18th International Workshop on ST
2015 US-Japan Workshop on ST Plasma

Princeton, NJ, USA, 3–6 Nov. 2015

Studies of Transient CHI Plasma Start-up on HIST

M. Nagata, T. Hanao, T. Kawai, Y. Uesaka, T. Matsui, Y. Kikuchi and N. Fukumoto

University of Hyogo, Himeji, Hyogo, Japan

Outline

1) **Introduction** : Helicity Injection
2) **HIST device and diagnostics**
3) **Experimental topics**
   a) Key features of T-CHI generated plasmas
   b) Flux closure, kink instability, current sheet and reconnection
   c) Helicity balance
4) **Summary**

Himeji castle !

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**, LHI

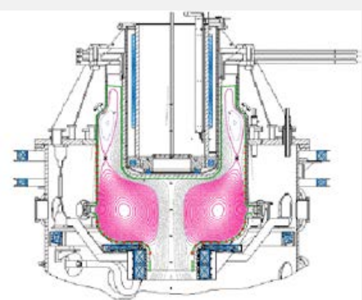
ST (NSTX, HIST, QUEST, Pegasus)

Steady-state **Driven/Muti-plusing CHI**

Spheromak(SSPX) ST(HIST,HIT-II)

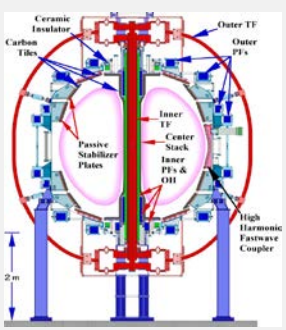
Inductive HICD

Spheromak (HIT-SI)

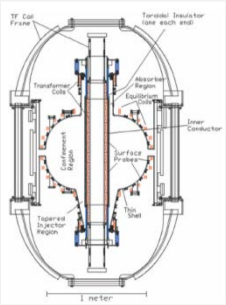


SSPX (LLNL)

HIST (U. Hyogo)

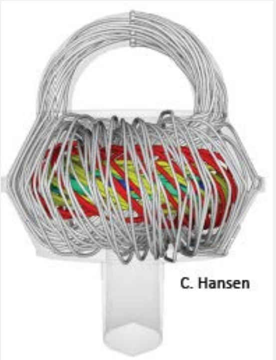


NSTX (PPPL)



HIT-II (U. Washington)

Pegasus (U. Wisconsin)



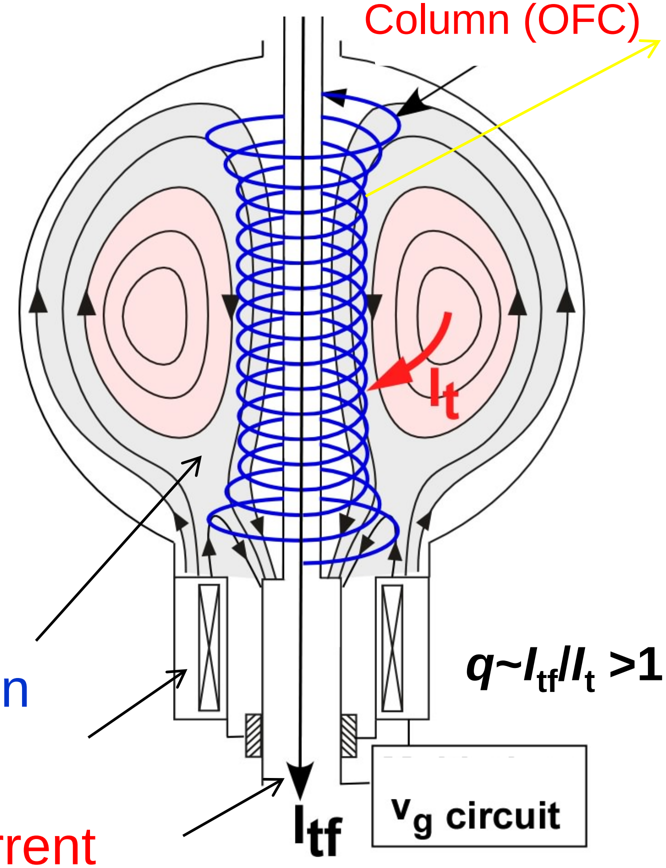
HIT-SI (U. Washington)

Transient Coaxial Helicity Injection

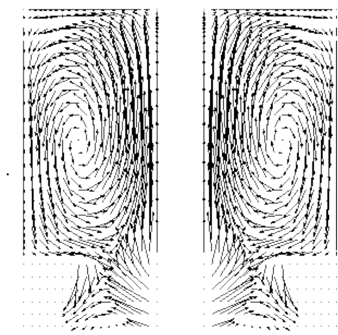
- The steady-state CHI relies on non-axisymmetric magnetic activity to drive current on closed flux regions. In the other hand, transient-CHI (T-CHI) does not need any dynamo mechanism.

Key issues in T-CHI

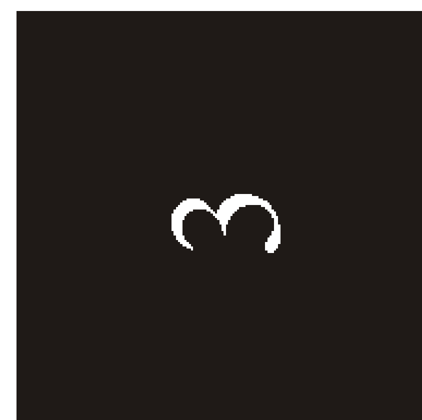
- ☐ *n*=1 helical kink
- ☐ Flux closure
- ☐ Magnetic reconnection
- ☐ Current density profile
- ☐ Helicity conservation



