The Joint Meeting of
5th IAEA Technical Meeting on ST
16th International Workshop on ST
2011 US-Japan Workshop on ST Plasma

# Flux amplification and sustainment of ST plasmas by double pulsed coaxial helicity injection on HIST

**M. Nagata, T. Higashi, M. Ishihara, T. Hanao,
K. Ito, K. Matsumoto, Y. Kikuchi, N. Fukumoto, T. Kanki(1)**

*University of Hyogo, Japan Coast Guard Academy* (1)

**Outline**

1) Introduction
2) HIST device and diagnostics
3) Experimental topics
    a) Flows and density profile
    b) Two-fluid dynamo measurements
    c) Propagation of magnetic fluctuation
4) Summary

# Introduction

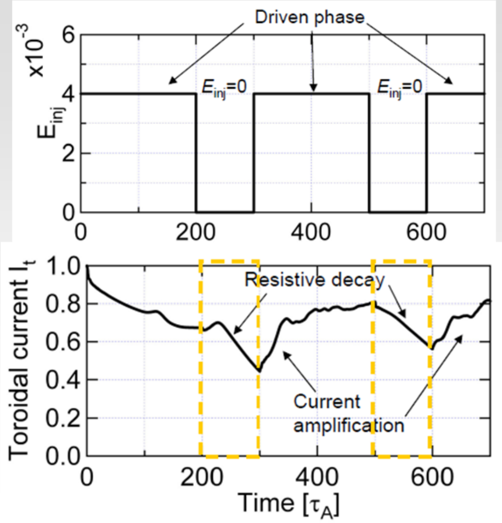
Coaxial Helicity injection (CHI) is an efficient current-drive and start-up method which was used in many spheromak and ST experiments.

A critical issue for CHI is achieving a good energy confinement.

➡ **A new approach of CHI : Multi-pulsing CHI or Repetitive transient CHI**

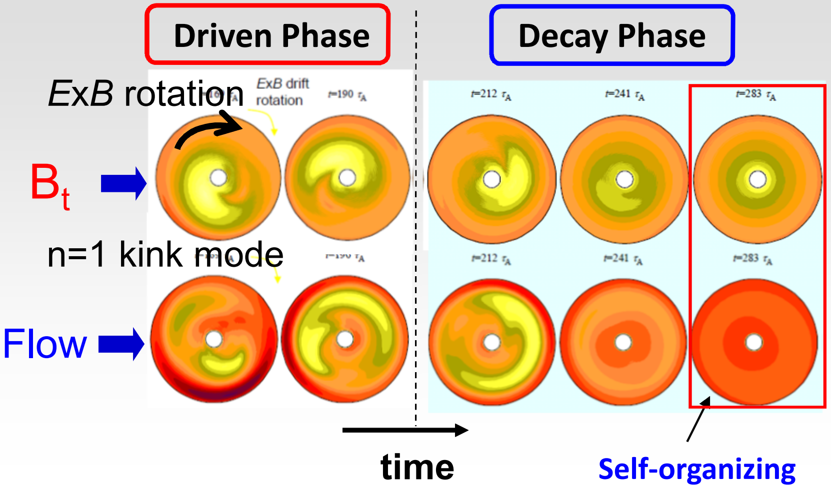
↓

**The multi-pulsing scenario of CHI aims to achieve simultaneously a quasi-steady sustainment and good confinement.**



**3D MHD simulation**

**Low q ST**



# Multi-pulsing CHI for ST configurations

The multi-pulsing CHI (M-CHI) discharges on SSPX at LLNL were successfully demonstrated for a high temperature spheromak. (see Ref.[1,2])

⇨ Application of the M-CHI to ST configurations

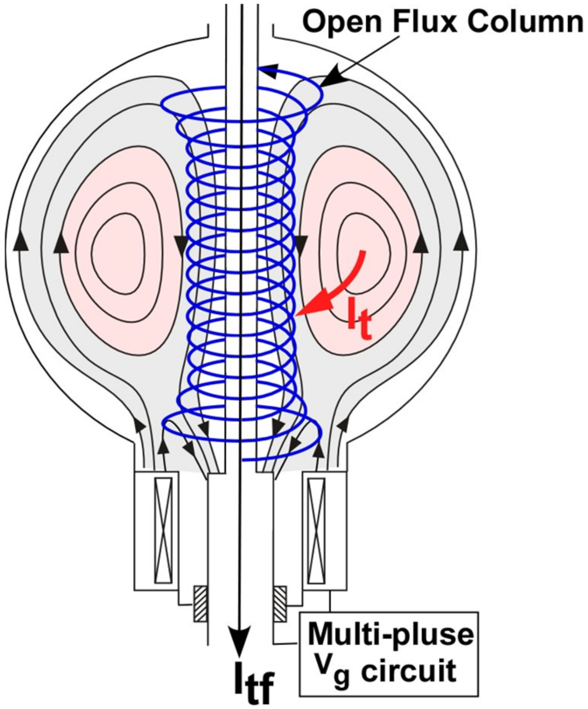
- What mechanism of current drive is different from spheromak ?

