10th International ST workshop 29th Sep. -1st Oct. 2004, Kyoto, Japan

Recent Results from Helicity Injection Experiments on HIST

M. Nagata, H. Hasegwa, K. Kawami, T. Takamiya, Y. Kagei

N. Fukumoto and T. Uyama

Graduate school of Engineering, University of Hyogo

Contents

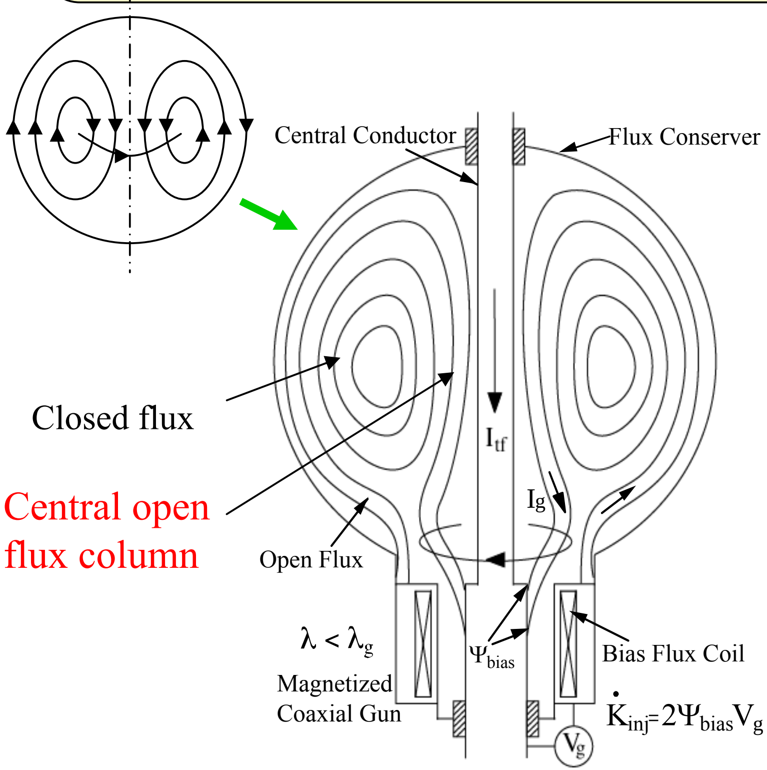
- Background and Objectives
- Hilights from helicity injection studies on HIST

  (Comparison between Spk and ST, Formation and sustainment of flipped ST)
- Comparison with 3D MHD simulation results
- Summary

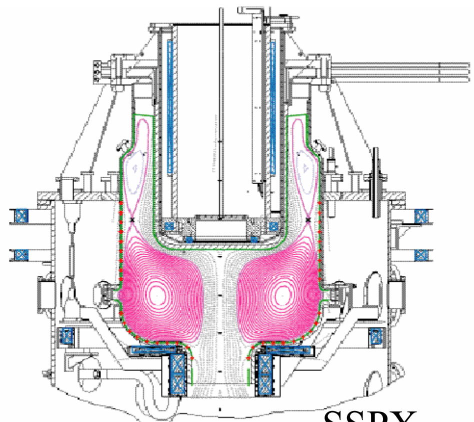
The university name was changed from Himeji Inst. of Tech..

Helicity Injection Experiments and the Underlying Physics

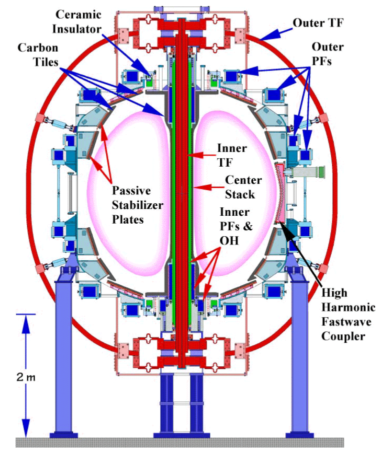
Coaxial helicity injection (CHI) technique was introduced to classical spheromaks and spherical tokamaks to **start-up and sustain a plasma current**. The ability of CHI to drive a current has been already examined and **the related MHD relaxation** have been observed in many spheromak/ST devices.



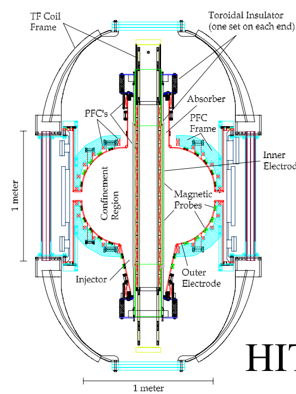
Helicity Injection Spherical Torus System



SSPX



NSTX

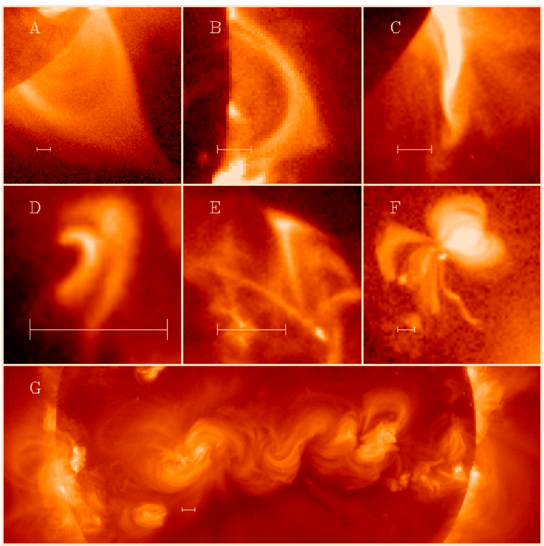


HIT-II

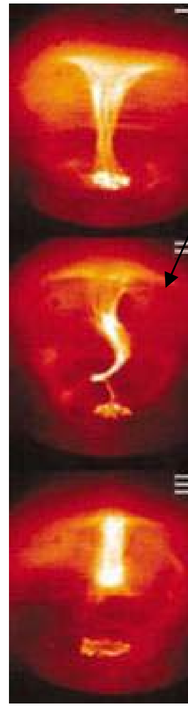
HIST

Common Relaxation Phenomena Observed between Laboratory and Astrophysical Plasmas

