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Mulitiple plasmoid formation and flux closure during transient-CHI start-up process on HIST

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Outline

1) Introduction
2) HIST device and diagnostics
3) Experimental topics
    a) Kink instability and relaxation in T-CHI generated plasmas
    b) Flux closure and plasmoid reconnection
4) Summary

Progress on Helicity Injection Experiments

The helicity injection is a promising candidate method for the non-inductive steady-state current drive and plasma start-up.

Electrostatic HICD

Start-up

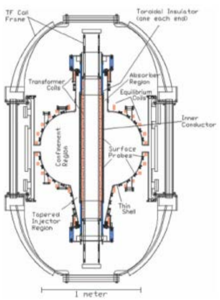
Transient CHI

ST (HIT II, NSTX, HIST, SPECTOR, QUEST)

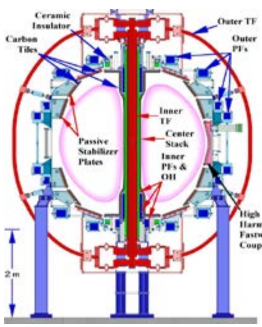
Steady-state

Muti-plusing CHI

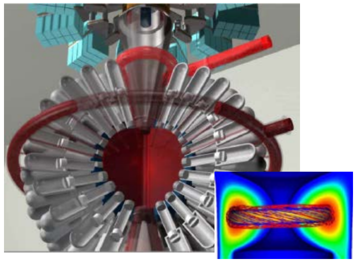
Spheromak(SSPX) ST(HIST)



HIT-II
(U. Washington)

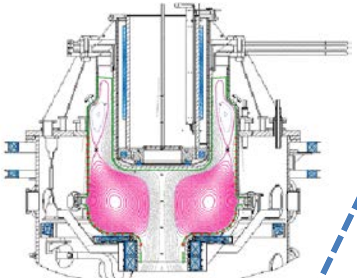


NSTX
(PPPL)



SPECTOR (General Fusion)

HIST
(U. Hyogo)

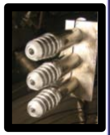


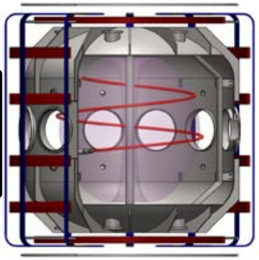
SSPX
(LLNL)

QUEST (Kyusyu U.)

LHI

ST (Pegasus)

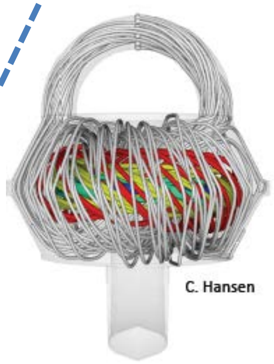




Pegasus
(U. Wisconsin)

Inductive HICD

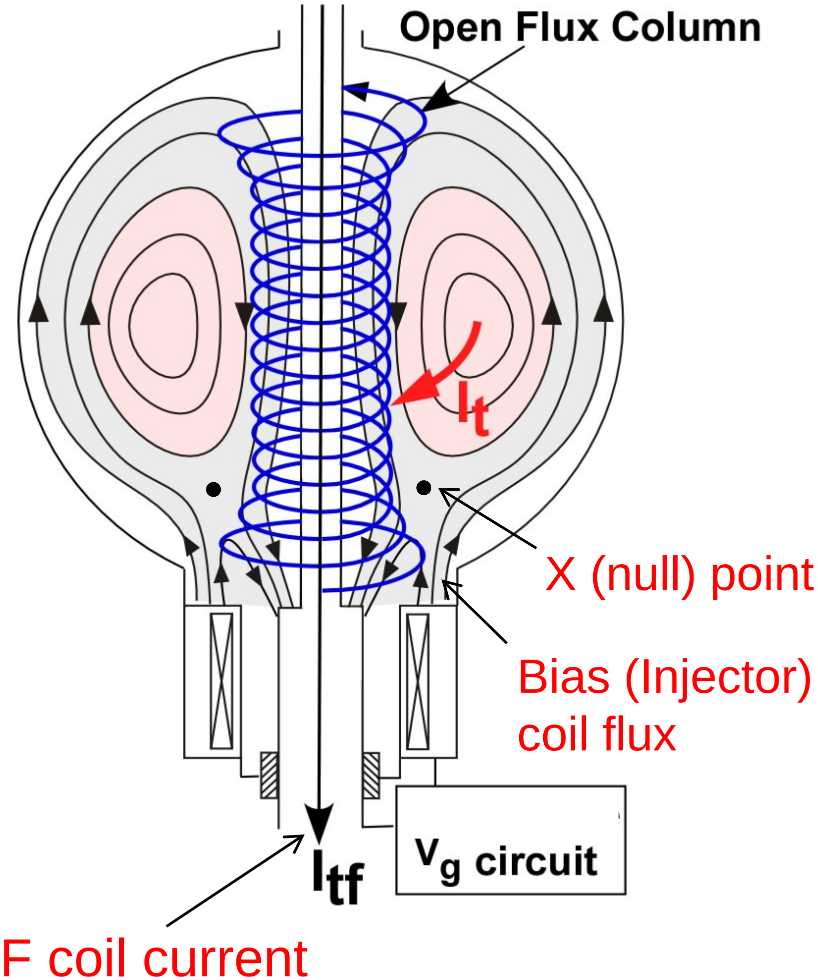
Spheromak (HIT-SI)



HIT-SI
(U. Washington)

Key features of T-CHI method

Gun-spheromak with Center conductor and External toroidal field; Spherical Torus



- T-CHI plasmas are generated by nearly an axisymmetric process.
- Any dynamo mechanism such as non-axisymmetric relaxation is not necessary, but only fast magnetic reconnection is required for the formation of the X-point during the short time scale of the start-up.
- Injection current in the OFC region
- ✓ the Kruskal-Shafranov limit
- T-CHI experiments provides a good platform for studying the MHD relaxation and reconnection physics.

What are key issues in T-CHI experiments ?

■ Formation of closed flux surfaces (flux closure)

- The magnetic reconnection for the flux closure should be completed as soon as possible. How fast the magnetic reconnection occurs during the start-up time scale ?
- The reconnection rate slows down at a large toroidal guide field and/or a high S number. What is the fast reconnection mechanism ?

■ Optimization of current density profile

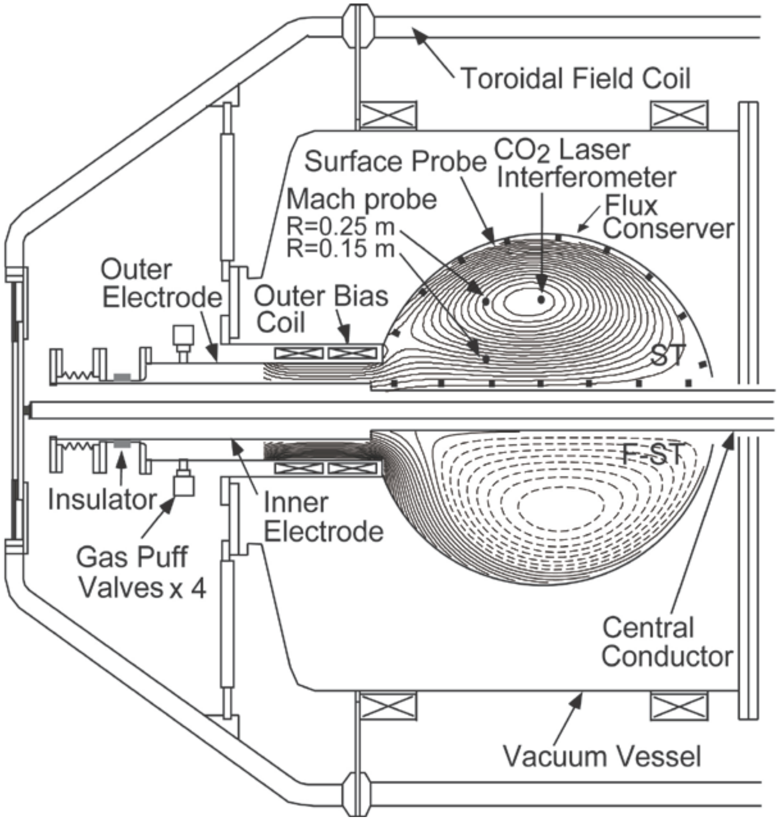
- The excess edge injection current causes the n=1 kink instability on the OFC. Absorber arc sometimes occurs at the rear gap of the FC. How to control the current profiles ?

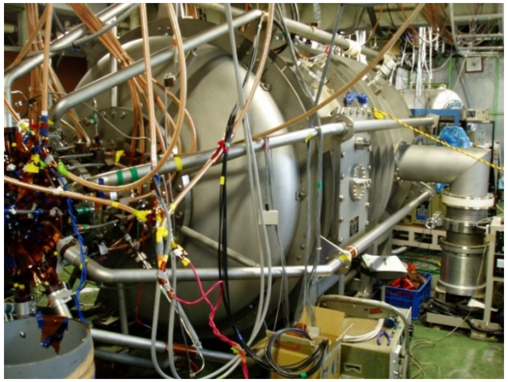
■ Verification of CHI and LHI scaling

$$\frac{dK}{dt} = -K/\tau_K + 2V_{gun}\Psi_{bias}$$

- Helicity balance based on the helicity conservation law in the presence of high TF should be experimentally verified.