Flow, Dynamo, Mode structure, etc.

High-q ST
Low-q ST ⟺ Spheromak

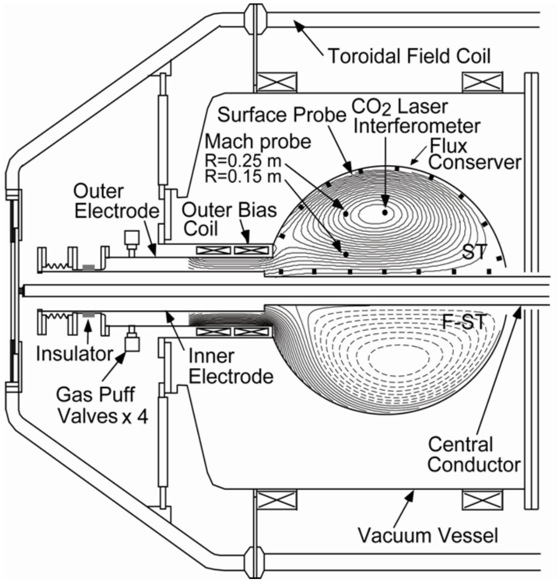
- **Central open flux column** plays an important role in driving a current.

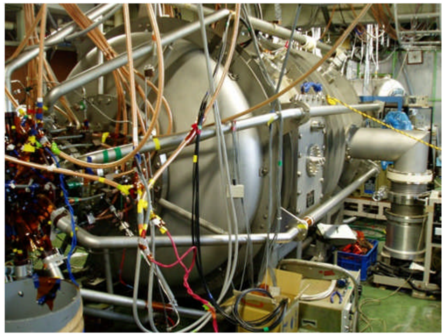
- A purpose of this experiment is to explore characteristics of the M-CHI driven ST.



[1] S. Woodruff, et al. PRL **90**, 205002-1 (2004)
[2] E.B. Hooper, PPCF **53**, 085008 (2011).

# HIST device and double-pulsing CHI





- **HIST plameters**

  R=0.3 m, a=0.24 m , A=1.25
  $n_e$=0.5-1 x 10 $^{20}$ $m^{-3}$
  $T_{e,}$ $T_i$ = 10-40 eV
  $I_t$< 150 kA, $h_e=\omega_{ce}\tau_{ie}$=50-200
  $S^*=R/l_i$~10 $l_i=(c/\omega_{pi})$=2~3 cm

- **TF coil current**

  **Spheromak, Low-q ST:** q ~ $I_{tf}$ (= 0-30 kA) / $I_t$<1

  **High-q ST:** q ~ $I_{tf}$(= ~ 150 kA) / $I_t$>1

- **Power supply system for double-pulse**

  **Formation capacitor banks**
  *V* = 3-10 kV, *C* = 0.6 mF
  Injection current : $I_g$ ~ 30 - 60 kA

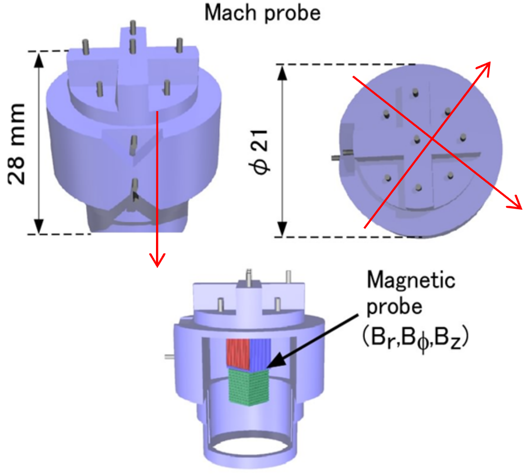
- **Sustainment capacitor banks**

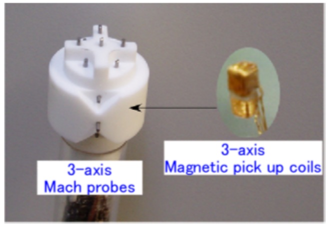
  First pulse : *V* < 900 V, *C* = 336 mF
  Second pulse : *V* < 900 V, *C* = 195 mF