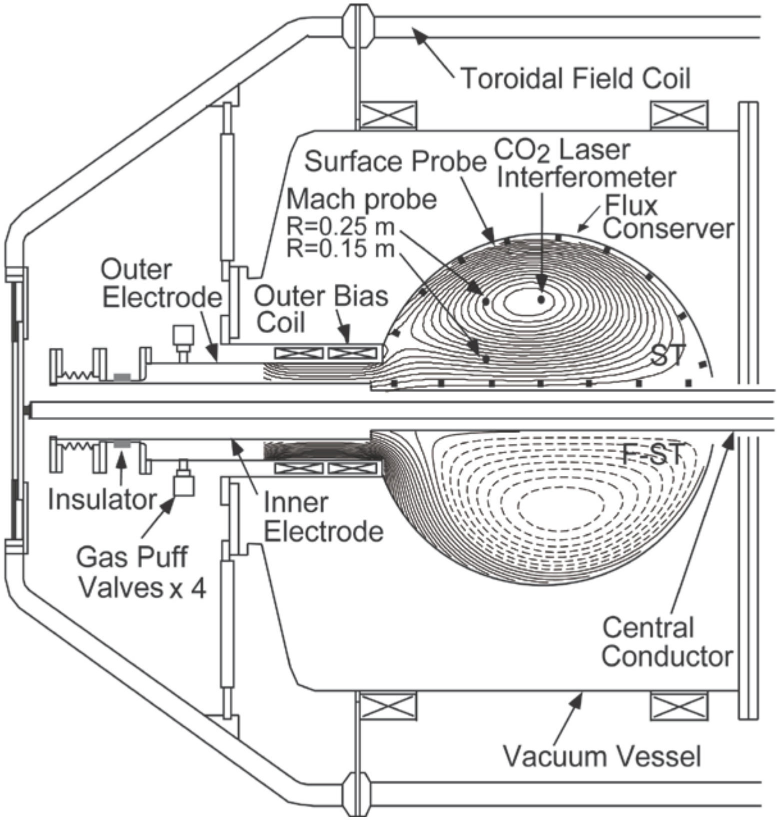
$q \sim I_{tf}/I_t < 1$

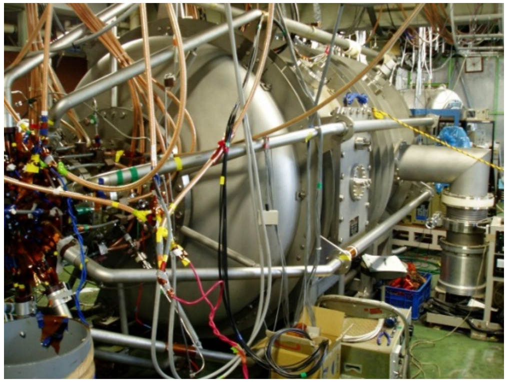


$q \sim I_{tf}/I_t > 1$



HIST device





- **HIST parameters**

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

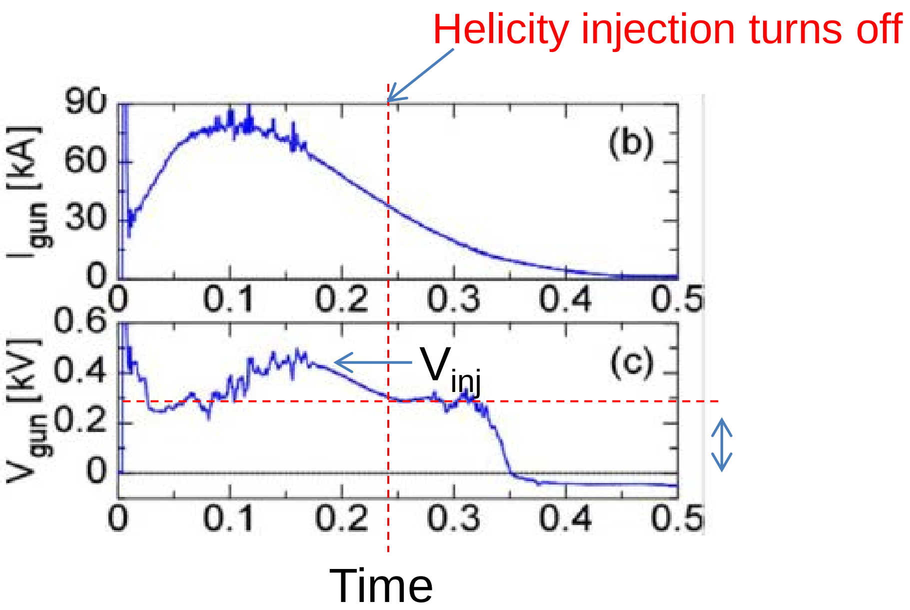
  TF coil current I_{tf}=150-250 kA

- **Transient-CHI capacitor banks**