Solar flares

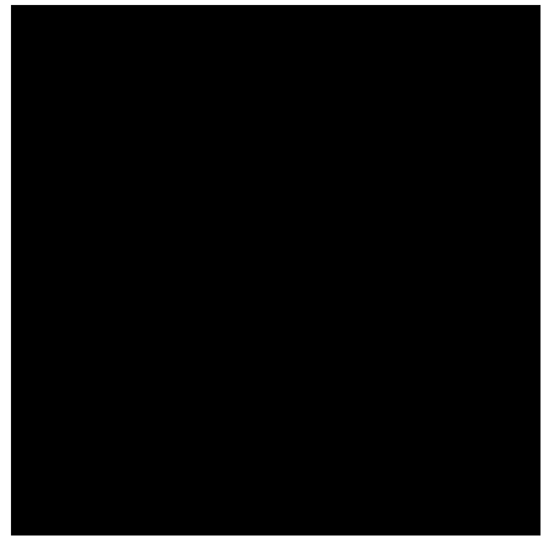


Yohkoh



Hsu and Bellan、PRL

Kink behavior created by the guns

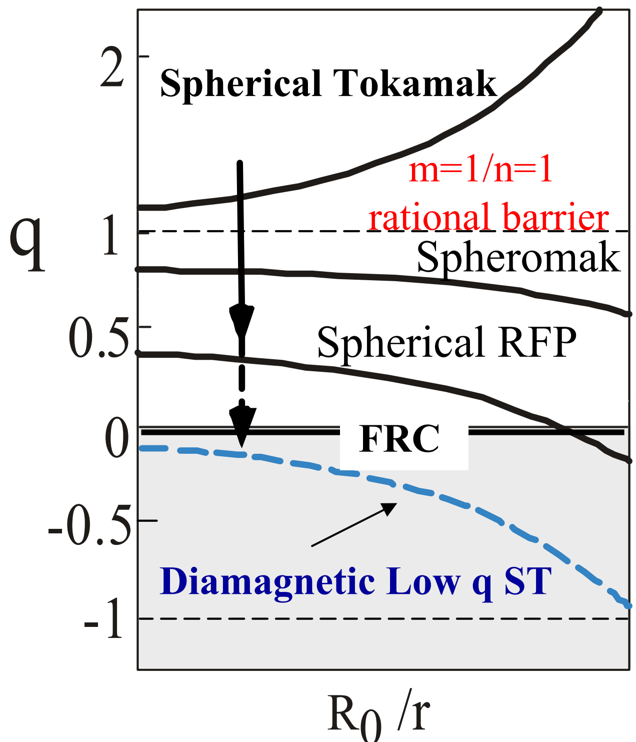


HIST

Plasmoid ejection, Helical twist, Magnetic reconnection, Rotation

- Helicity injection experiments are also useful to study similar MHD activities observed in space plasmas.

How to Approach to Understand Generic Properties of MHD Relaxation in Helicity-driven Toroidal System

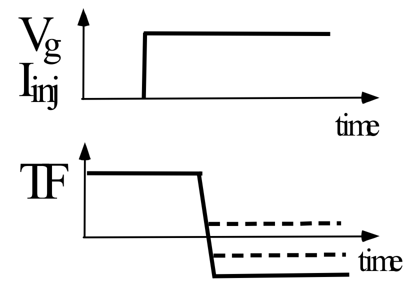


Dynamics of driven spherical system

Various utilizations of TF coil current in a single machine

A. Present works

1) Comparison study of MHD activites between SPK and ST during CHI current drive.
2) To see what happens to ST by a rapid reversal of TF.



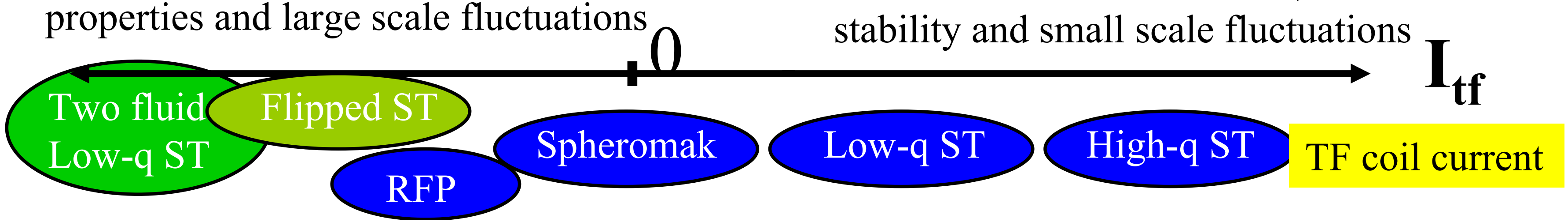
→ Whether do ST plasmas collapse or survive after they pass through the rational barrier ?

B. Future works

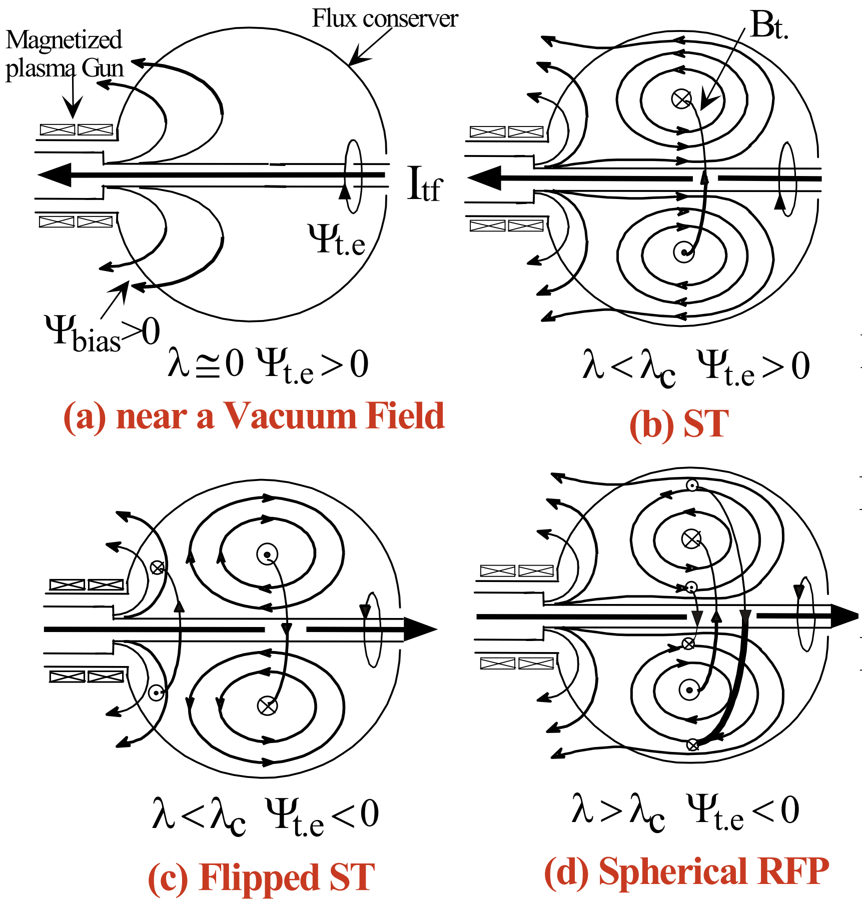
New Prediction: (see Dr. Kanki's presentation)
Diamagnetic high beta low-q STs with two fluid effect may be generated by driving fast flow by CT injection.