HIST device





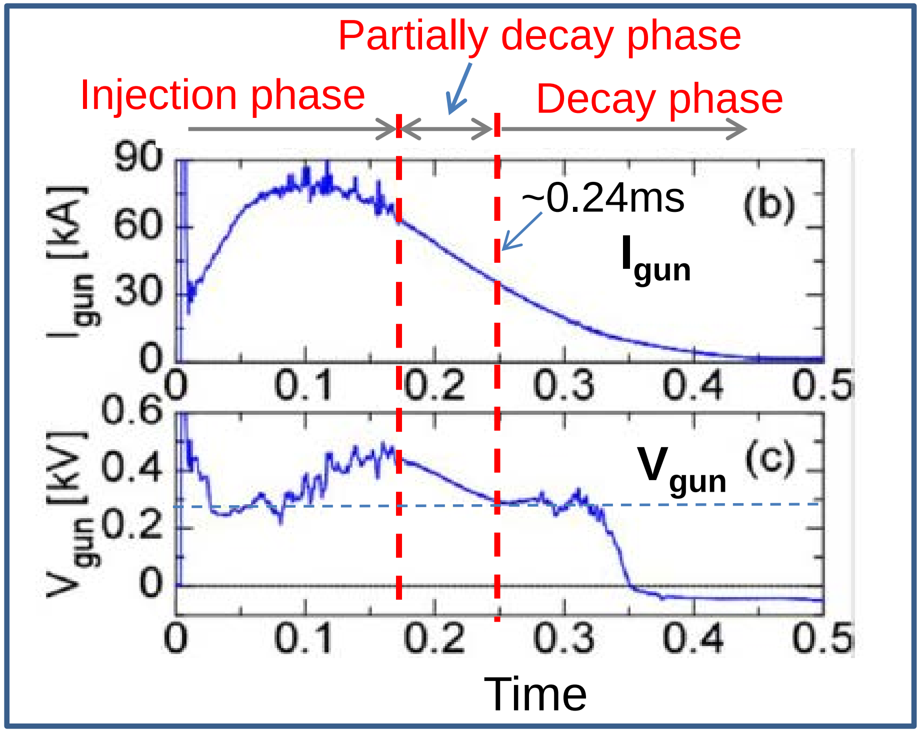
- **HIST parameters**

  R=0.3 m, a=0.24 m, A=1.25

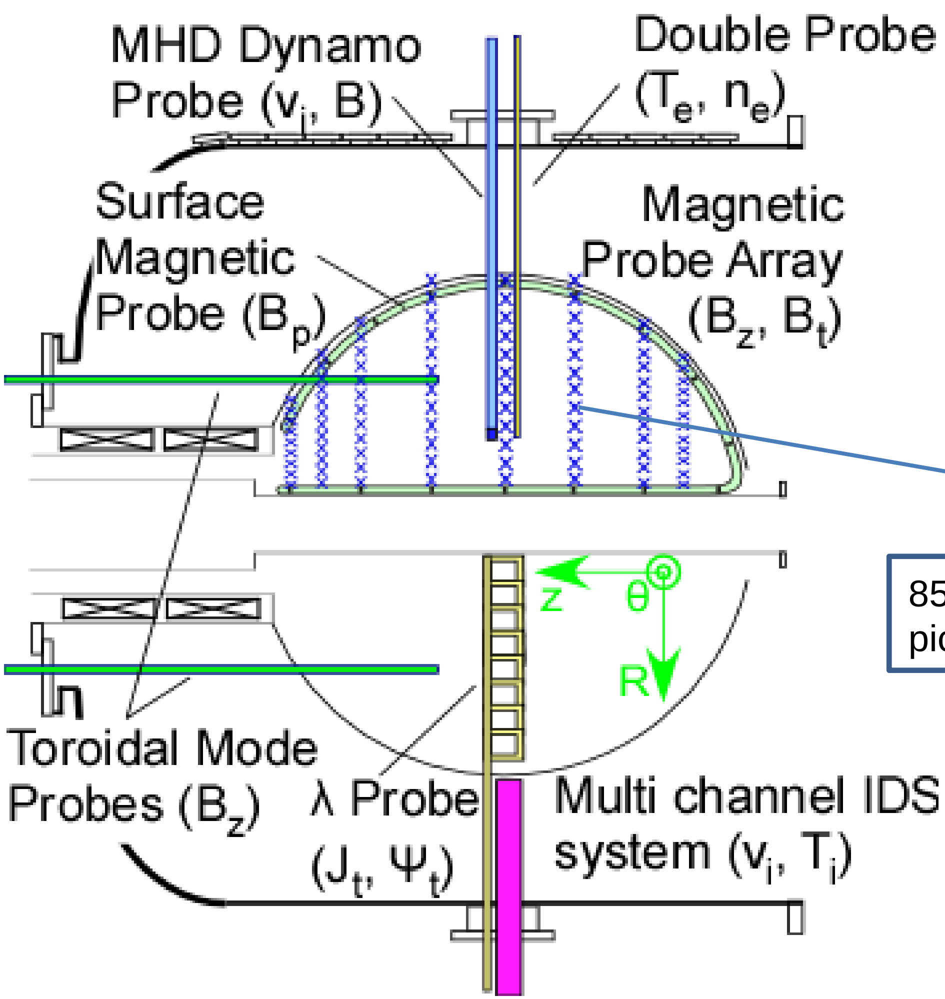
  TF coil current I_{tf}=150-250 kA

- **T-CHI capacitor banks**

  Voltage : V = 5 kV, C = 2.9 mF



Diagnostics



85 x B_z and 85 x B_t pick-up coils

Diagnostics

- **Surface magnetic probes:** I_{tor}
- **Internal magnetic probes:** B_θ, B_z, (B_r)
- **λ probe:** J_t, ψ_t
- **Dynamo probes:** V_θ, V_z, V_r, B_θ, B_z, B_r
- **Hall probe:** J_θ, J_z, J_r
- **Double electrostatic probe :** T_e, n_e
- **Ion Doppler Spectroscopy:** $T_{D.i}$
- **Electric field probe:** E_r
- **CO_2 laser interferometer** $\langle n_e \rangle$

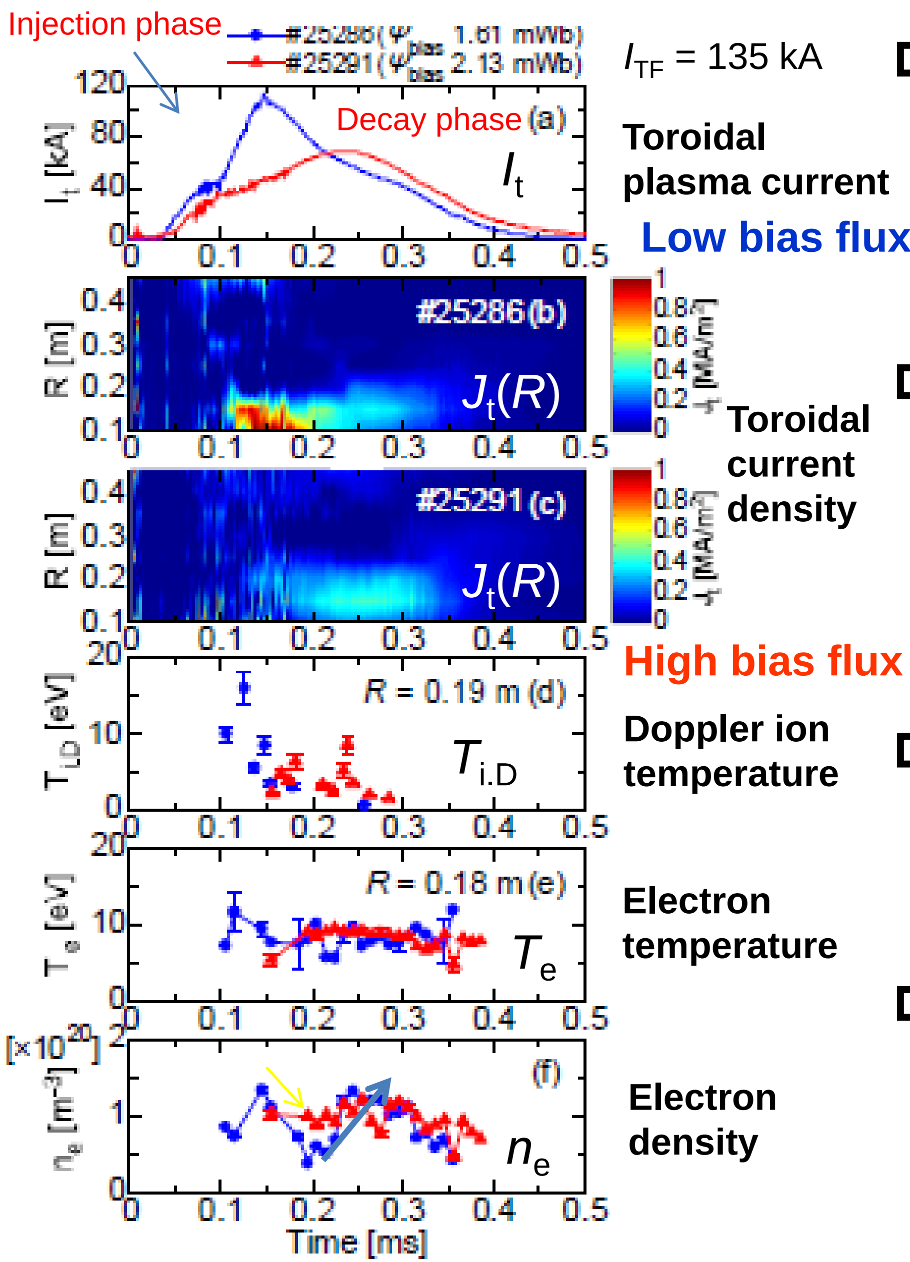
Channel distance	
ΔR	20 - 50 mm
ΔZ	74 or 148 mm

Poloidal flux

$$\Psi_p = \int_0^R 2\pi r B_z(t) dr$$

by assuming axisymmetry

Characteristics of T-CHI generated ST plasmas



- Typical T-CHI discharge characterized with varying the amount of the bias (injector) flux.