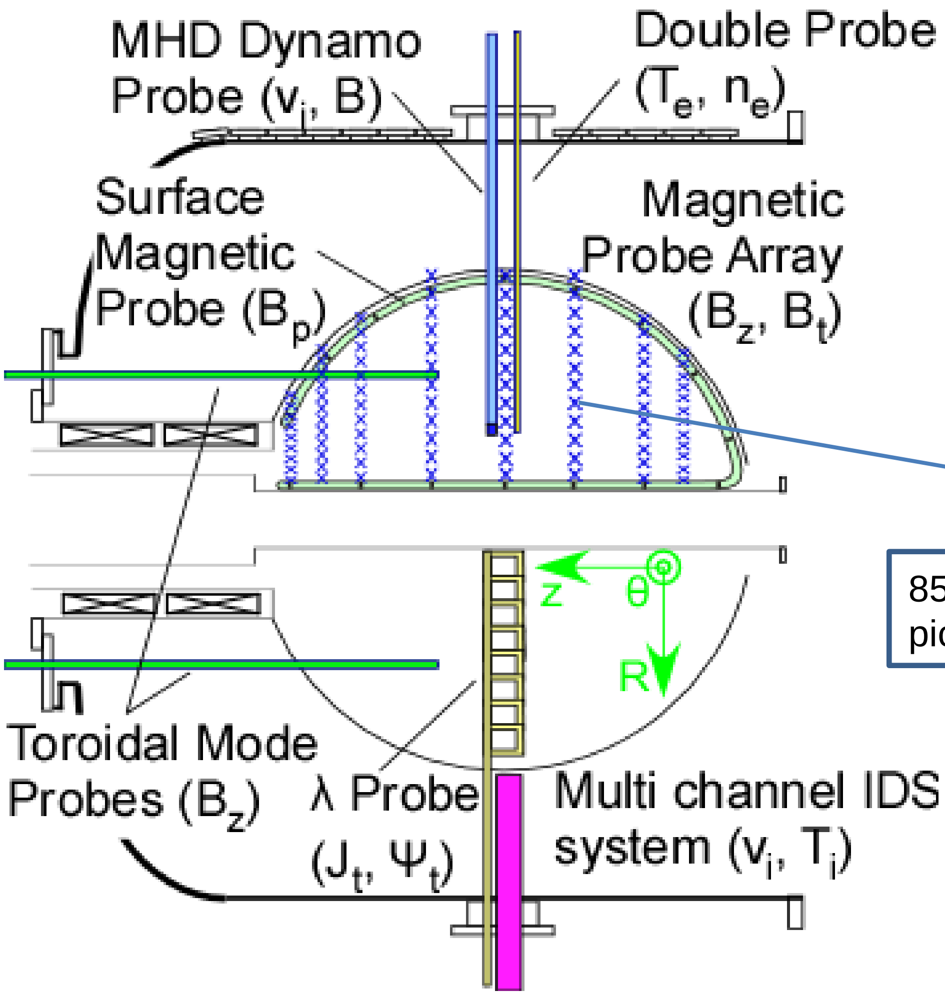
  Voltage : V = 5 kV, C = 2.9 mF

  Gun current : I_g ~ 60-80 kA

Gun current>>Injection current



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** $\langle n_e \rangle$

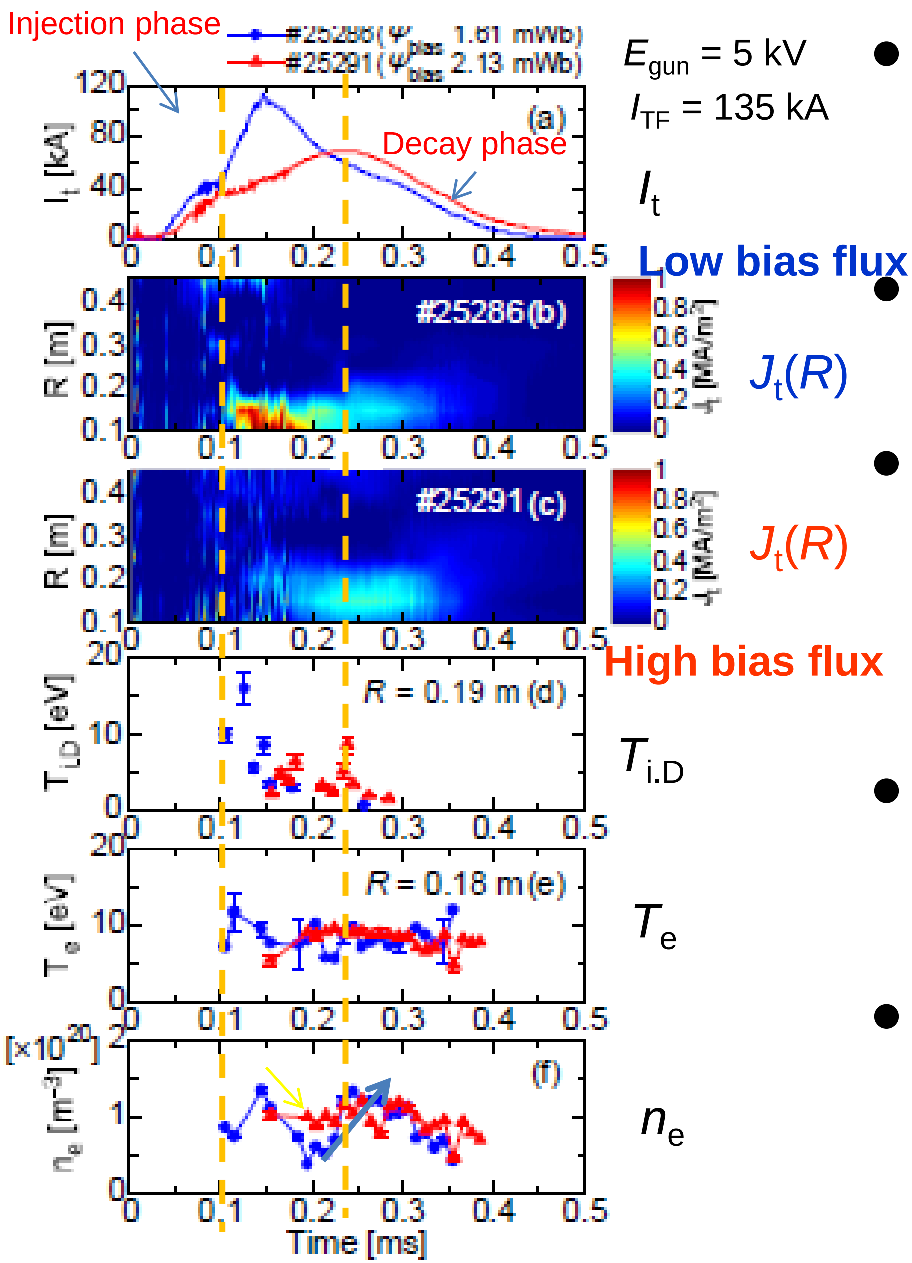
Channel distance	
ΔR	20 - 50 mm
ΔZ	74 or 148 mm