Increase in MHD activity, self-organized properties and large scale fluctuations

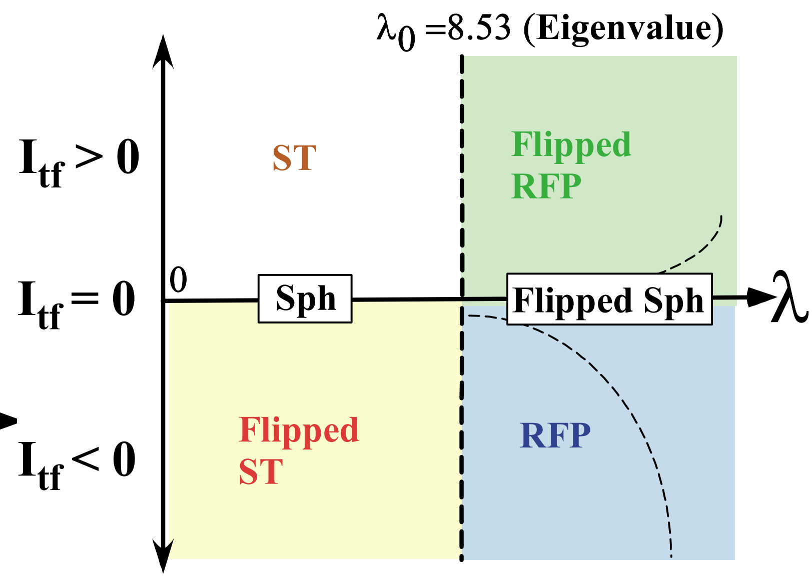
Increase in classical diffusion, stability and small scale fluctuations



Helicity-driven Relaxation Theory Predicts the Existence of Flipped ST States in the Regime of TF < 0

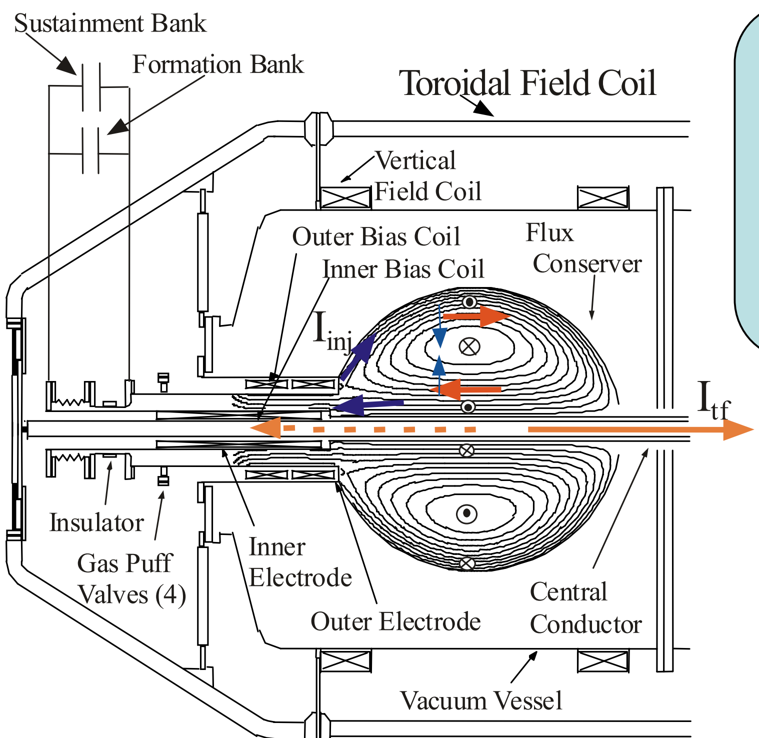


$$\nabla\times\boldsymbol{B} = \lambda\boldsymbol{B}$$



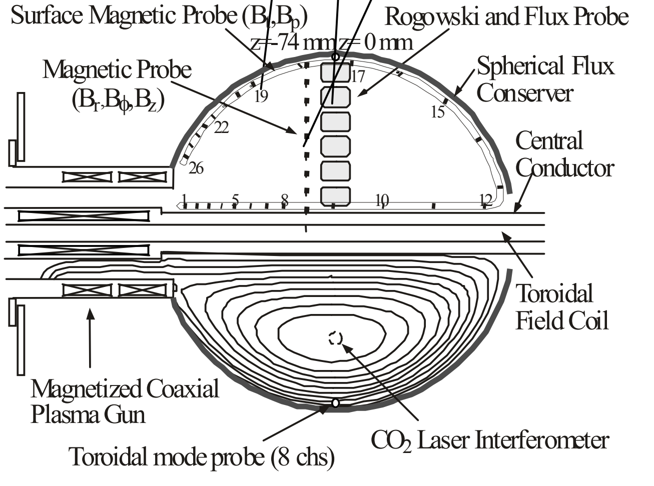
Sequence of poloidal flux topologies of driven plasmas as λ is increased from zero to above the eigenvalue λ_c

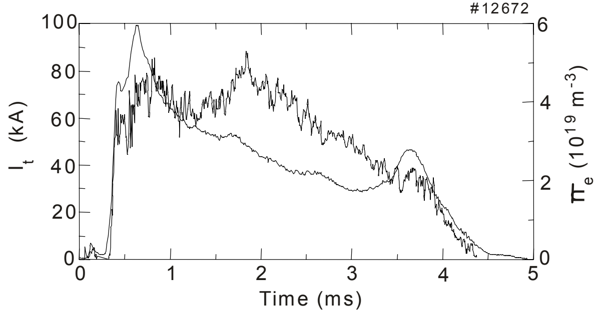
HIST and Diagnostics



Injection Current 20 kA,
Injection Voltage < 600 V
Bias Flux < 5 mWb
TF coil current < 0.25 MA

R = 0. 30 m
a = 0.24 m
A =1.25





ST operation

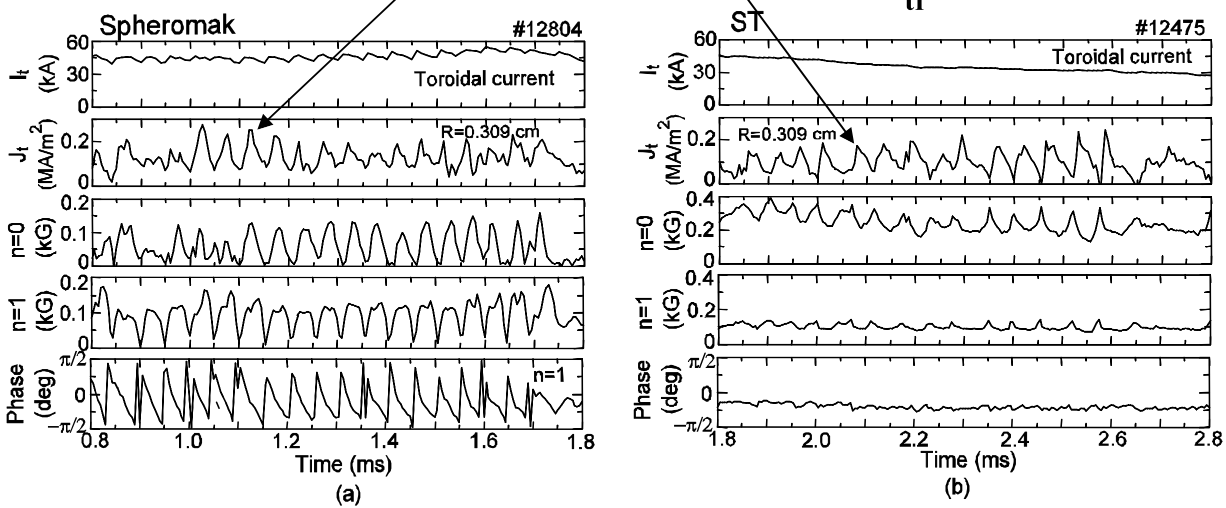
I_t < 150 kA
Δt = 4 - 8 ms
n_e = 2 - 8 x 10^{19} m^{-3}
$T_e \sim T_i$ =20 -40 eV