  Blue line : Low bias flux

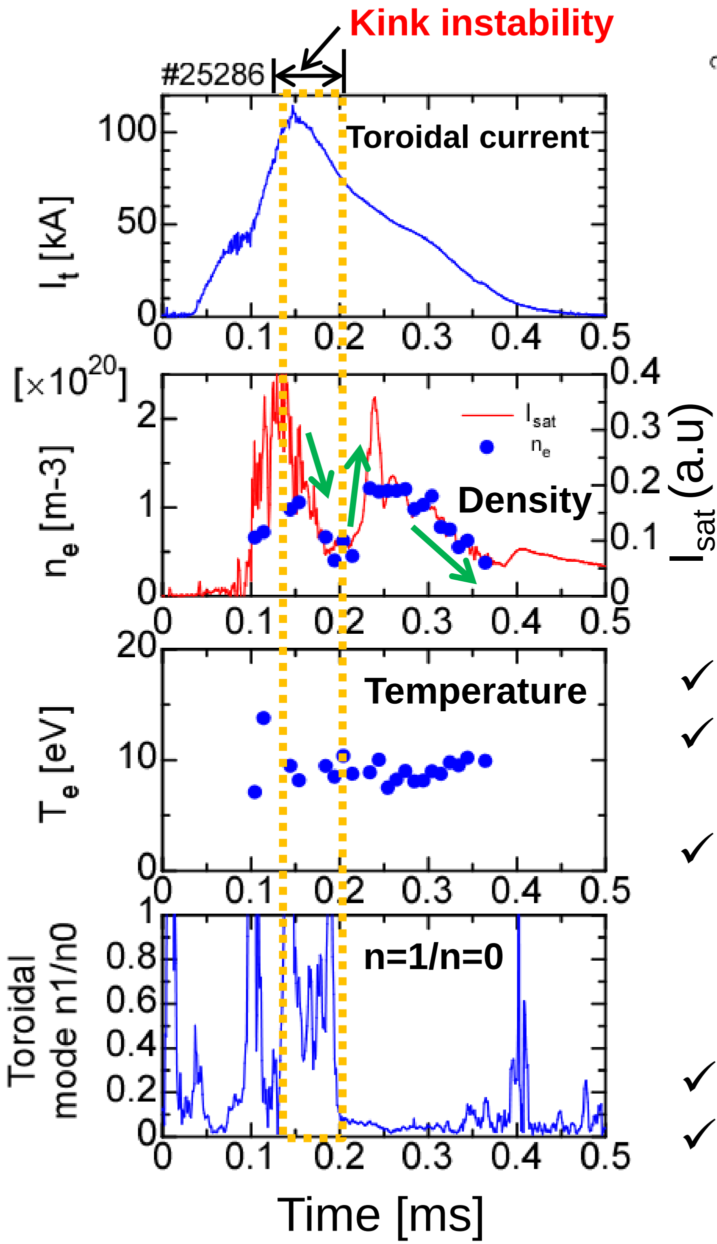
  Red line : High bias flux

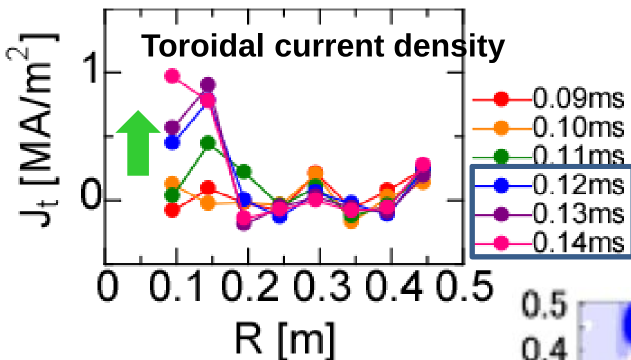
- In the low bias flux case, the rise time of I_t is faster and its peak value is higher compared to the high bias case. Time evolution of I_t is divided by the injection phase and the decay phase.

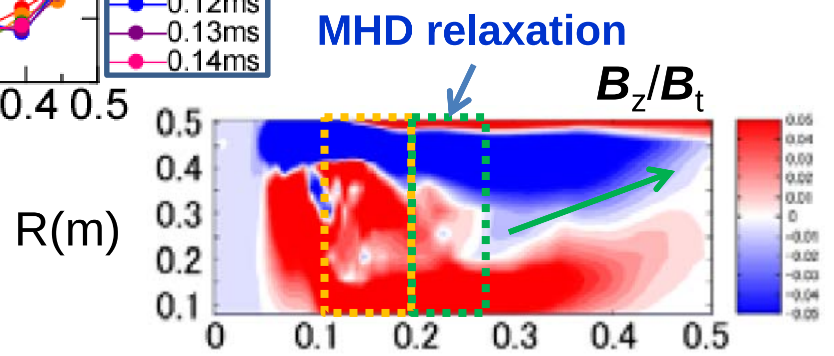
- We found that the radial profile of the toroidal current density $J_t(R)$ depends on the amount of injector flux.

- The current density J_t is concentrated mainly in the open central column (OFC). Therefore, $J_t(R)$ in the low bias flux shows a kink instability occurring at t = 0.14 ms.

Kink instability and MHD relaxation







A) During the injection phase ➡ **Kink instability**

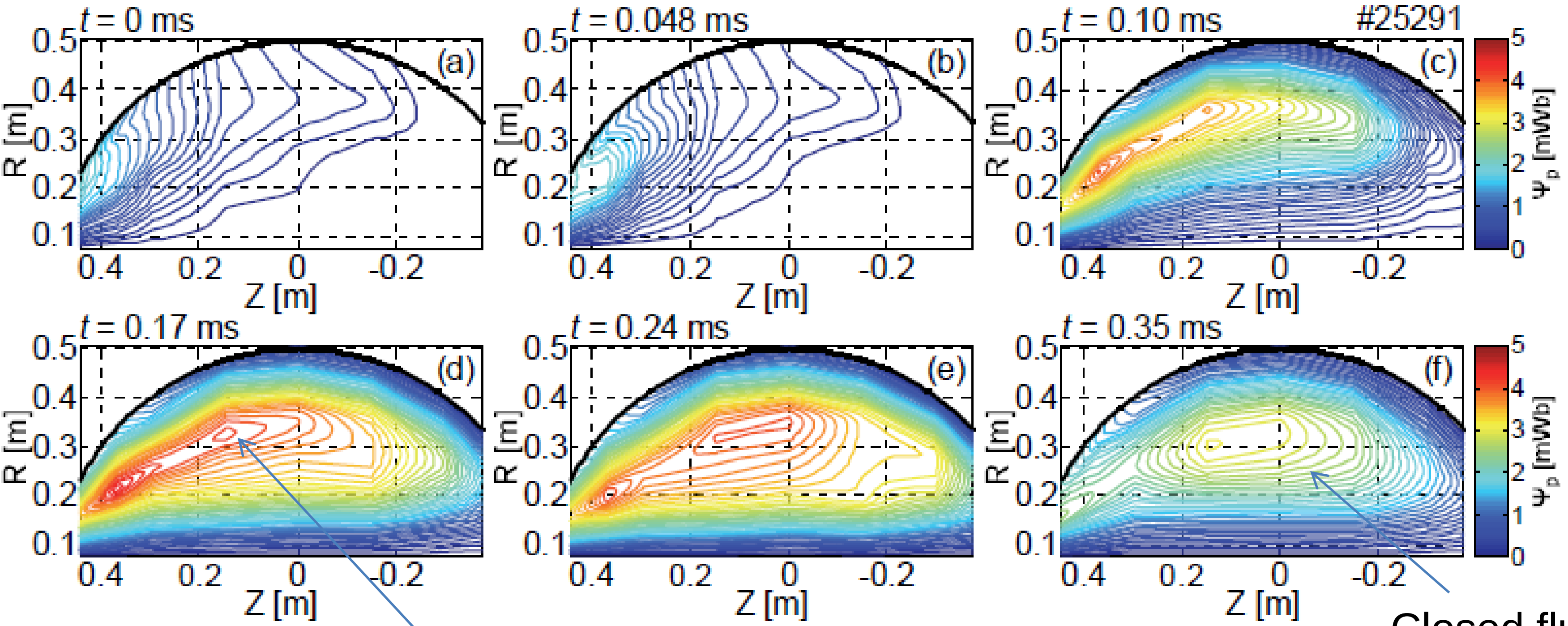
- ✓ Inner edge current increases and becomes unstable.
- ✓ The density decreases rapidly, but temperature does not so change.
- ✓ Correspondingly, the n=1 toroidal mode grows rapidly at t=0.12 ms

B) During the decay phase ➡ **MHD relaxation**

- ✓ Density recovers shortly and the n=1 mode goes down
- ✓ The plasma relaxes into a stable state.