Poloidal flux

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

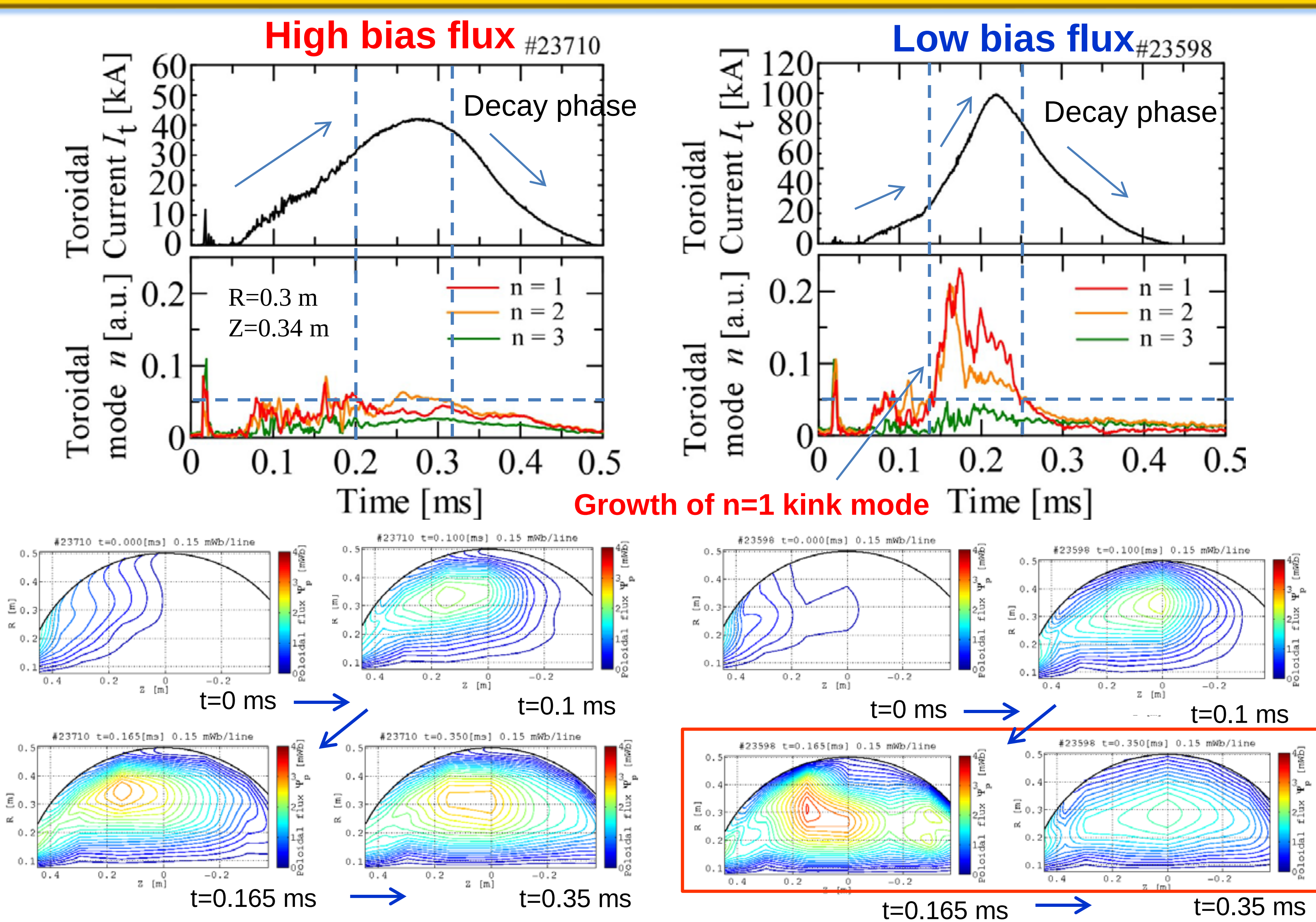
by assuming axisymmetry

Characteristics of T-CHI generated ST plasmas



- Typical T-CHI discharge is characterized by varying the amount of the bias (injector) flux.
  - Blue line : Low bias flux (1.81 mWb)
  - Red line : High bias flux (2.13 mWb)
- The injection current I_{inj} in the low bias case is higher than that in the high bias case.
- 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. The discharge evolution is divided by the injection phase, the short current ramp-up phase and the decay phase.
- We found that the radial profile of the toroidal current density $J_t(R)$ depends strongly on the bias flux.
- The current density J_t in the low bias flux is concentrated mainly in the open central column (OFC). The kink instability occurs at t = 0.14 ms.

Time evolution of toroidal *n* mode and comparison of poloidal flux contours



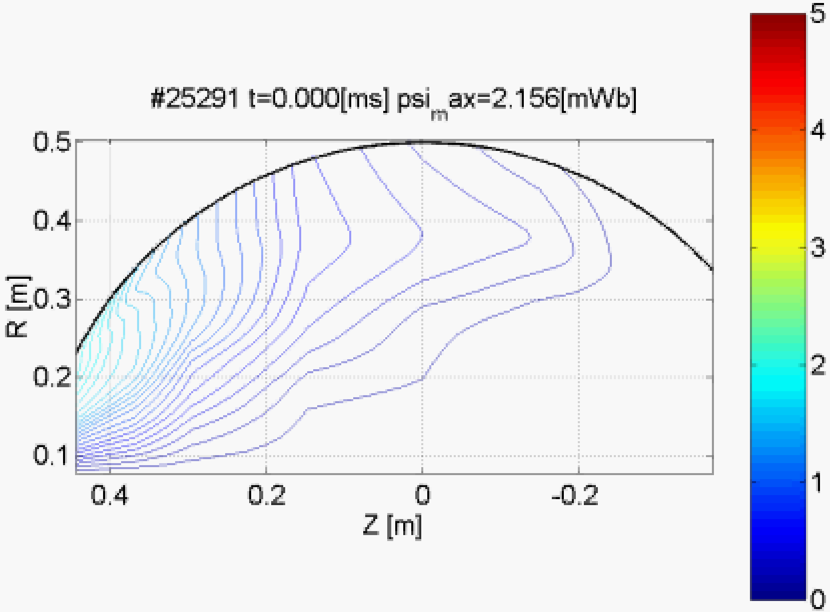
✓ The distorted magnetic configuration relaxes back to an axisymmetric state during the decay phase.

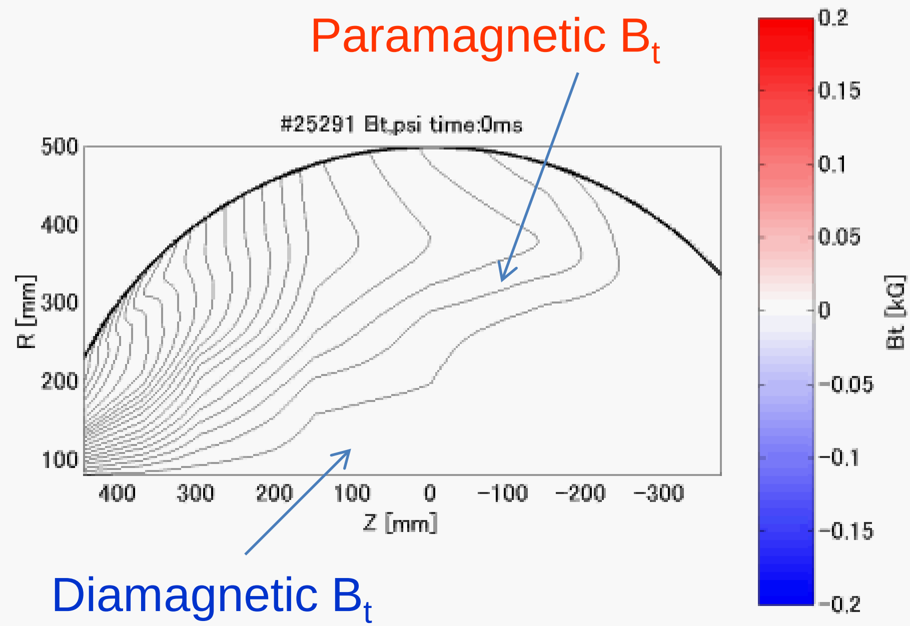
Time evolution of Ψ_p and self-generated ΔB_t