M. Nagata, et al., Phys. of Plasmas **10,** 2932 (2003).

Comparison of Magnetic Fluctuations between Spk and ST

Current generation on axis

$T_i > T_e$ | Spheromak $\mathbf{I_{tf} = 0}$ | Spherical Tokamak $\mathbf{I_{tf} >> 0}$ | $T_i \sim T_e$



Toroidal current

Current density on the magnetic axis

n = 0

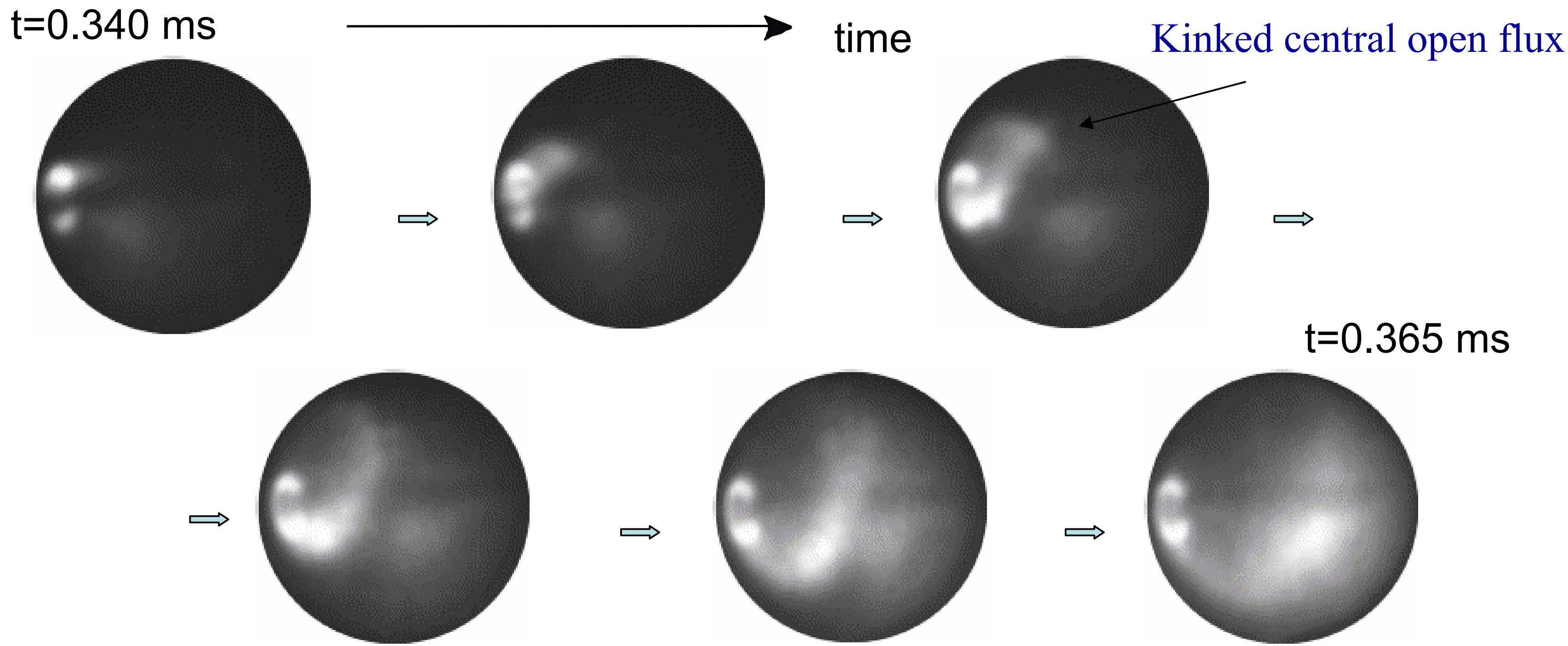
n = 1

Phase of n =1

n=1 kink mode and its rotation | **n=0 mode dominant**

- Intermittent generation of the toroidal current at the magnetic axis was observed in both operations.
- Flux amplification/current generation in the spheromak case is associated with n=1 MHD activity. In the other hand, that in the ST is associated with repetitive merging of plasmoid injected from the gun which we proposed as a model of current drive so far.

Evidence of Rotating Kink Behavior Driven by MCPG



Exponential growth of the kinked central column with the E×B toroidal rotation

Kruskal Shafranov limit

$$\frac{2\pi^2 R_c{}^2 I_t}{\lambda_c R_0 I_g} > 1$$

Kink mode is unstable → Fluctuations of v and B $\langle \tilde{v} \rangle, \langle \tilde{B} \rangle$

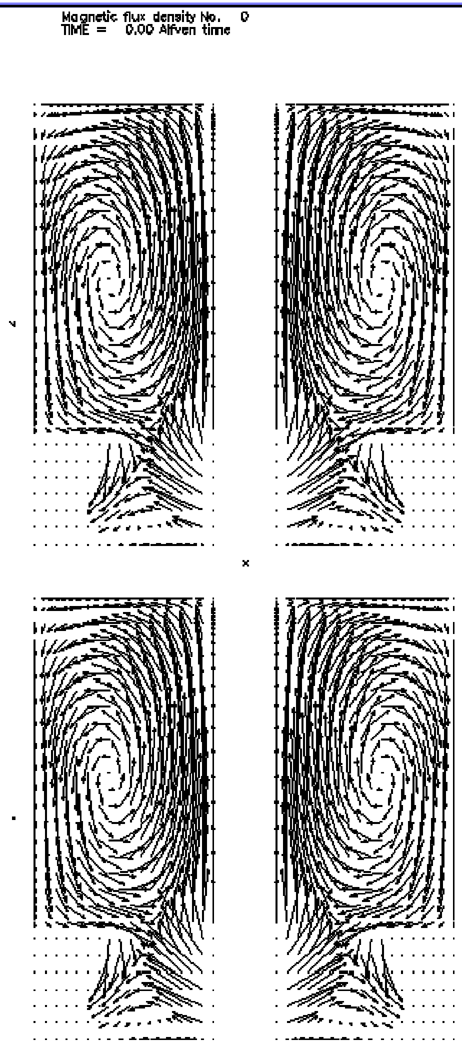
$$\langle E \rangle + \langle \tilde{v} \times \tilde{B} \rangle = \eta \langle j \rangle$$

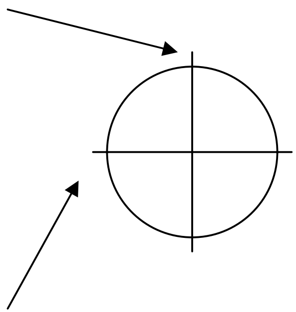
MHD dynamo

→ **Current drive**

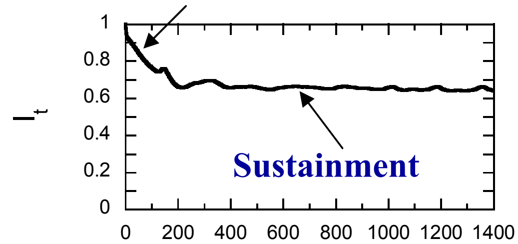
$v_Z = 30$ [km/s] , $v_R = 18$ [km/s]