Poloidal flux contour plots from 2D magnetic probe measurements

High bias flux case



Closed flux

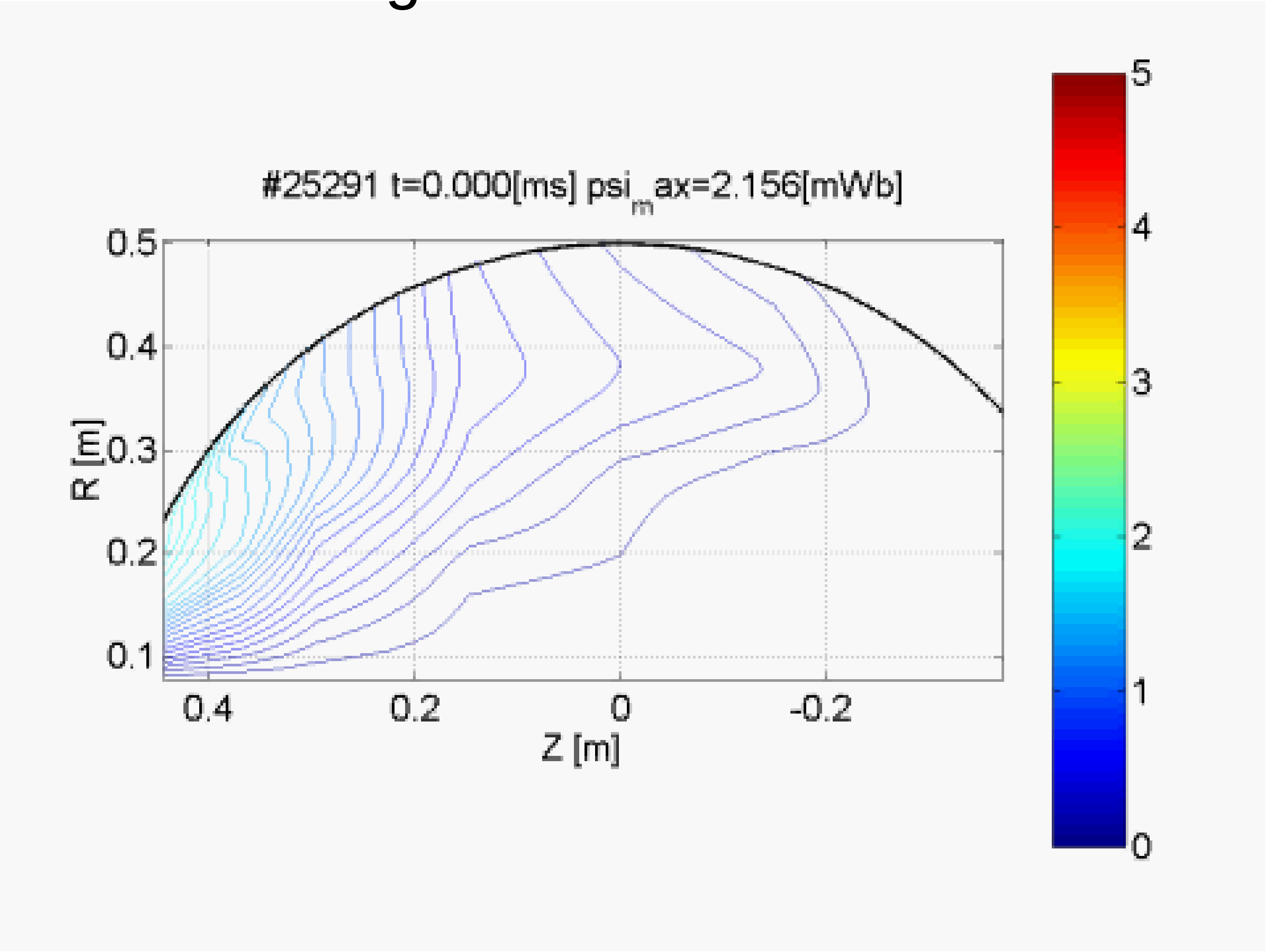
Small-size plasmoid

Decay phase

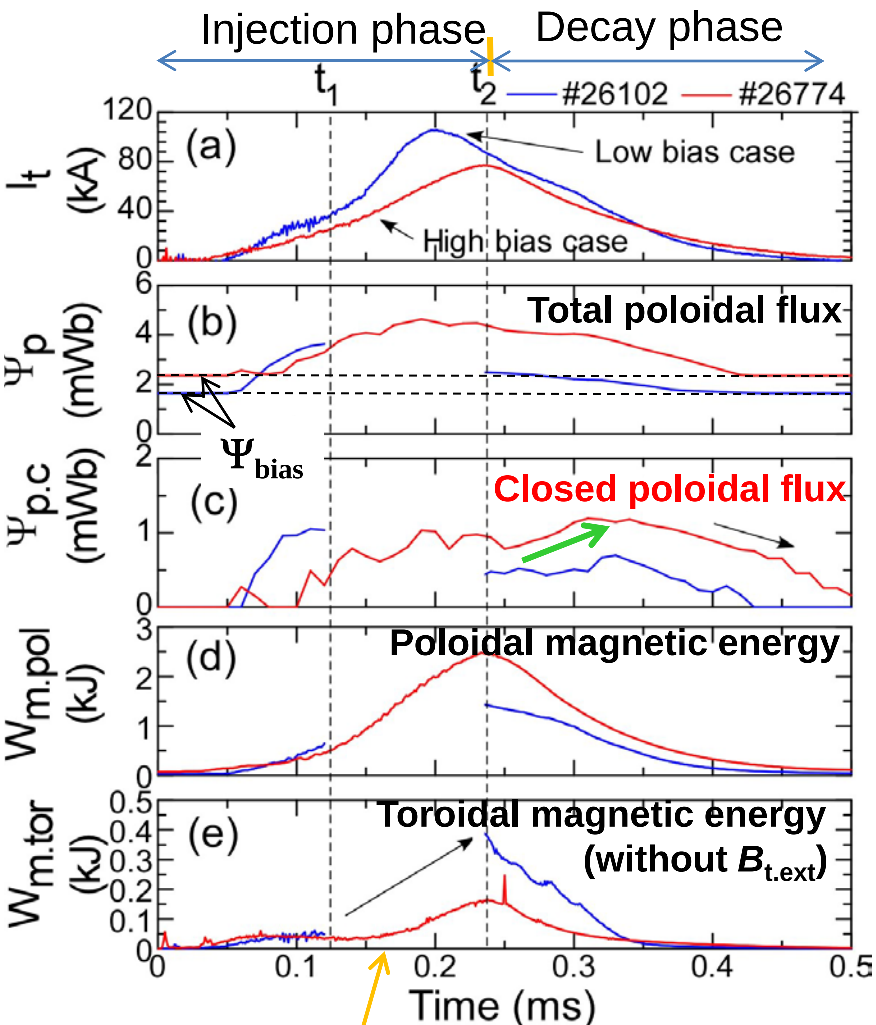
Time evolution of poloidal flux contour plots

Ψ_p

High bias flux case



Closed flux formation and flux conversion



Kink relaxation period in the low bias case

- The **stable closed configuration** can be obtained under the high bias flux case.
- The ratio of poloidal flux/the bias poloidal flux in the both cases is about 2.
  Flux amplification (Ψ_p/Ψ_{bias}) = 2
- In the high bias case, the ratio of closed poloidal flux /the total poloidal flux increases from 25 % to 35 %.

$$\Psi_{p.closed}/\Psi_p = 25\text{-}35\ \%$$

Poloidal magnetic filed energy $W_{m.pol}$

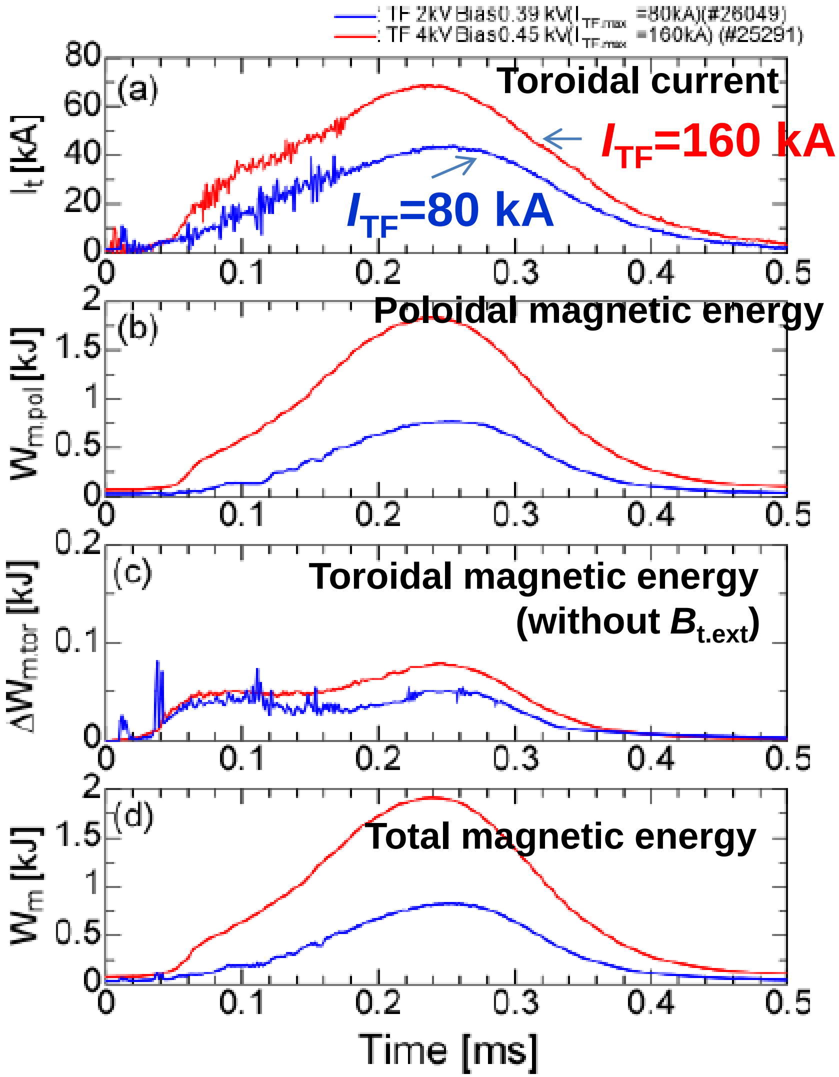
Kink relaxation

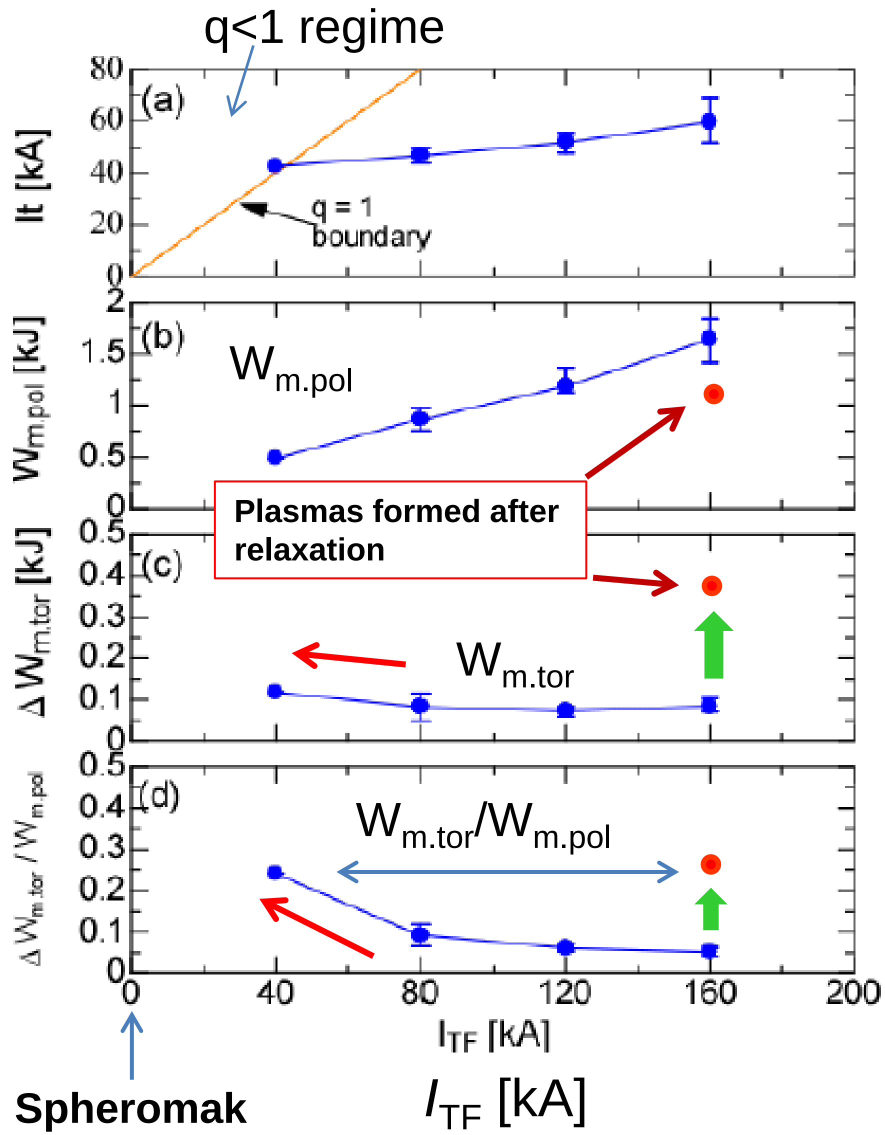
Toroidal magnetic field energy $W_{m.tor}$

✓ The toroidal (injection) current in the OFC is converted to the poloidal current.

◆ This should be utilized for the steady-state CHI dynamo current drive.