High bias flux case

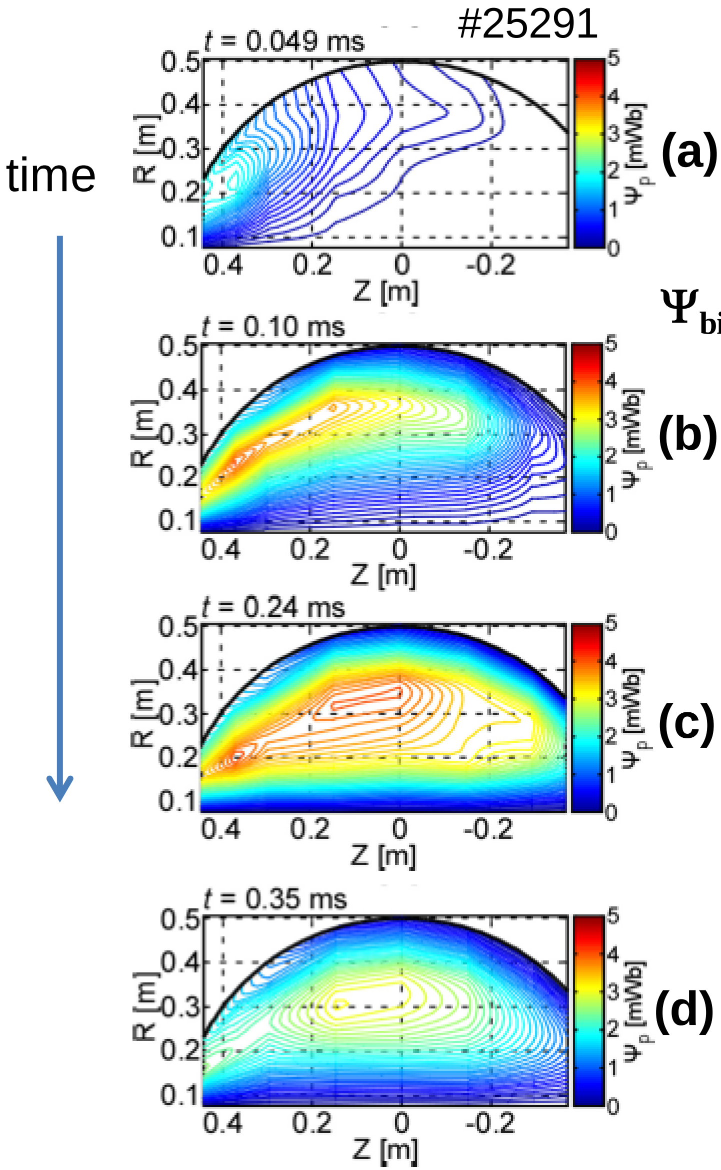
Ψ_p

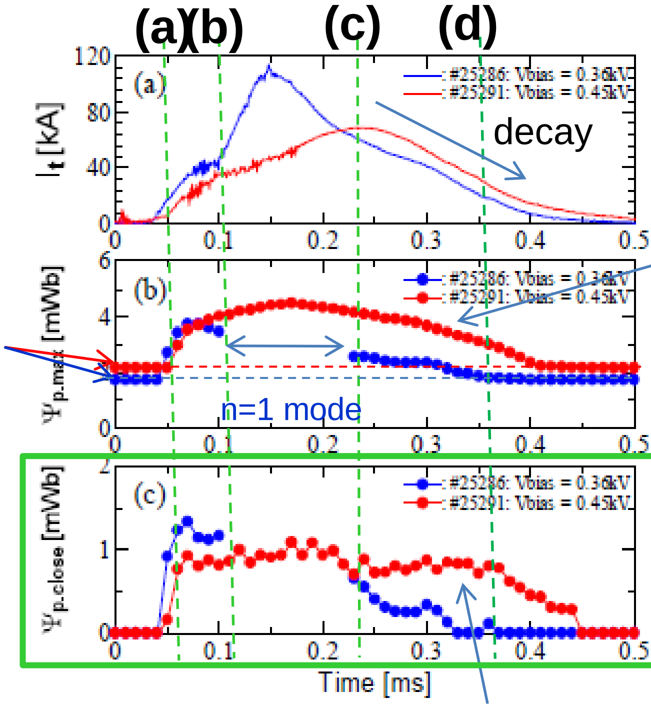
$\Delta B_t = B_t - B_{t.ext}$





Time evolution of the closed poloidal flux





I_t

Resistive decay

Ψ_p

Ψ_{bias}

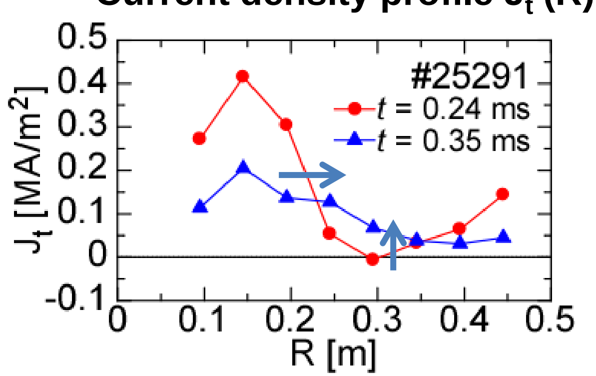
Ψ_p/Ψ_{bias}=2

$\Psi_{p.closed}$

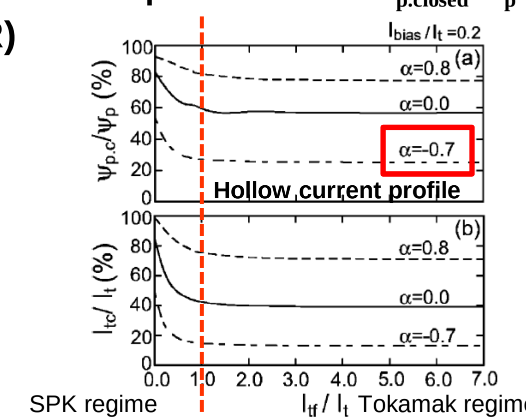
$\Psi_{p.closed}/\Psi_p$=25 % ➡ 35 %

$\Psi_{p.closed}$ is maintained due to the inward current diffusion.