Dynamo Drive of Spk Demonstrated by 3D MHD Simulation

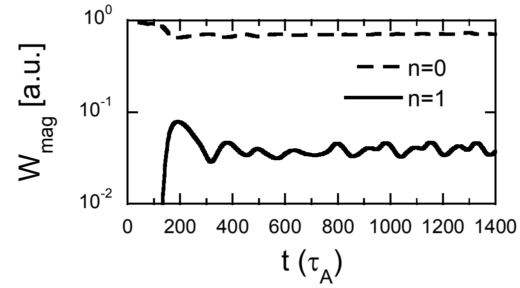


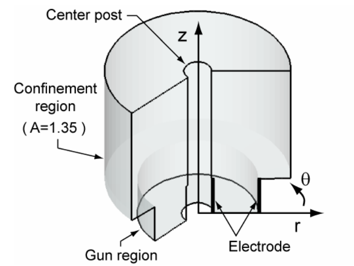


Resisitve decay



Toroidal mode n=0, 1





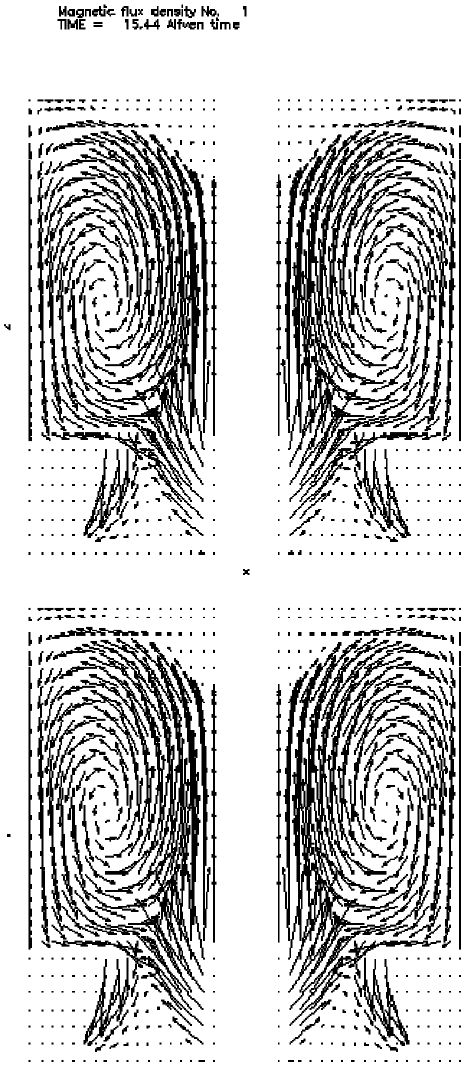
- Nonlinear evolution (Growth, nonlinear saturation and the following relaxation) of the kinked flux column produces dynamo electric field.

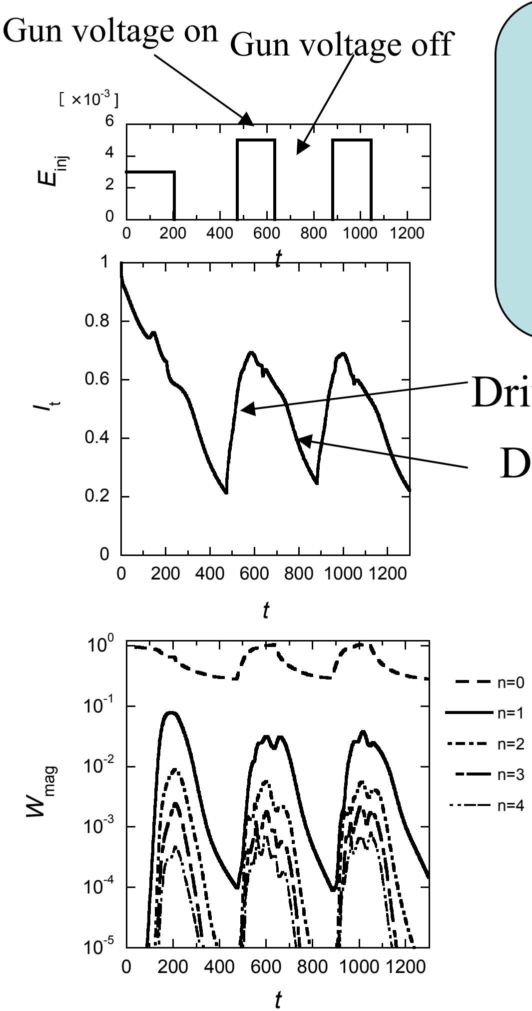
$$\longrightarrow \quad \mathbf{E}_{\text{dynamo}} = \langle \tilde{\mathbf{v}}_e \times \tilde{\mathbf{B}} \rangle$$

- Closed flux surfaces are identified only as mean fields.

 # In collaboration with Y. Suzuki and Y. Kishimoto, JAERI

Multiple Pulse Operation for Improvement of Spheromak Confinement

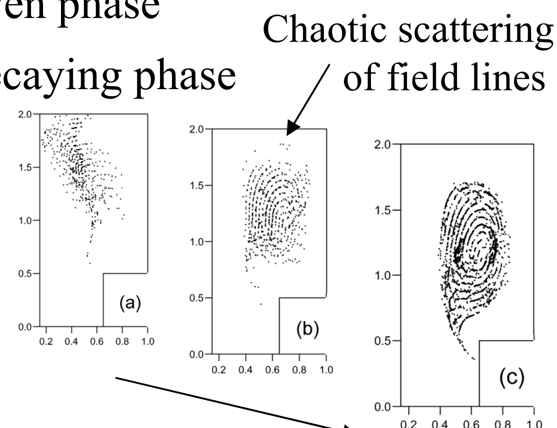




Multi-Pulse Helicity Drive is effective for suppressing the n = 1 fluctuation.

↓

Improvement of confinement quality.