Dependence of TF coil current I_{TF}



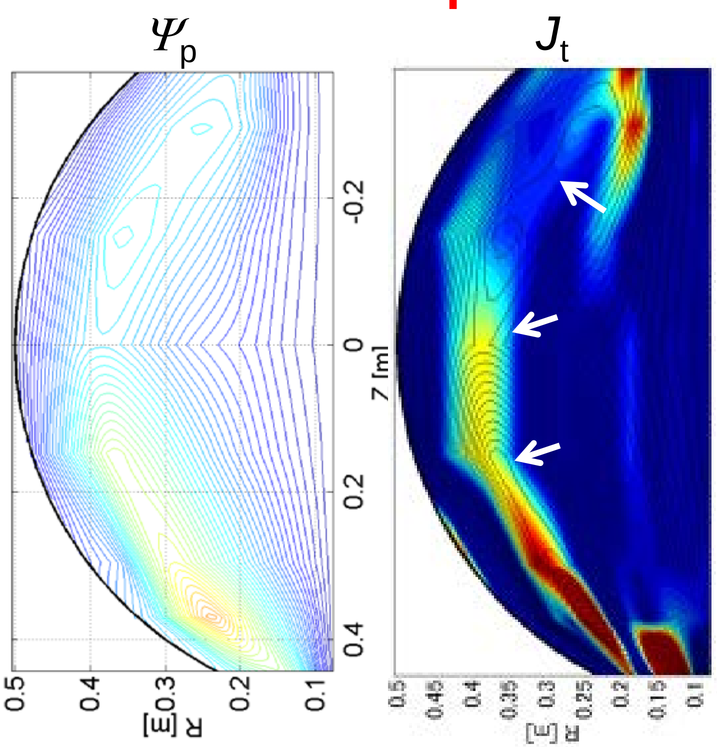


✓ Paramagnetic toroidal flux in the core region increases.

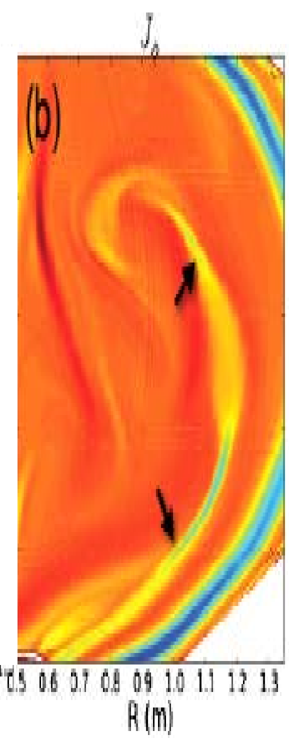
Why is the current density localized and extended so long ?

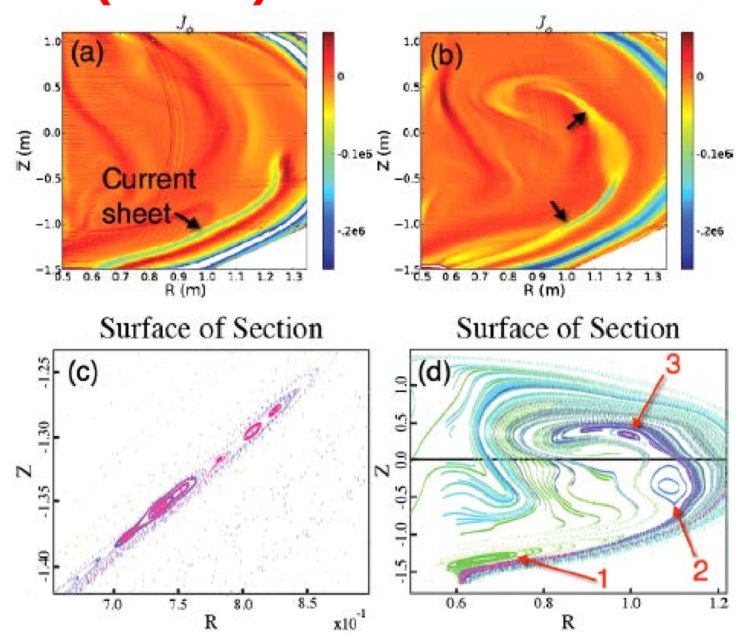
- **Ebrahimi's MHD simulation predicted that at high S > 3000, the elongated current sheet becomes tearing unstable, then the transition to plasmoid instability occurs during the injection phase, leading to the fast flux closure.**
- **In the HIST experiments, formation of the elongated current sheet and two or three plasmoids have been observed during T-CHI.**

HIST Exp.



MHD Simulation (NSTX)

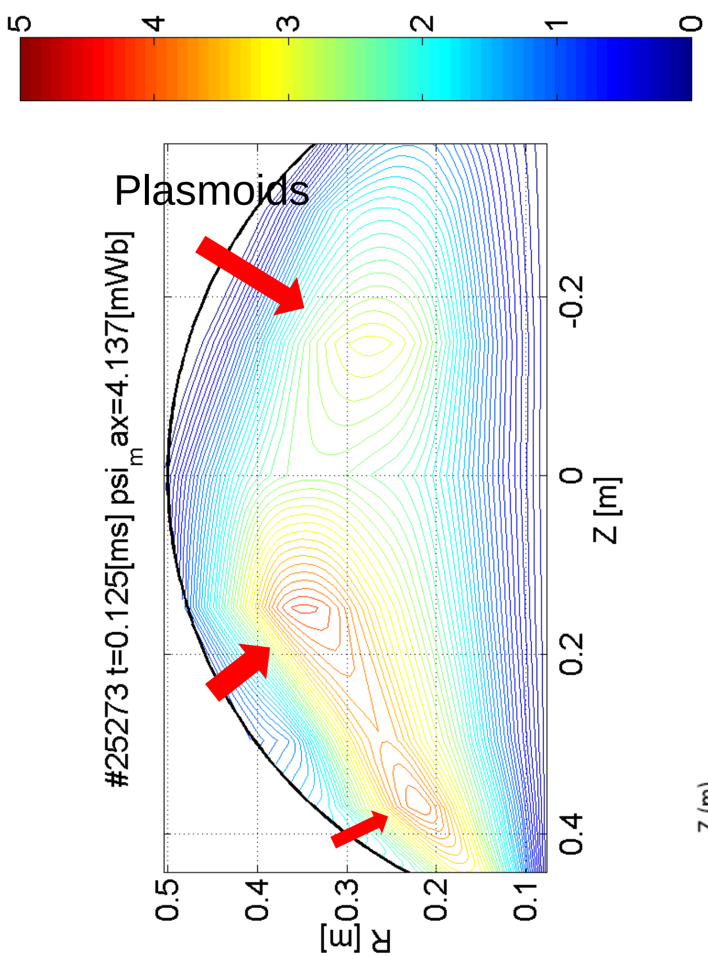


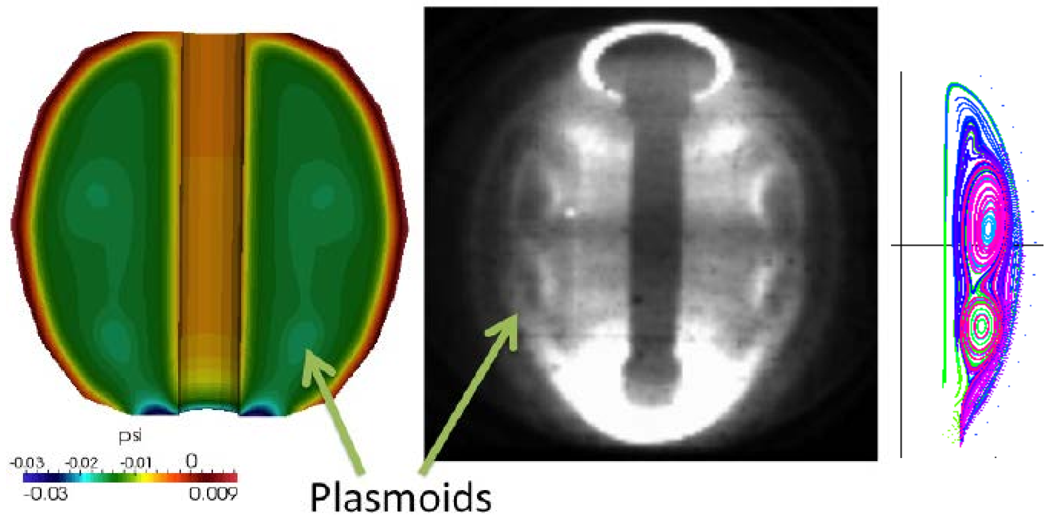


F. Ebrahimi and R. Raman, PRL, 114, 205003 (2015).

Doublet type equilibrium configuration formed by two discrete plasmoids

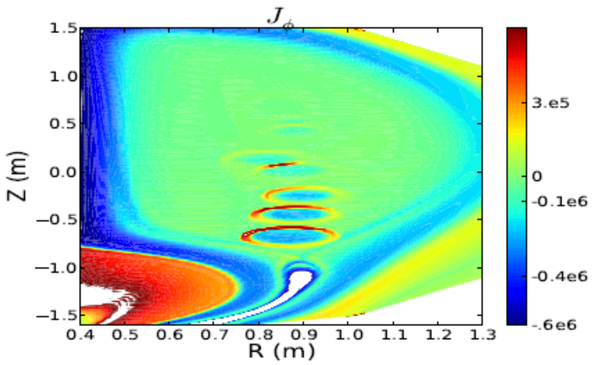
HIST exp.





T_e~5 eV, n~ 4-5 x10^{18} m^{-3}, B_{rec}~0.01 T, L~ 1m, S=2000-4000.

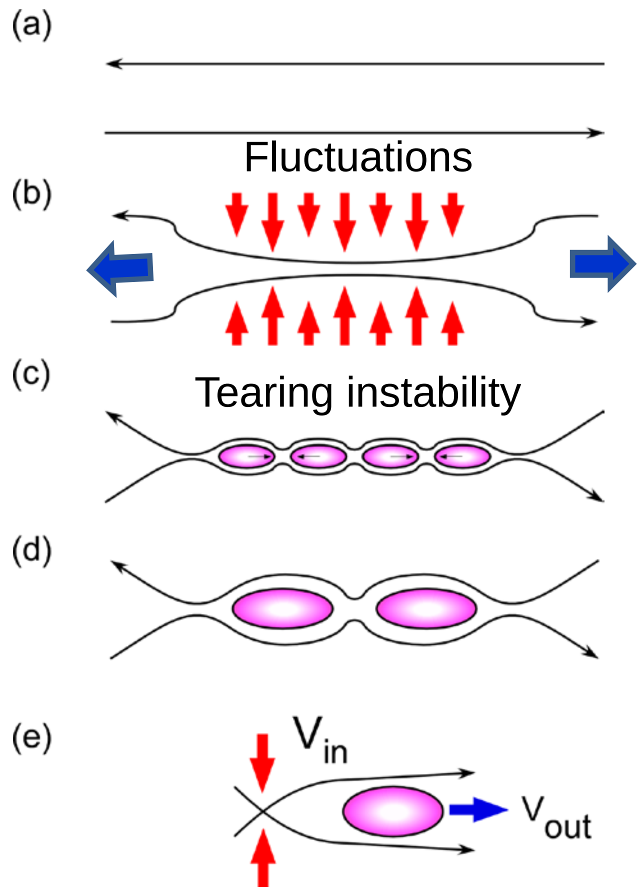
- ✓ Camera image during CHI discharge in NSTX shows the formation of two discrete plasmoids.