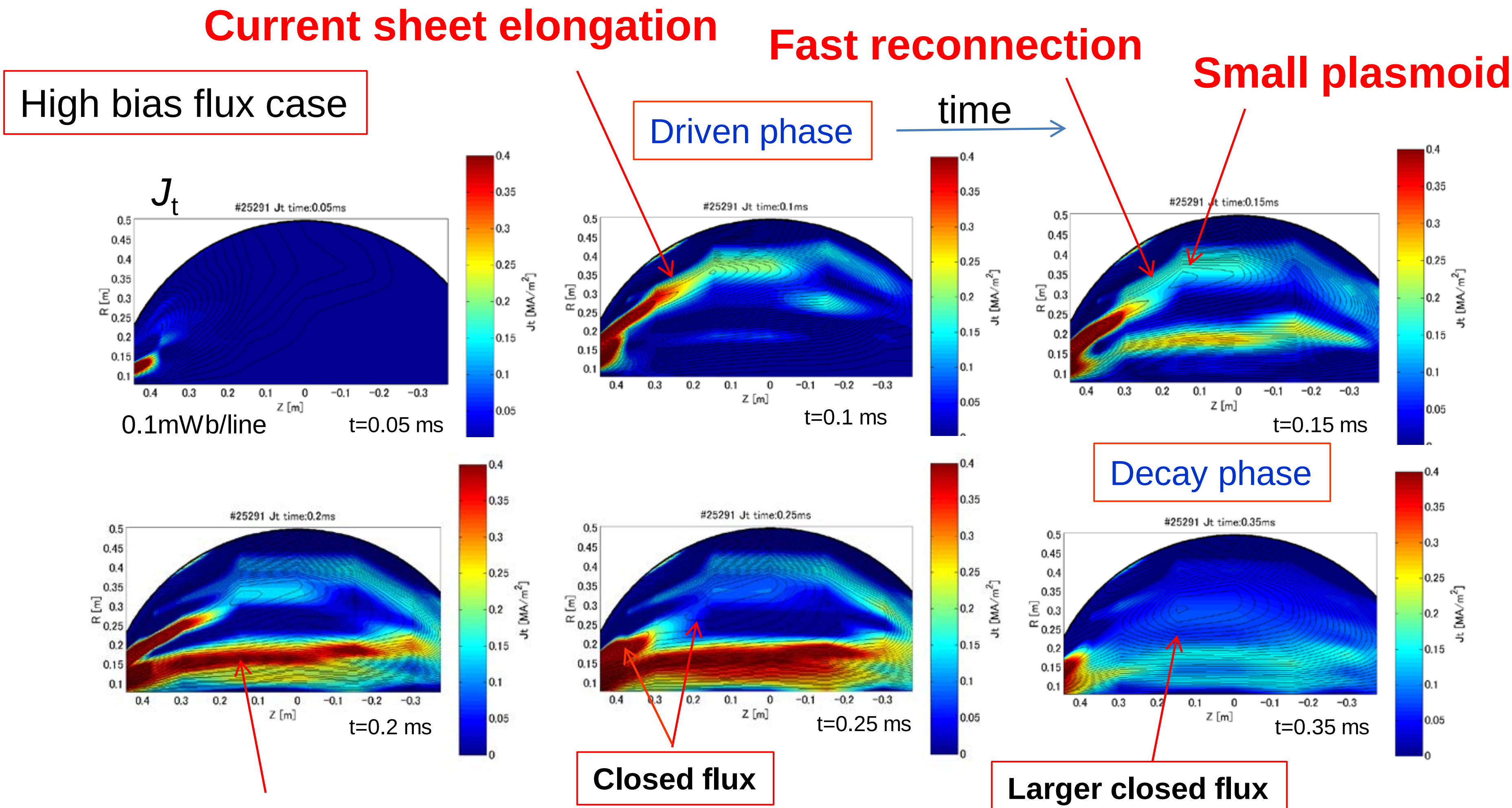
Current density profile J_t (R)



Equilibria cal. of $\Psi_{p.closed}/\Psi_p$



Current sheet elongation, magnetic reconnection and small plasmoid



Current sheet on the OFC surface

Leading to generation of diamagnetic B_t in the OFC

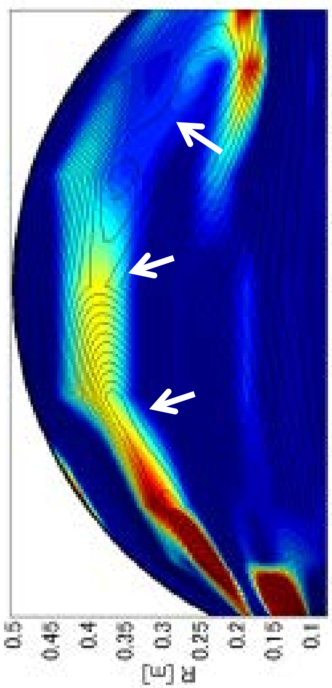
✓ J_t at the edge decreases during the decay phase, but J_t in the closed flux region increases.

Observation of plasmoid instability

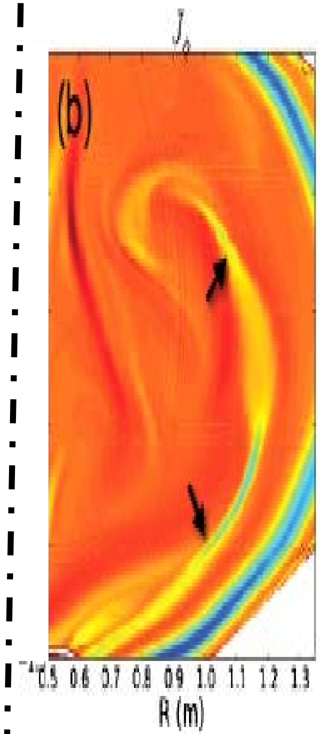
- **Formation of multiple X points and plasmoids in the presence of TF**
- **Plasmoid instability could lead to mechanism for fast flux closure. However, the question is how the small islands become more large-scale volume of the closed flux?**
- **One possible explanation is because of the inward current diffusion from the inner edge after the injection current is terminated.**

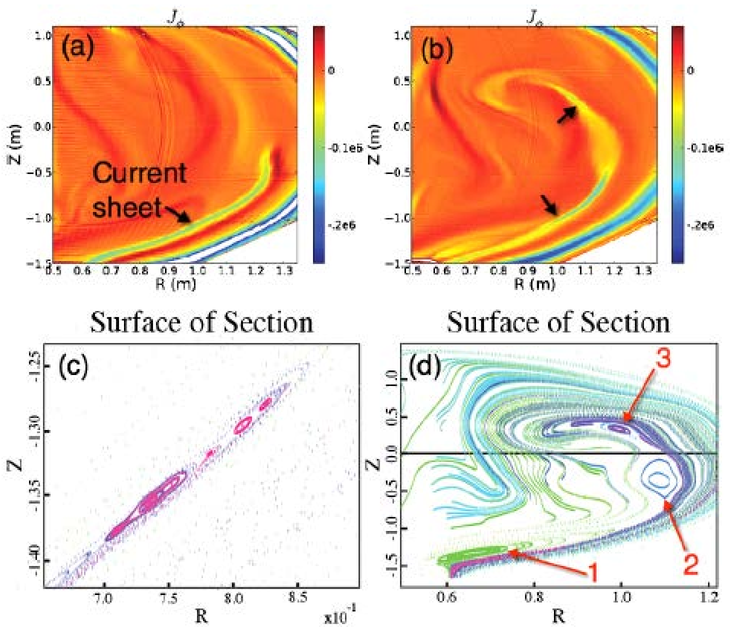
Low bias flux case

Exp. J_t



MHD Simulation





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

Investigation of helicity balance

- The time dependence of the magnetic field strength during the T-CHI start-up can be predicted, if the helicity balance is experimentally verified.