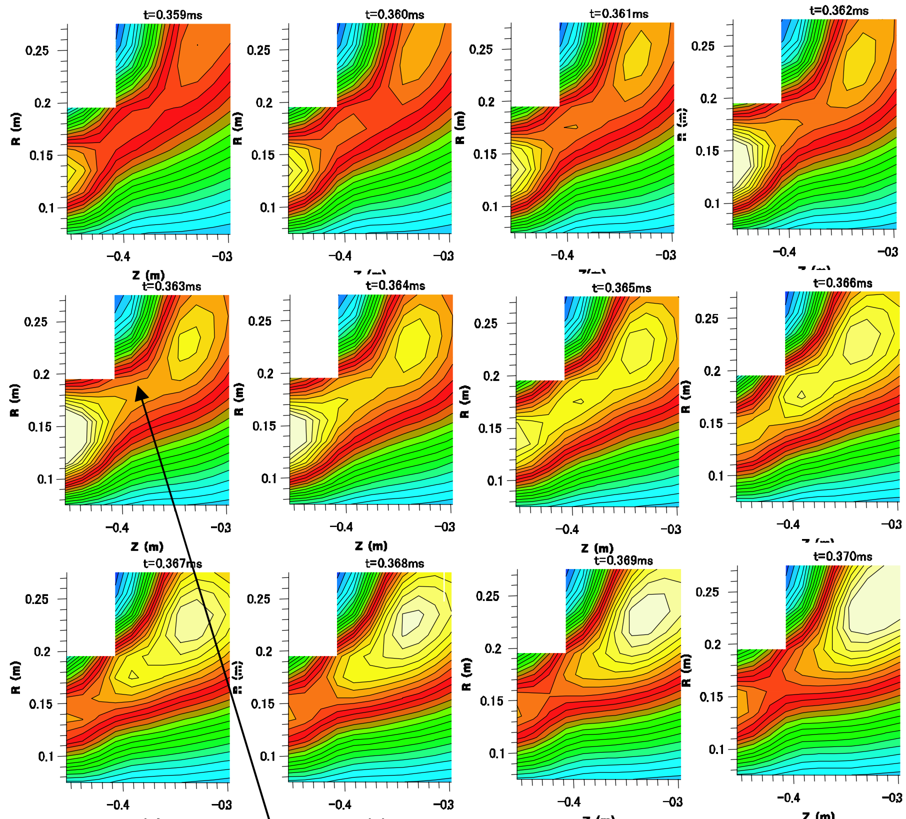
Poincare plot of magnetic field at the time when the magnetic energy in the n = 1 mode gets down to ~10^{-4}

↓

Closed flux surfaces are produced during the decay phase.

Plasmoid Ejection is Key Dynamics for Formation of ST

Plasmoid ejection speed ～60km/s



Stabilization of kink instability by TF

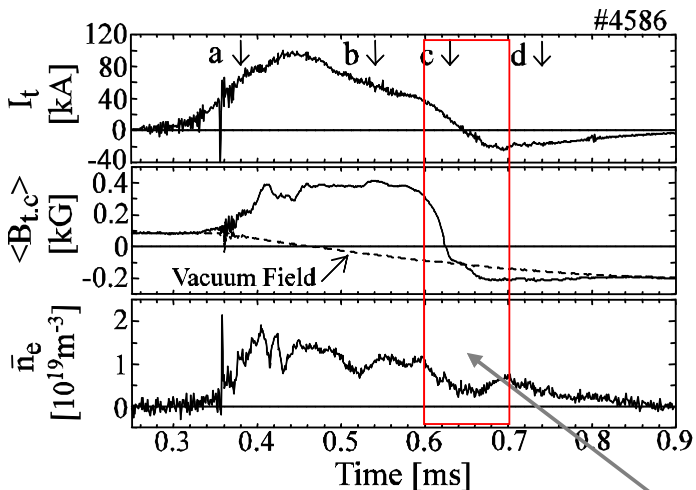
In the ST case, the global relaxation like Taylor type does not seem to occur and it becomes more important to understand local features of reconnections around the X (null)-point.(Ti >Te ? at X-point, Ti ~Te in the core region)

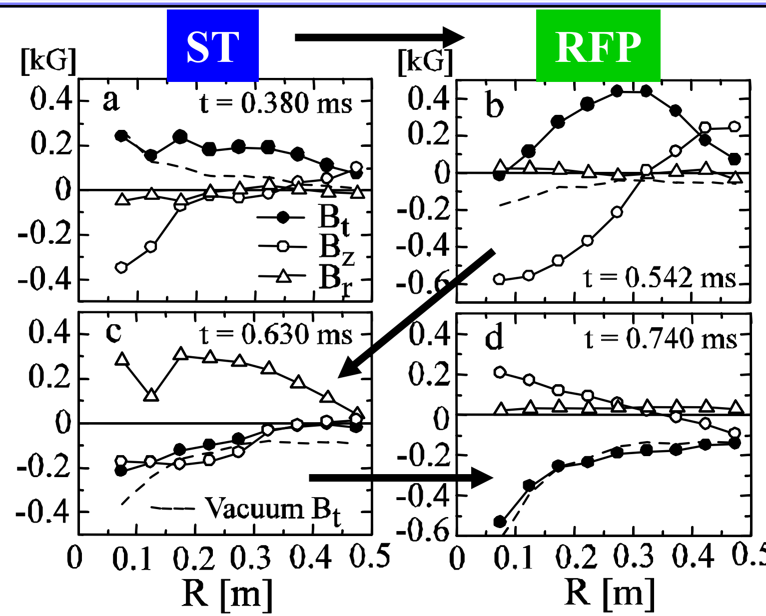
Magnetic reconnection point can be clearly identified.

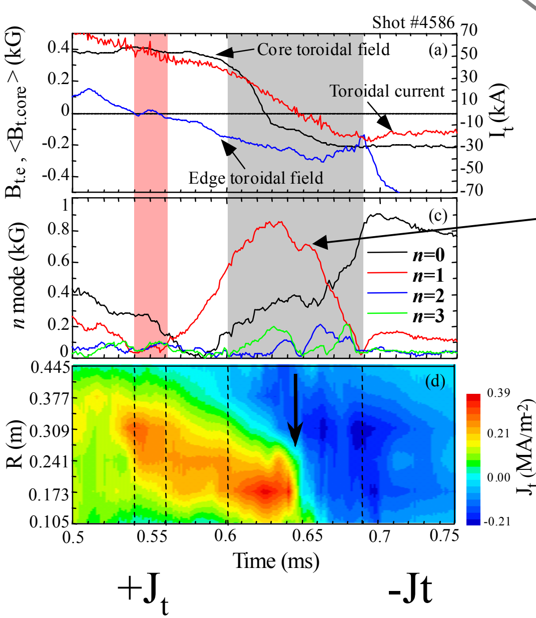
Reconnection layer ~Ion skin depth ~ 3.2 cm,
Electron skin depth ~ 0.07 cm, Ion-gyroradius ~ 0.4 cm

→ Two-fluid reconnection theory may become important.

Observation of Self-reversal of Magnetic Fields by Reversing TF ; Relaxation from the ST toward the Flipped ST State.







