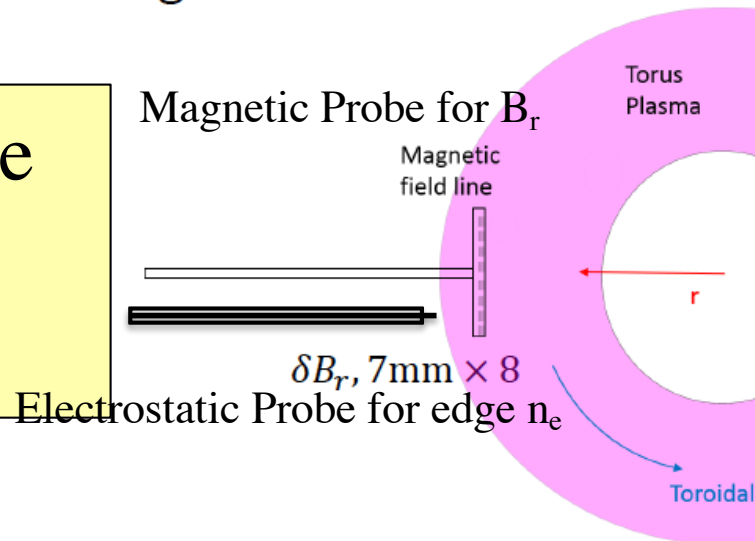
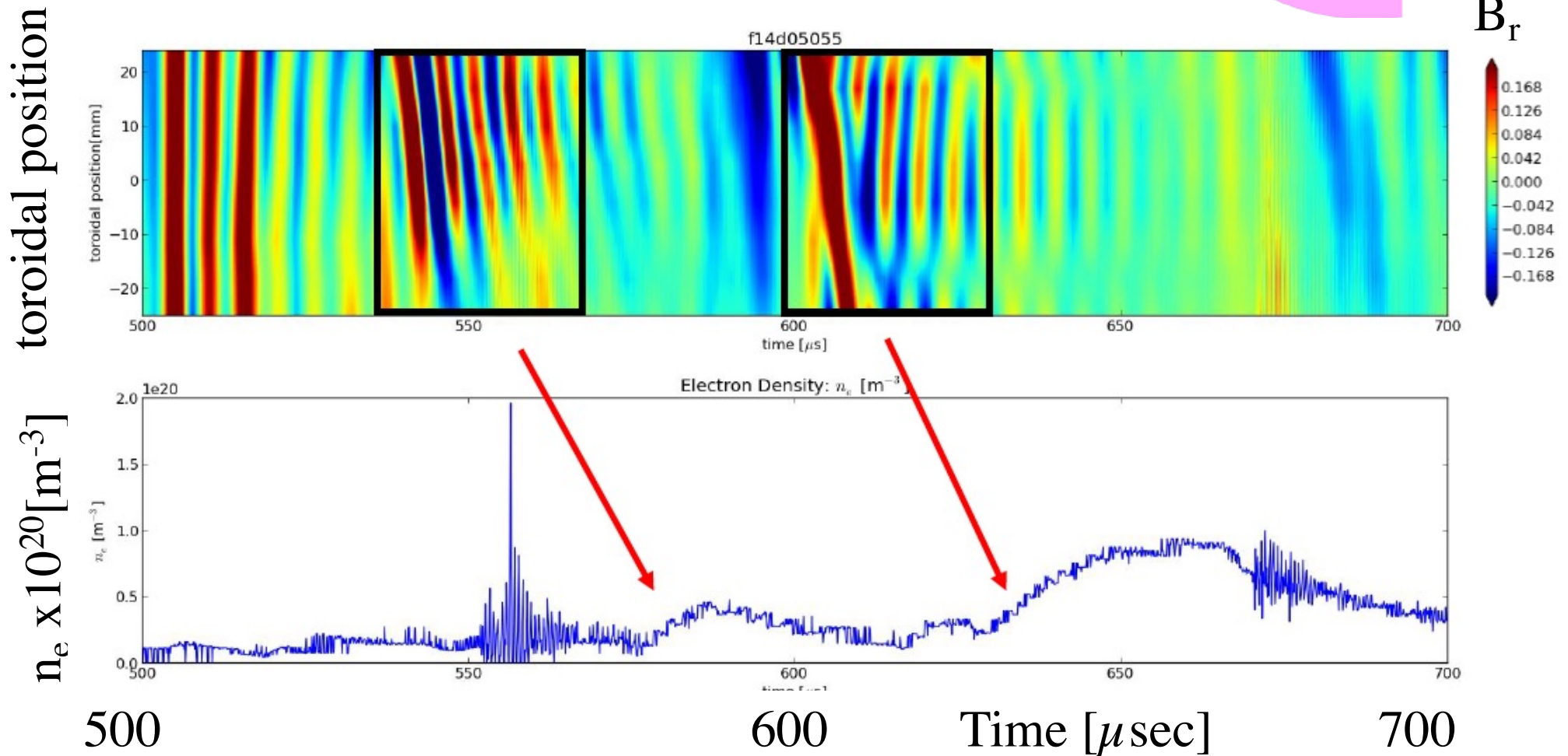
low pressure grad. and
 high shear at the edge
 $\Rightarrow$ **Unstable Regime**