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

Free parameter τ_K — Helicity injection rate (measured value)

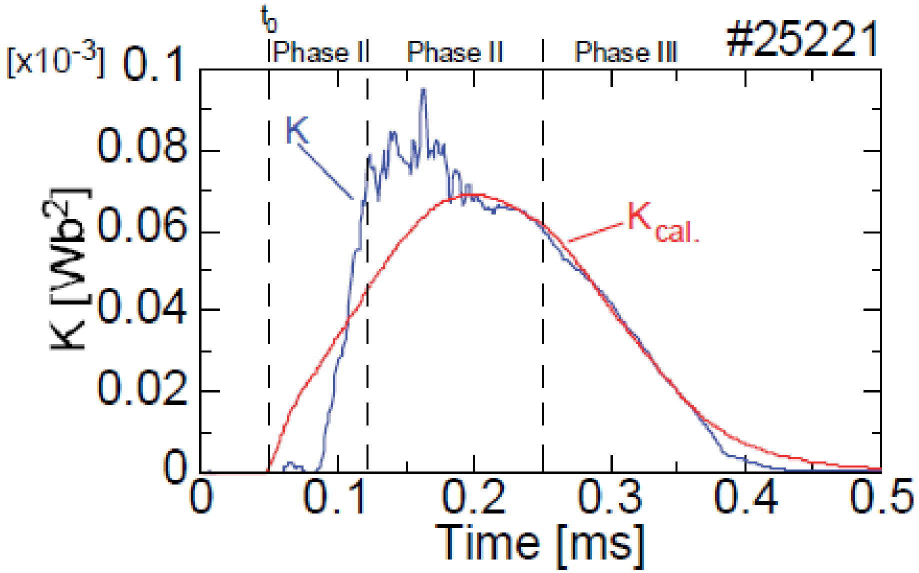
Prediction

$$K_{cal.} = \exp(-t/\tau_K)\int_{t0}^{t} 2V_{gun}\Psi_{bias}\exp(t'/\tau_K)dt'$$

Experiment

$$K = \int_V \boldsymbol{A}\cdot\boldsymbol{B}dV - \int_V \boldsymbol{A}_V\cdot\boldsymbol{B}_V dV \sim \Psi_p\Psi_t - \Psi_{bias}\Psi_{t.v}$$

(measured values)



- Helicity decay const. τ_K can be estimated from the plasma resistivity.

$$\tau_K = \tau_B/2 = 0.05 \text{ ms}$$

$E_t = V_t/2\pi R_{axis} = \eta_{spitzer}\,\Delta J_t$

$\eta_{spitzer} \sim 5.3\text{x}10^{-5}\ \Omega\text{m.}$

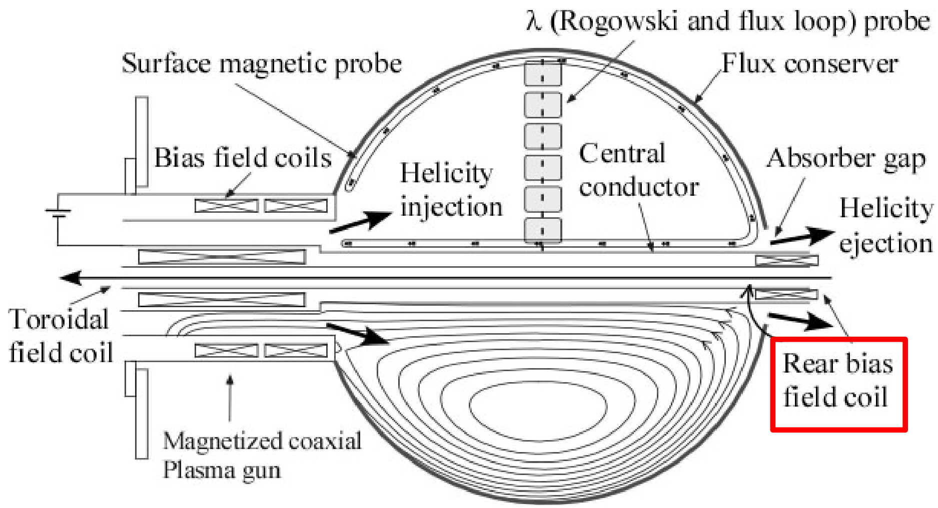
$(T_e = 5 - 10 \text{ eV})$

$\Delta J_t \sim 0.1 \text{ MA/m}^2$

$V_t = \Psi_p/\tau_B$

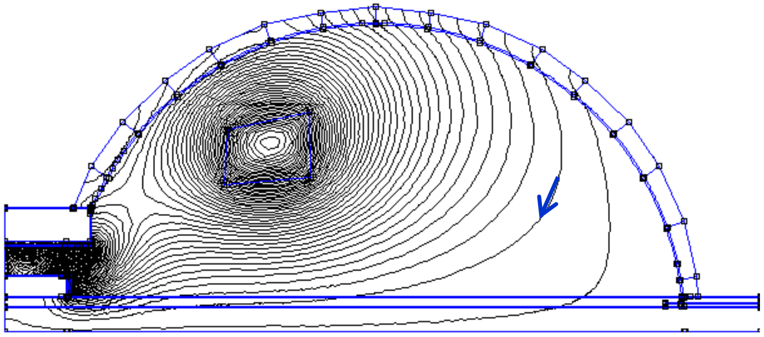
- Helicity balance based on the helicity conservation law has been roughly justified !

Rear bias field coil installed to improve absorber arc

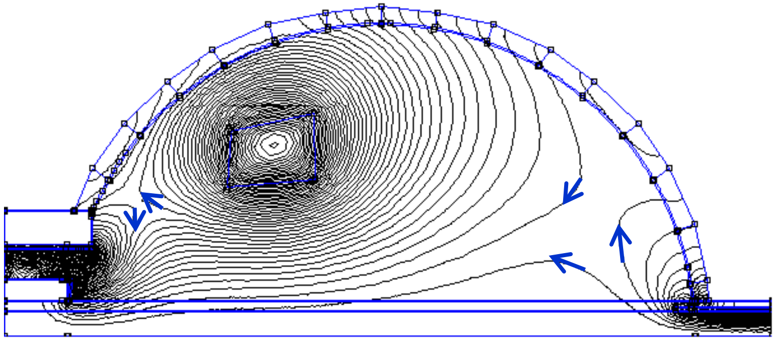


- As the ejected plasma contacts the rear gap of the FC or after the kink instability occurs, the injection current flows between the FC and the central conductor due to the arc discharge on the gap (Absorber arc).