- ✓ Plasmoid instability with continued injection of plasmoid is observed during the injection phase.(S~29000)

F. Ebrahimi and R. Raman, PRL, 114, 205003 (2015).

Spontaneous magnetic reconnection driven by plasmoid instability



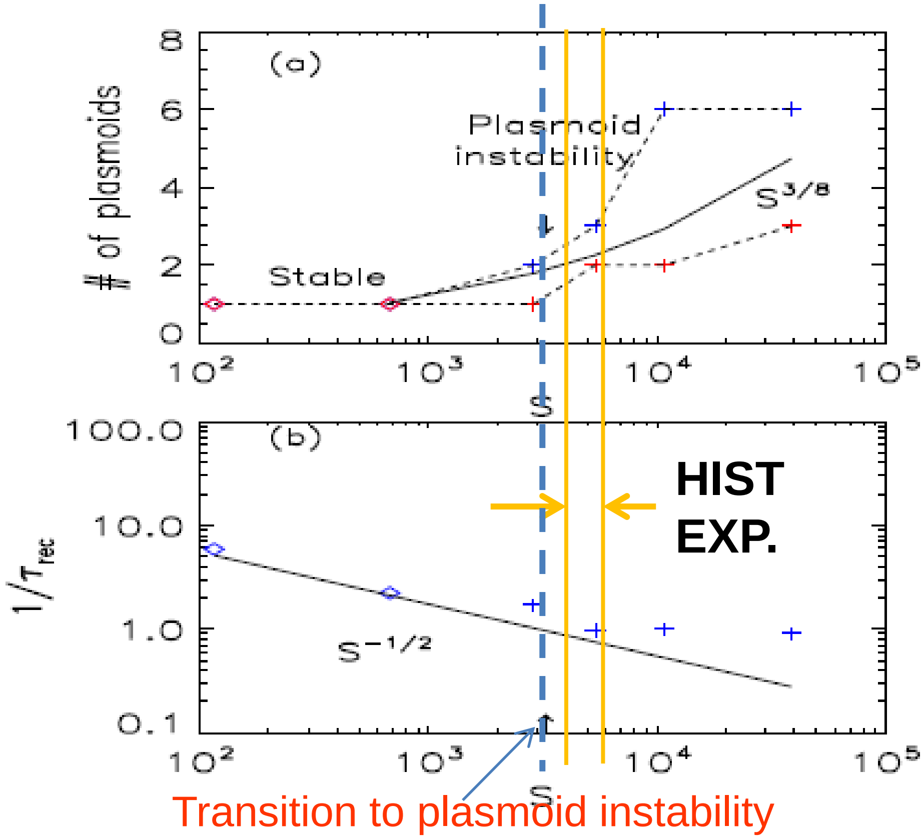
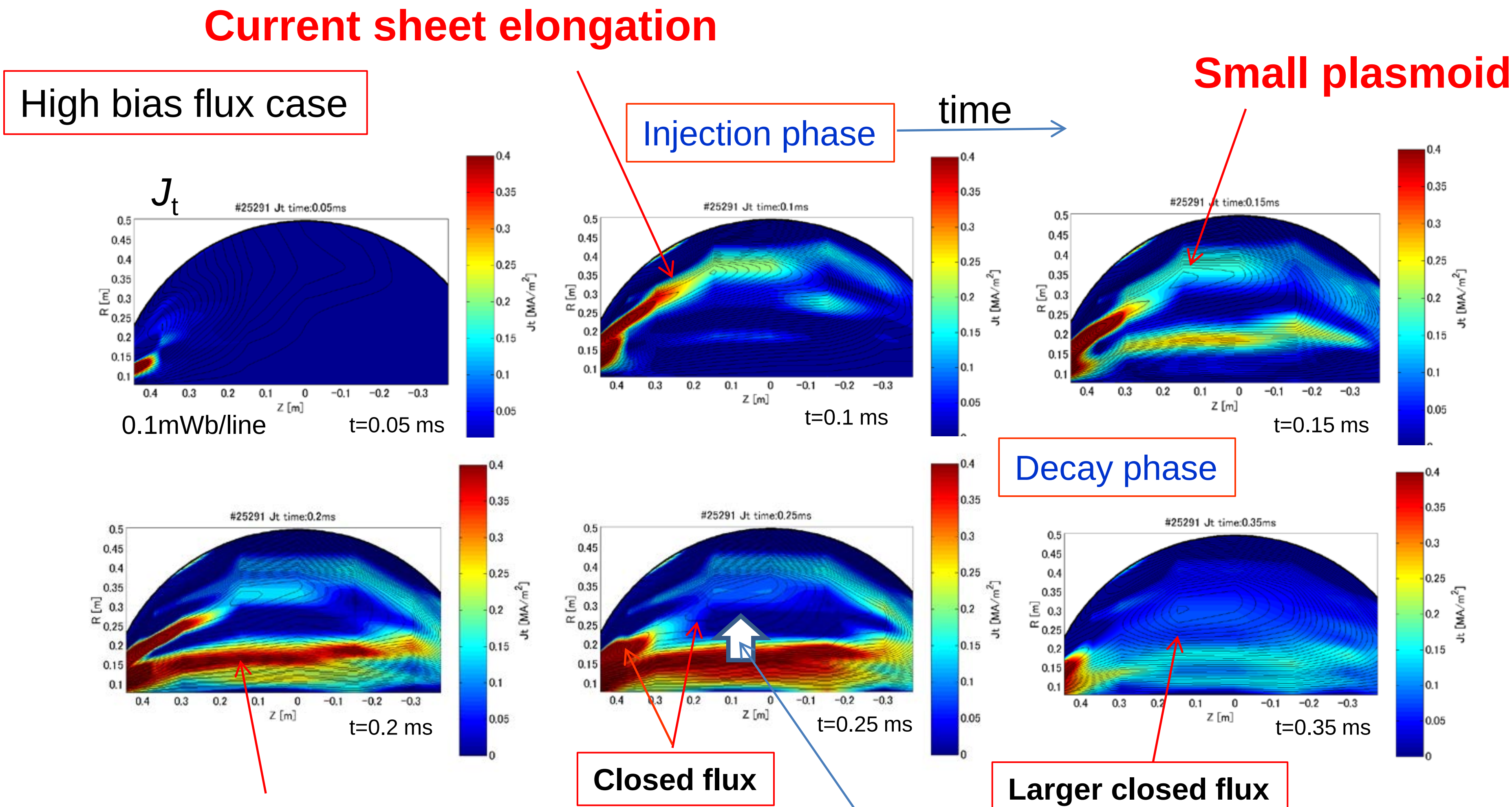


FIG. 3 (color online). (a) Number of plasmoids vs S. Blue: small sized transient plasmoids during the early phase of discharge (Fig. 2). Red: large scale and persistent plasmoids during the later phase of discharge. The solid line is the linear theoretical S scaling. (b) The reconnection rate, $1/\tau_{rec}$ vs S. The transition to plasmoid instability is shown at $S \sim 3000$. The solid line is the S-P scaling.

✓ Plasmoid formation allows the fast reconnection rate, nearly independent of Lundquist number S at the high S regime.

F. Ebrahimi and R. Raman, Phys. Rev. Lett. **114**, 205003 (2015)

Current sheet elongation, magnetic reconnection and small-size plasmoids



Current sheet on the OFC surface

⬇

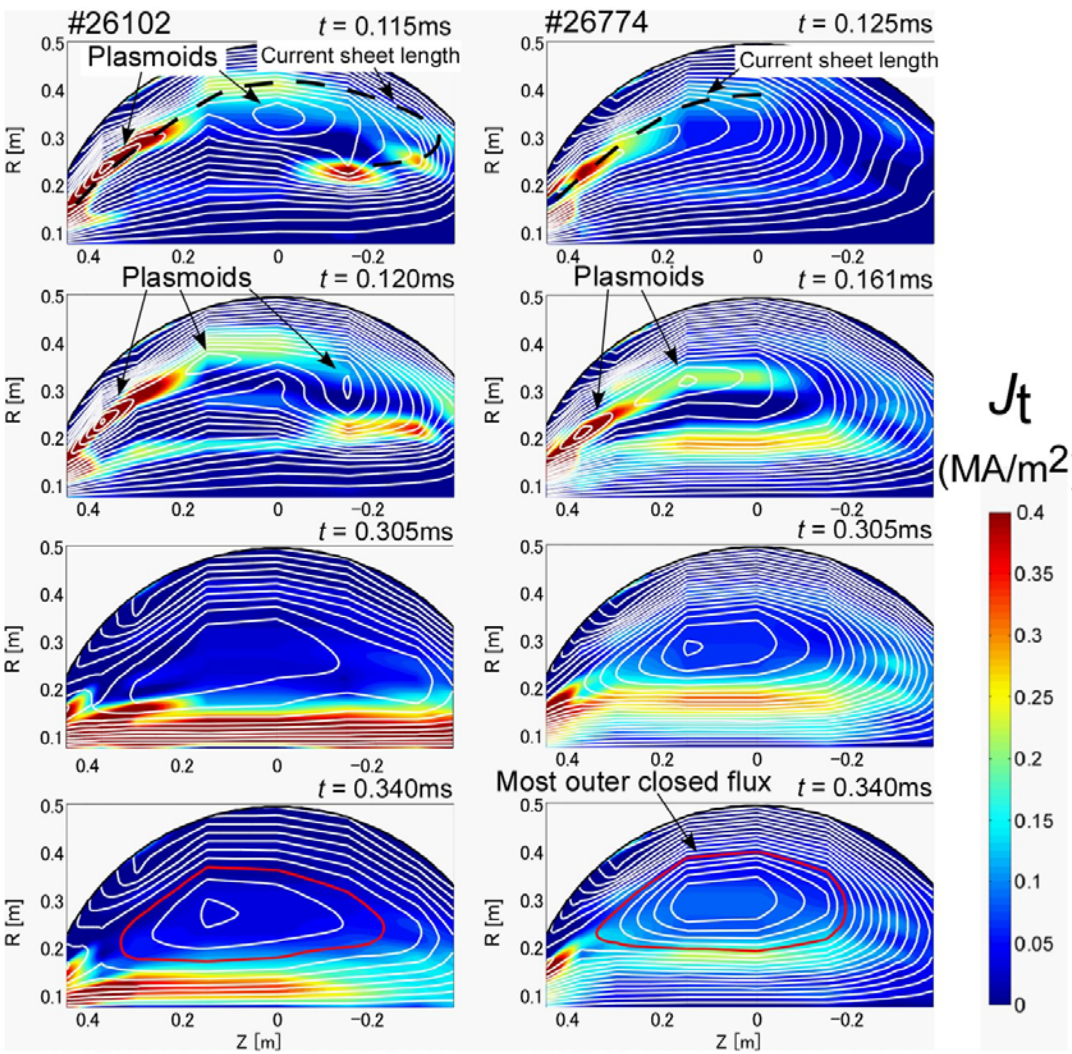
Diamagnetic B_t in the OFC

✓ **Inner edge current diffuses into the small plasmoid, leading to a large-scale closed flux.**