Evidence of 2nd stable ST
 formation
 Hollow current is essential
 to 2nd stability.
 Why not current-driven
 mode?

TS-3

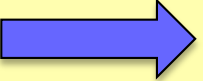


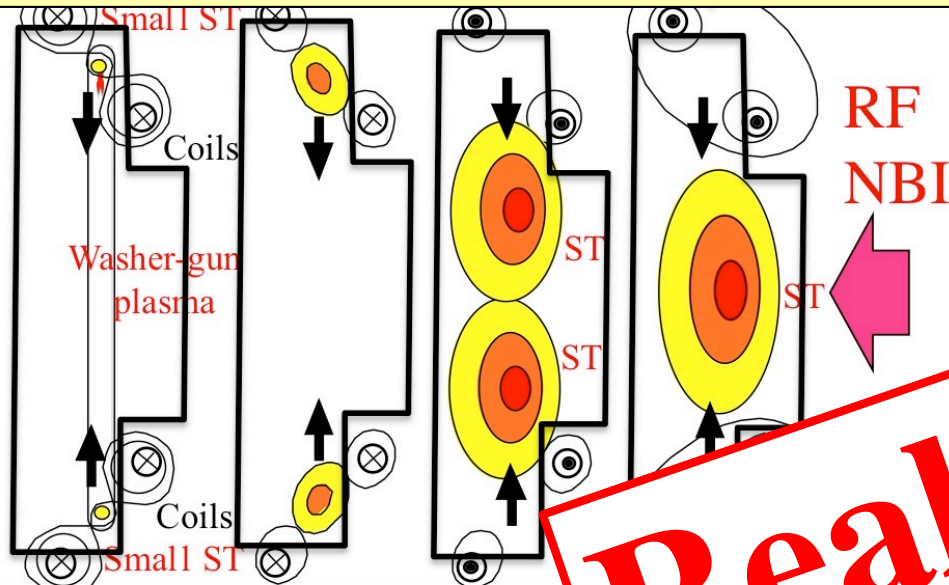
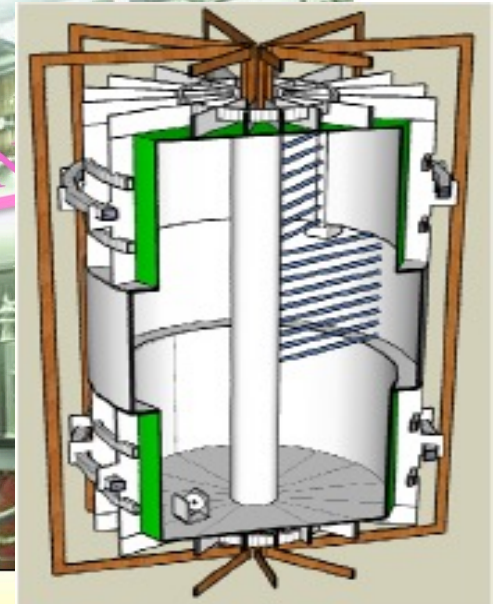
The high- n instabilities cause large increase in the edge density.



How can we use the merging startup for future reactor?

1) No internal PF coils can be installed in fusion reactor.