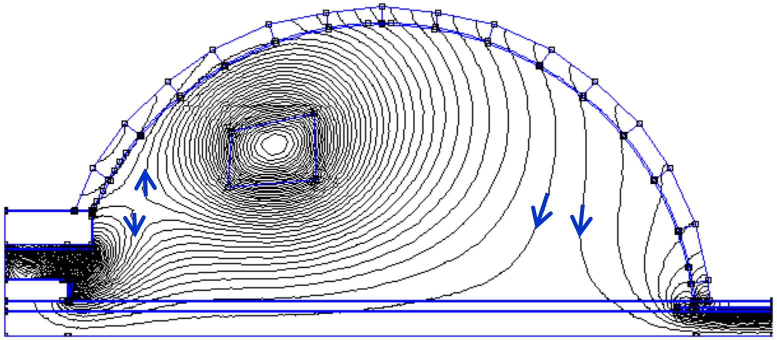
- The rear bias coil is installed near the absorber gap to avoid the occurrence of arc there.



Without Rear Bias Field



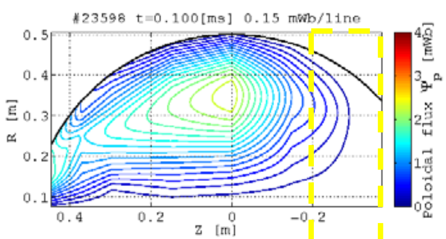
Rear Bias Field (Positive direction)



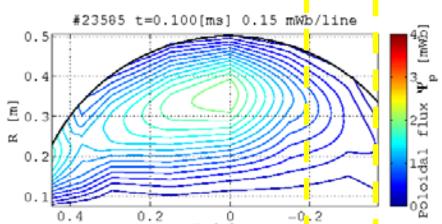
Rear Bias Field (Negative direction)

Effects of the rear bias field on the magnetic configurations

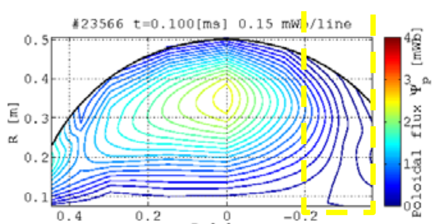
W/O Rear bias



Positive direction

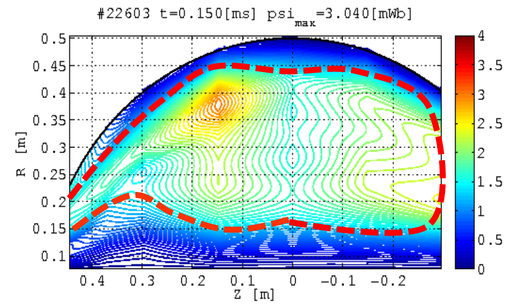


Negative direction

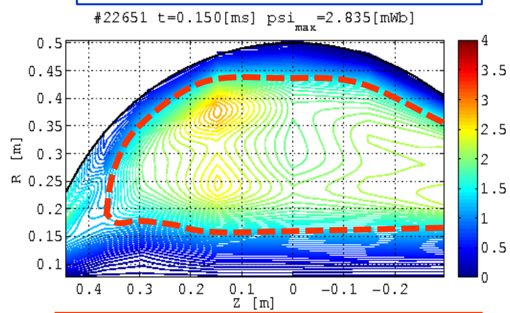


t = 0.100 ms

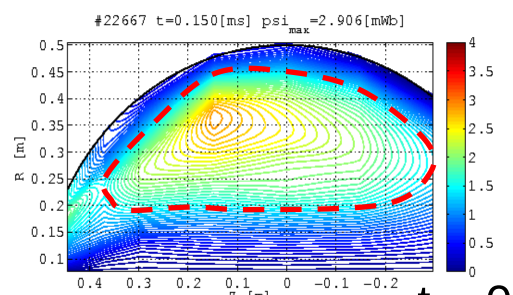
W/O Rear bias



Positive direction



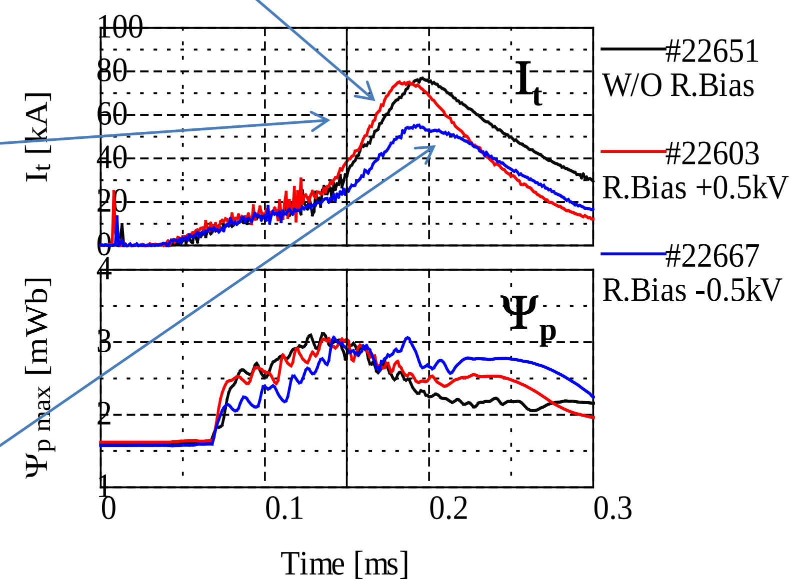
Negative direction



t = 0.250 ms

- ✓ The occurrence of the n=1 kink mode is delayed with the application of the rear bias field, but not enough effect.

Low bias flux



Summary

- **T-CHI start-up has been successfully demonstrated on HIST.**

Flux closure and fast magnetic reconnection

The internal magnetic field measurements have verified the formation of the closed flux surfaces (flux closure) during the start-up phase. The formation of X-points after bubble burst has been observed. Small plasmoids have also been created due to the fast magnetic reconnection in the elongated current sheet. This experimental observation agrees very well with the MHD simulation.

Kink instability and current density profile

The excess injection current at the inner edge causes the magnetic field to become non-axisymmetry due to the kink instability. When the plasma starts to decay as the injection current terminates, the configuration relaxes to the original state with closed flux (relaxation?). The helical distortion has been slightly improved with the application of the rear bias flux at the absorber gap.

Helicity conservation

Helicity balance has been experimentally verified. it is useful for the prediction of the poloidal flux evolution in the T-CHI start-up.