Comparison of J_t and Ψ_p contours between in both cases

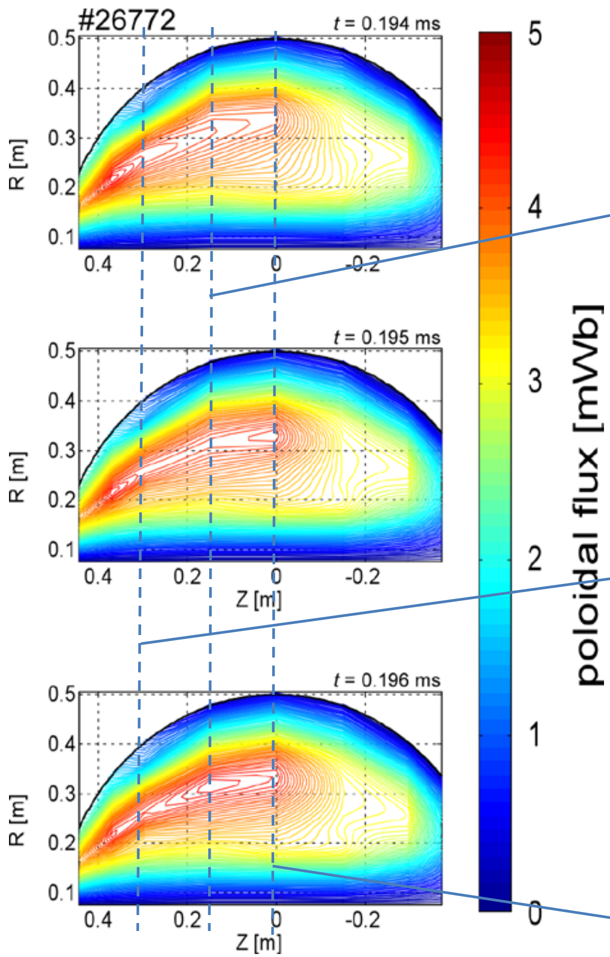
Low bias flux case | High bias flux case

(a) Low bias case | (b) High bias case

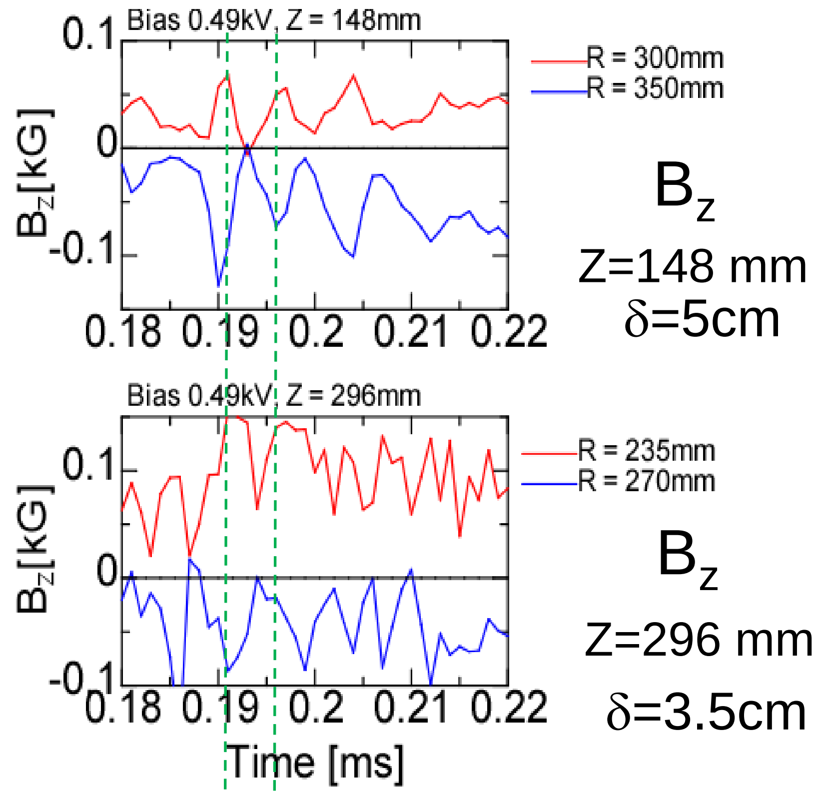


- The current sheet is elongated during the current rise phase in both cases.
- The reconnection occurs as the **current sheet length *L*** increases and so the **current sheet width δ** becomes enough thin.
- The **plasmoids** are generated due to the reconnection in the **elongated current sheet**.
- The **number of plasmoids** in the low bias case with a longer *L* is larger by one or two than that in the high bias case.

Behavior of plasmoids and reconnected field lines



Plasmoid dynamics



B_z

Z=148 mm

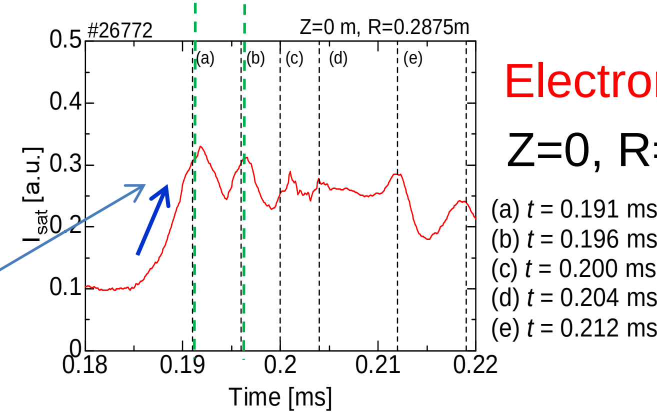
δ=5cm

B_z

Z=296 mm

δ=3.5cm

I_{sat} (a.u.)

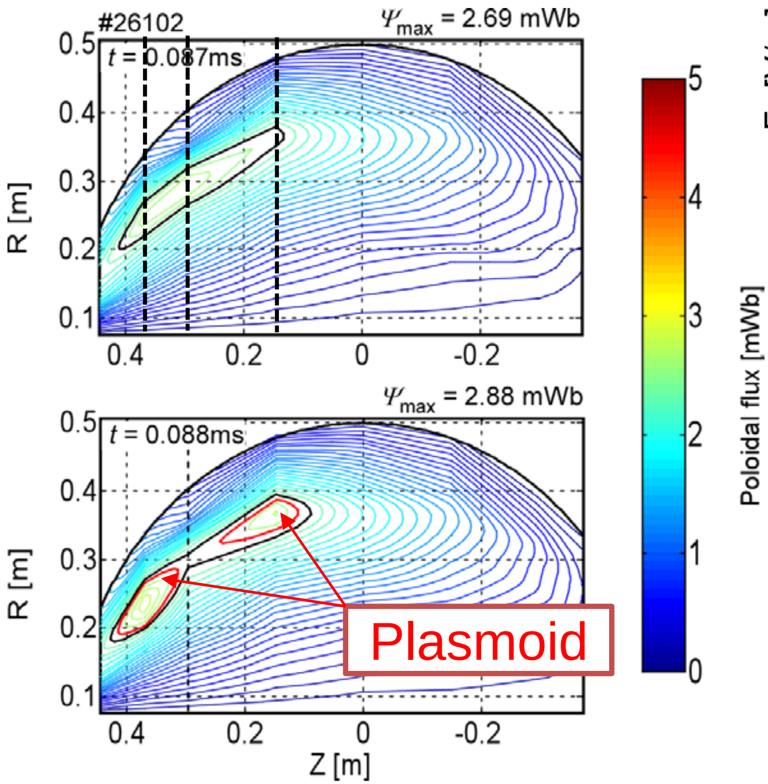


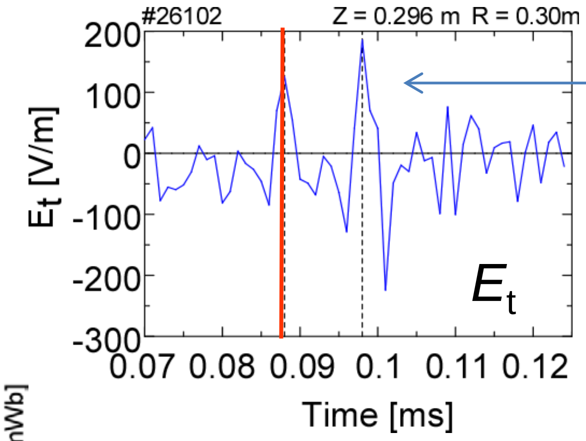
Electron density

Z=0, R=0.288 m

✓ Oscillation of the oppositely directed poloidal fields B_z ,which together to be reconnected, synchronizes with that of the electron density.

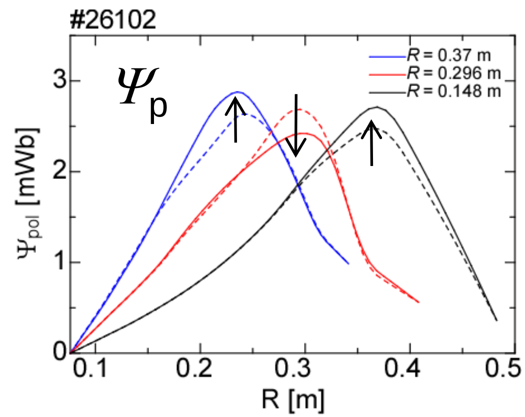
Time evolution of reconnection E_t and Ψ_p during plasmoid's separation

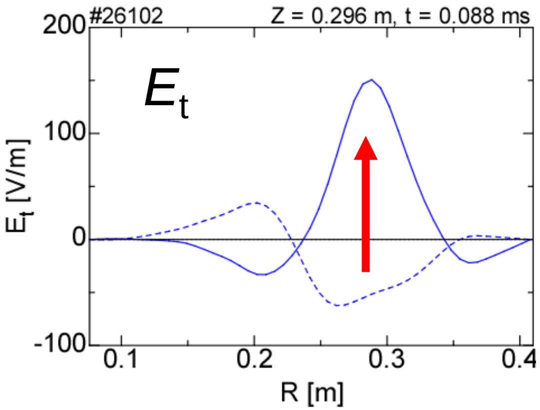




The reconnection E_t is enhanced.