Self-reversal process

Flipped ST

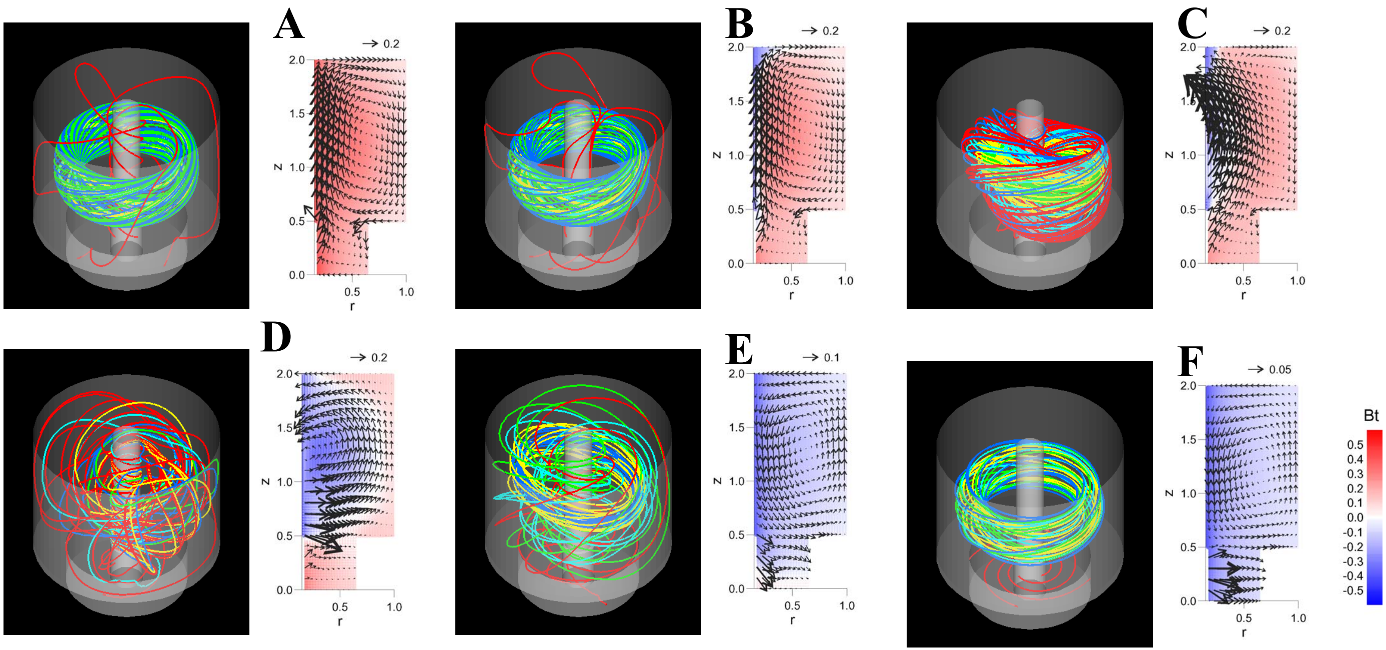
Large growth of the n=1 kink mode

- Note that not only toroidal flux but also poloidal flux reverses the sign spontaneously during the relaxation process.

 # M. Nagata et al. Phys. Rev. Lett. 90, 225001 (2003)

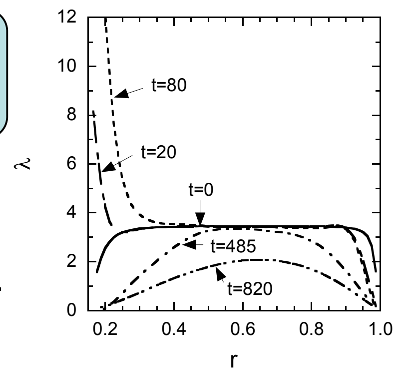
 # In collaboration with S. Masamune, Kyoto Inst. of Tech. and M. Katsurai, U of Tokyo

3D MHD Simulation of Self-organizing from ST to F-ST Relaxed States



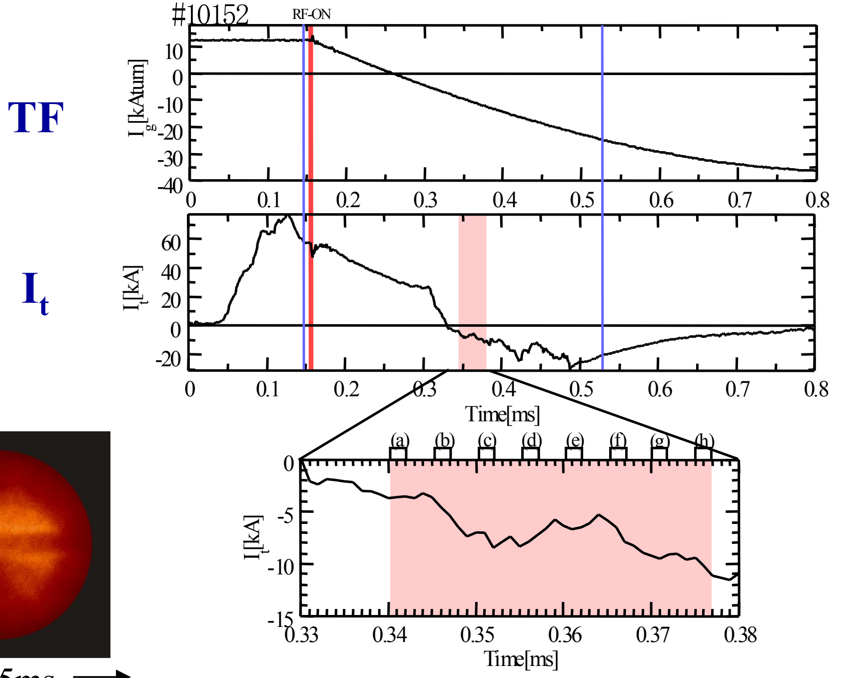
Magnetic reconnection between the open and closed field lines.
Spontaneous reversal of not only toroidal but also poloidal flux.

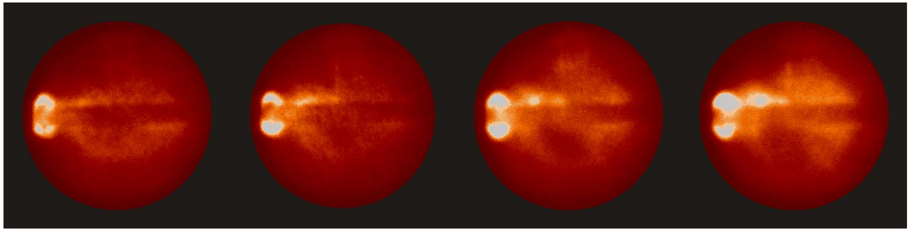
- The system relaxes to a lower energy state by rearranging current distribution. The parallel current profile λ becomes peaked. Kink of the central open flux is essential to the self-reversal process.



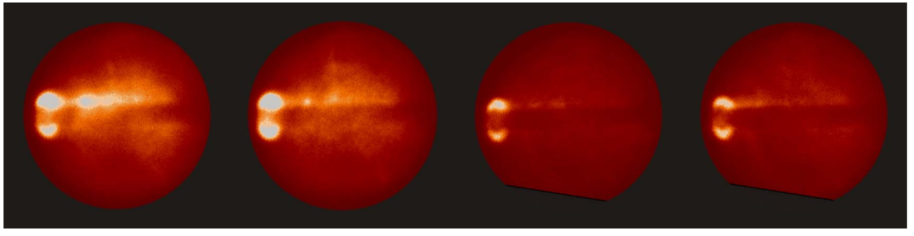
 # Y. Kagei et al. PPCF, 45, L17 (2003) **# In collaboration with Y. Suzuki and Y. Kishimoto, JAERI and T. Hayashi, NIFS**

Fast Camera Images Display Kink instability around the Center Conductor during the Current-reversal Process