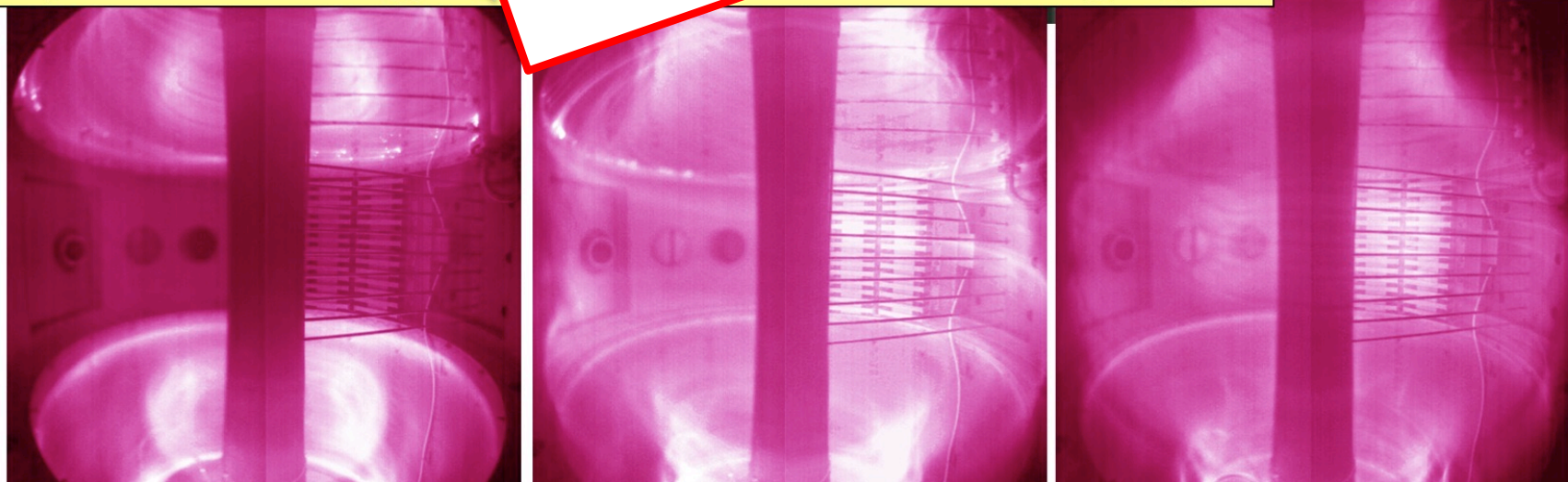
 **Merging startup by external coils in UTST**