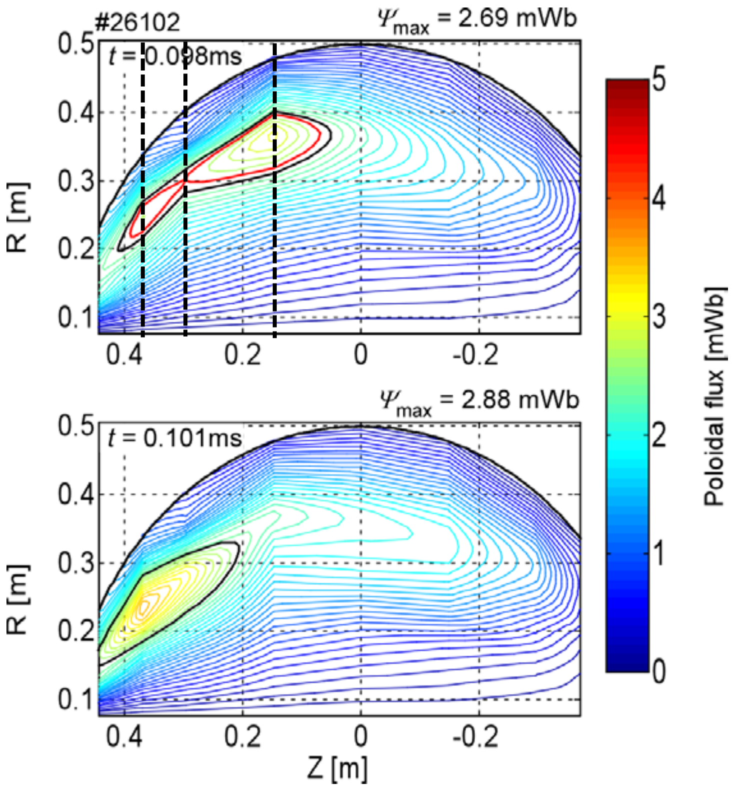
$$E_t = -\frac{1}{2\pi R}\frac{d\psi_p}{dt}$$

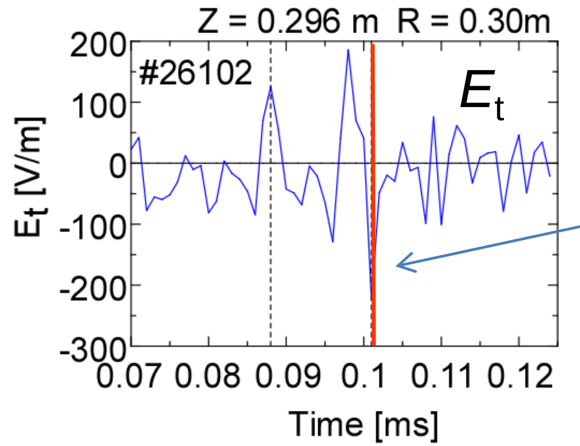




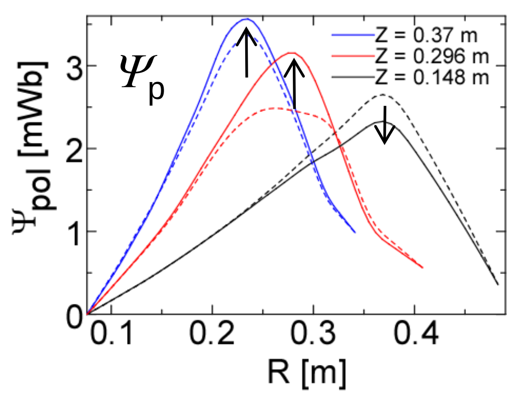
- ✓ One plasmoid separates to two smaller size plasmoids.
- ✓ At t = 0.088 ms, one plasmoid separates to two small plasmoids and the poloidal flux decreases. At this time, *E*t shows a positive spike signal and the polarity of the profile is reversed during the merging.

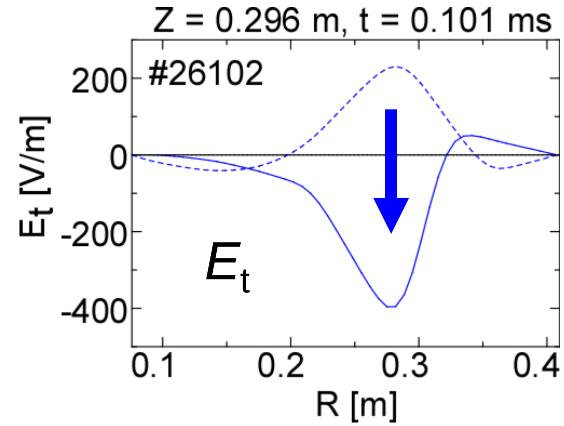
Time evolution of reconnection E_t and Ψ_p during plasmoid's merging





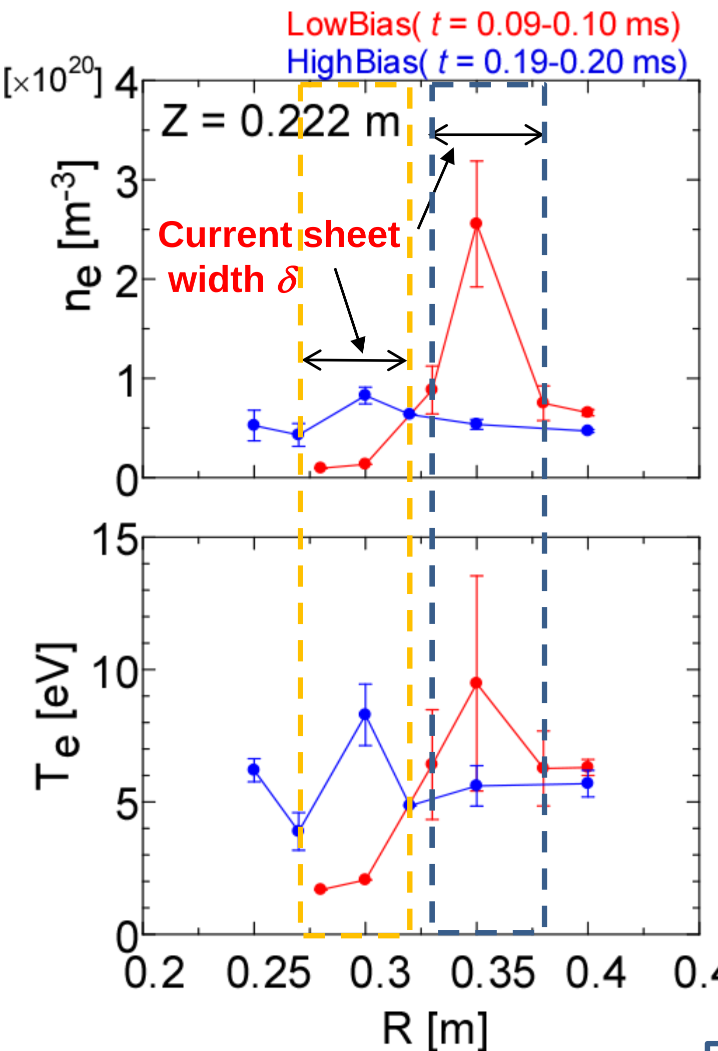
the reconnection j_t current is reduced





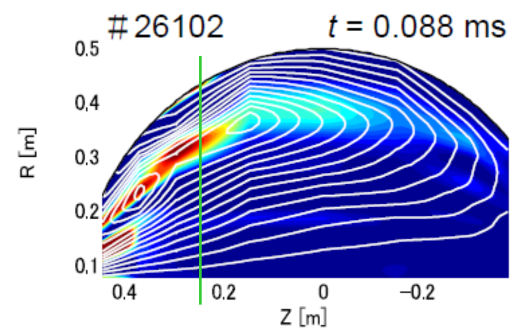
- ✓ Two plasmoids merge to one plasmoid.
- ✓ At t = 0.101 ms, two plasmoids merges and plasmoid's poloidal flux increases. At this time, *E*t shows a negative spike signal and the polarity of the profile is reversed during the merging.

Estimation of Lundquist number S in the current sheet
- Correlation with its width δ and length L, and the number of plasmoids -



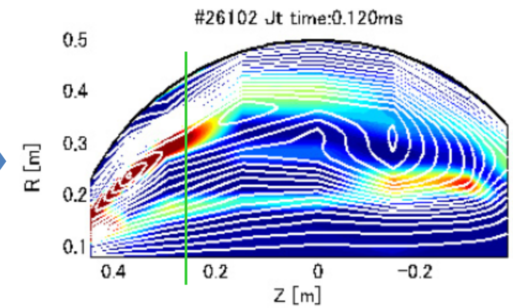
S-P scaling: $\delta_{sp}/L \sim S^{-1/2}$

t=0.038 ms



The number of plasmoids: N=2
L~0.59 m, n_e~2.5×10^{20} m^{-3}

t=0.12 ms



The number of plasmoids: N=3
L~1.1 m, n_e~0.9×10^{20} m^{-3}

$B = B_p + B_t$

$$S = \frac{\mu_0 \cdot v_A \cdot L}{\eta}$$

Bias flux	B [T]	L [m]	δ [cm]	T_e [eV]	n_e [m^{-3}]	S	The number of Plasmoid
Low	0.08	0.59	~ 5	10	2.5×10^{20}	5000	2
Low	0.08	1.1	~ 5	6	0.9×10^{20}	7200	3
High	0.08	0.56	~ 5	8	0.8×10^{20}	5800	2

Ion skin depth
d_i =2~3 cm $\quad \delta \geq d_i \quad$ No two-fluid effect?

Summary

- **Flux closure and magnetic reconnection in the T-CHI generated plasmas have been investigated on HIST.**

- It has been found that the toroidal current sheet is elongated in the presence of the high TF.
- Two or three plasmoids in the elongated current sheet have been directly detected by internal 2D magnetic probe measurements. Also, we have examined the dynamics of plasmoids (merging and separation).
- The each parameter (δ, L, S, T_e, n_e) of the elongated current sheet has been measured. The S number is estimated to be in the range of 5000-7000. According to the MHD simulation, the onset of the plasmoid instability may be possible around the measured S number.
- Plasmoid instability could be one possible mechanism for generation of larger-size closed flux surfaces.

- **Self-organization of T-CHI generated plasmas have been observed.**

- The relaxation process exhibited the current conversion from toroidal to poloidal direction.