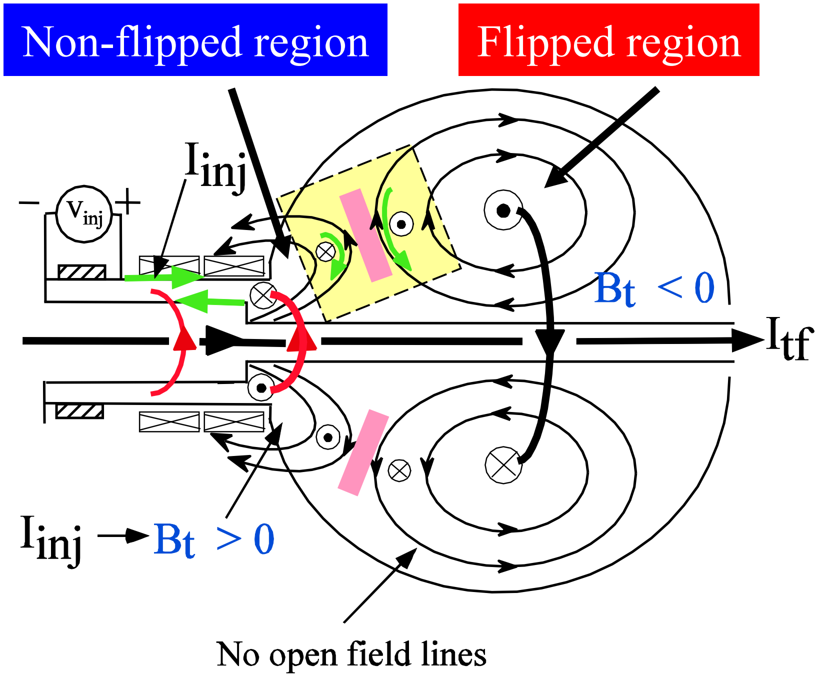


0.340ms → 0.345ms → 0.350ms → 0.355ms →



→ 0.360ms → 0.365ms → 0.370ms → 0.375ms

Key Question; Can We Sustain the Flipped ST plasmas in Spite of No Central Open Flux ?



The F-ST configuration is consisted of only closed flux surfaces so that it may have a better confinement quality ! ?

↓

But, the F-ST is isolated from the electrodes, so can we drive it by helicity injection?

↓

No Magnetic Reconnection

↓

How to drive current?

↓

A key point is to cause the kink deformation of the non-flipped field lines.

Unique magnetic field lines geometry:

B_t: opposite direction,

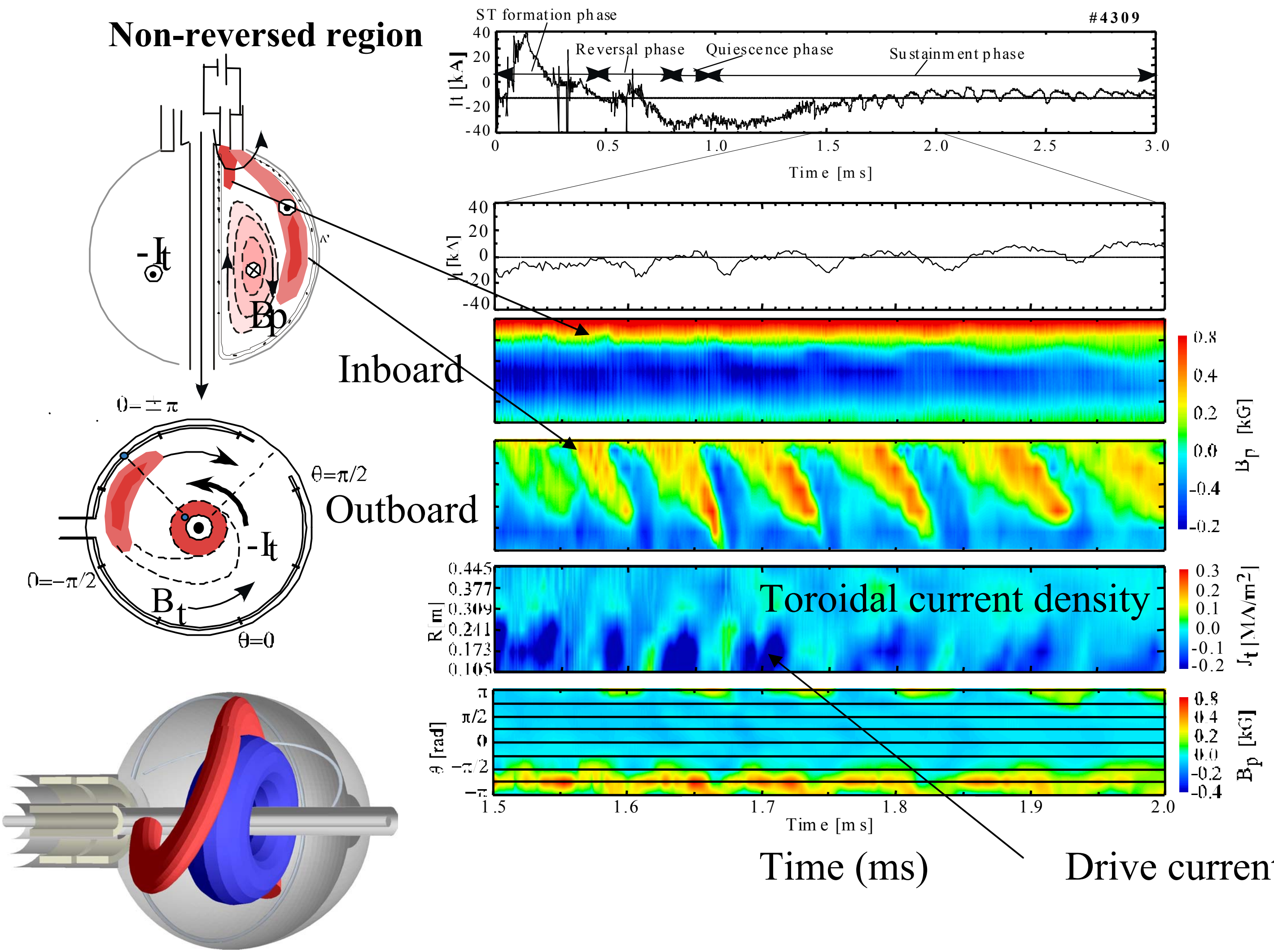
B_p: same direction

Ejection condition: $\mathbf{I_{inj} > 2I_{tf}}$

$\mathbf{q \sim I_{tf}/I_t > 1}$ $\mathbf{I_{inj} > 2I_{tf} > 2I_t}$.

- **Large injection current is required to sustain a large plasma current in the F-ST.**

Dynamo Current Drive of F-ST Plasmas by Kink behavior of Non-flipped Open Flux



Summary

- We have reviewed the MHD relaxation observed in the driven system by varying TF.
- The rotational kink behavior of the open column (central or outboard open flux) is common basic feature of dynamo activities, which plays a major role in CHI current drive in spheromak and low-q ST plasmas.
- 3D MHD simulation investigated the nonlinear evolution of the kink instability during sustainment and revealed its dynamo drive.
- Plasmoid ejection and the following magnetic reconnection process may play an important role in the formation and sustainment of the ST.

Future plans

- An OH coil and a new FC with cut will be installed on the HIST machine.
- CT injection experiment into a small torus chamber to study two-fluid effect and the m=1 helical relaxed state of RFP plasmas.