1) Ion Heating

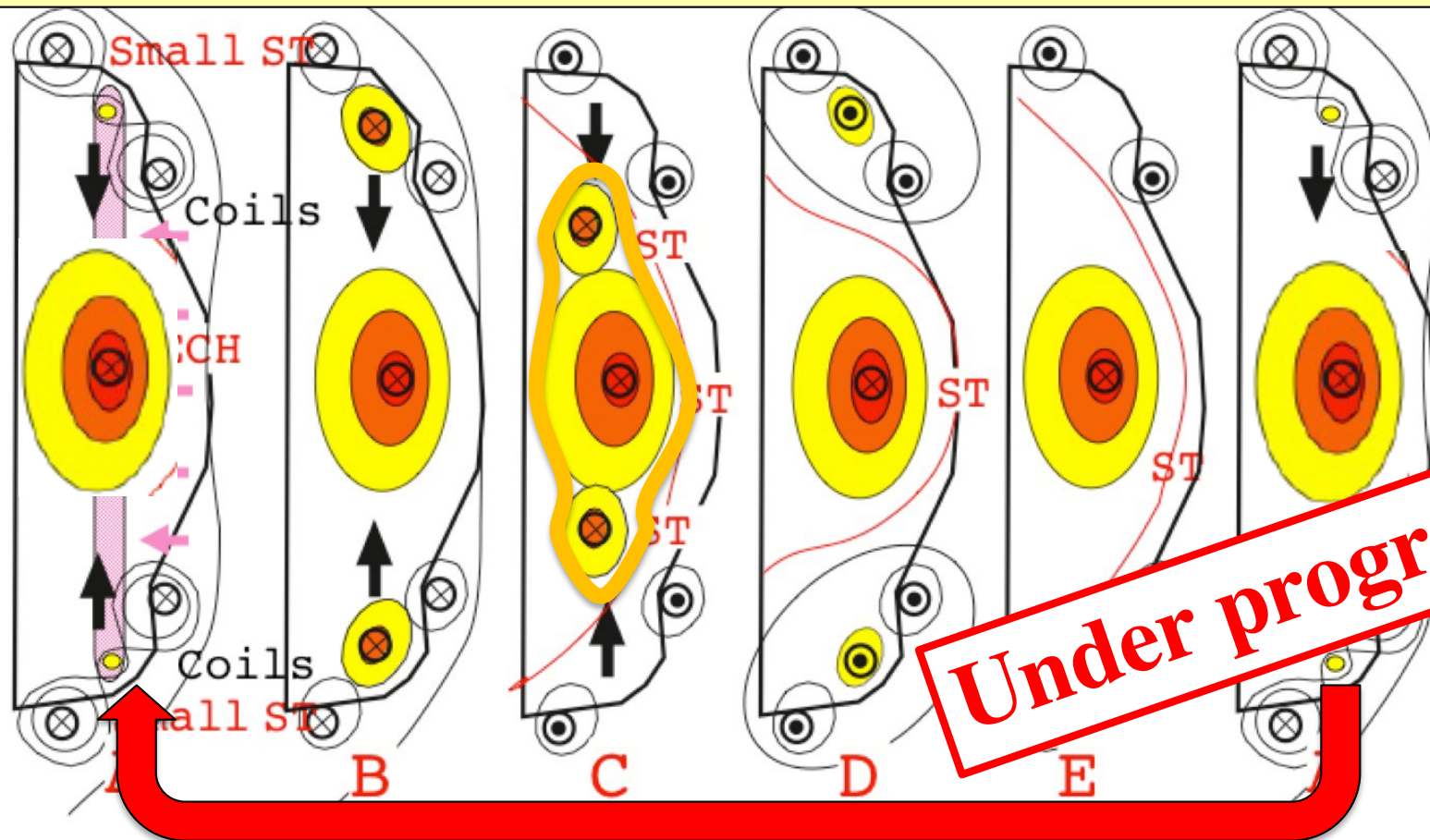
Realized

Steady State Merging

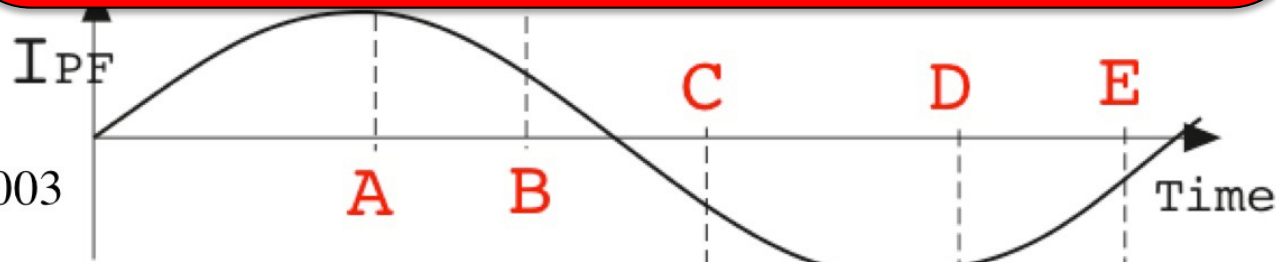


2) Intermittent operation ?

The AC operation of PF coil current realizes intermittent heating & current drive.



Under progress



Summary and Conclusions

1) **Scaling of reconnection heating/ acceleration effects:**

- a) **Major outflow heating of ions** increasing with B_{rec}^2
- b) **Electrostatic potential gap $\Delta\Phi$** increasing with B_{rec} , B_t ,

indicating
$$V_{out} = |E_{rec} \times B| / B^2 \sim E_{rec} / B_t \sim B_{rec}$$
$$T_i \propto m_i V_{out}^2 \propto B_{rec}^2 / n_i$$

c) **Electron acceleration in the downstream**, forming $\Delta\Phi$.

2) **Rec. heating forms high-Beta/ hollow current ST with**

- a) **Reversed shear**
- b) **Absolute minimum-B profile in the 2nd stable regime**
- c) **High-n instabilities and plasma ejection in edge**

The rec. is a promising method for heating ions $> 10\text{keV}$:

➡ **Future directions: (1) Merging startup by external coil & (2) Intermittent rec. heating & current drive.**