  2nd pulse voltage : $V_g$ ~ 400 V
  2nd pulse current : $I_g$ ~ 10-20 kA

# Dynamo-Mach Probe Measurement

**3-axis flows and 3-axis magnetic fields are simultaneously measured.**





## - Mach probe analysis -

## Hutchinson model

→ $r_p/\rho_i < 1$ **: unmagnetized**

$$V_i = C_s \times M_i$$ **: $C_s$=30 km/s ($T_e$=$T_i$)**

**Ion Mach Number $M_i$**

$$M_i = M_c \ln(J_{up}/J_{down})$$

**$J_{up}$ upstream rod current**

**$J_{down}$ downstream rod current**

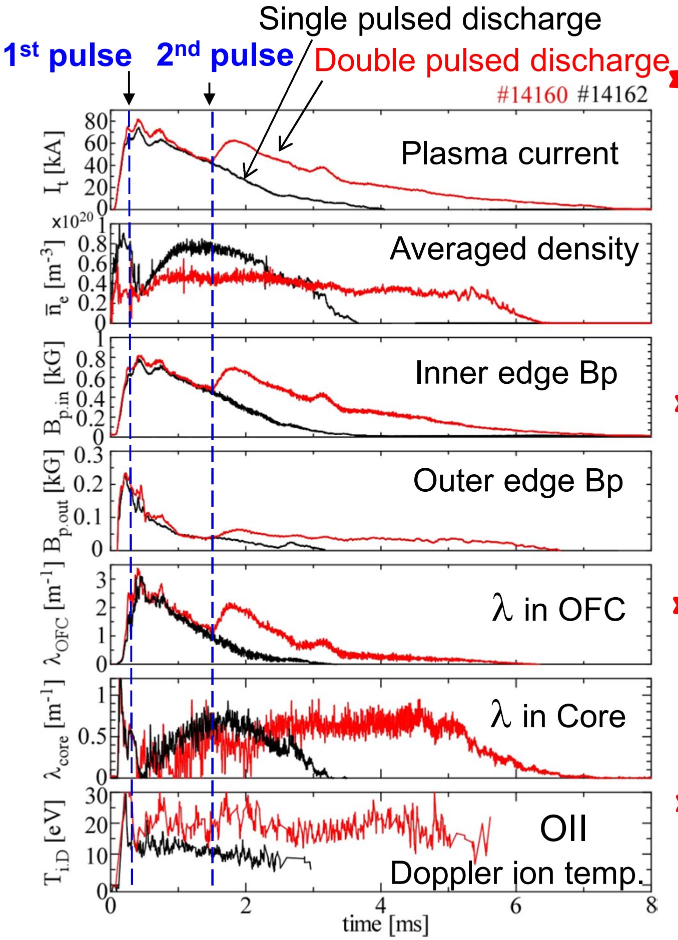
$$\frac{1}{M_c} = K\sqrt{\gamma_e + (T_i/T_e)\gamma_i}$$

$$K = 1.34 \;\; T_i/T_e = 1 \, (\gamma_e = \gamma_i = 1)$$

$$\rightarrow \; M_c = 0.53$$

$V_i$: ion flow, $C_s$: ion sound velocity, $M_i$: ion Mach number, $M_c$: proportionality constant, $T_e$ ($T_i$): electron (ion) temperature, $\gamma_e$ ($\gamma_i$): specific heat ratio for electron (ion), $r_p$: probe radius, $\rho_i$: Larmor radius (~ 1 cm)

# Double pulsing CHI discharge (High-q)

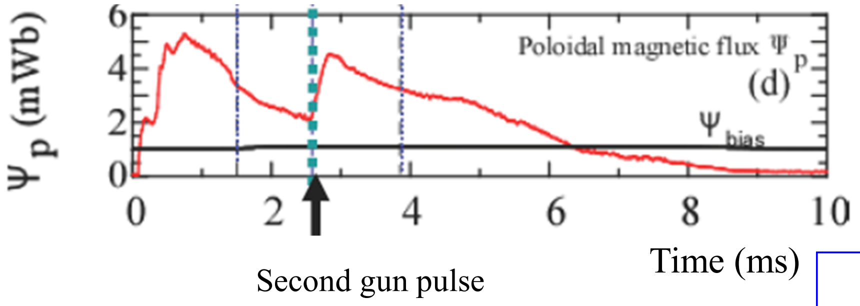


- By secondly pulsing the MCPG at t = 1.5 or 2.5 ms during the partially decay phase, total plasma current is effectively amplified against the resistive decay. The core current density is generated due to dynamo.
- The sustainment time has increased up to 6 -8 ms which is longer than that in the single CHI case.
- The edge λ in the OFC is larger than the core λ , causing helicity transport.

$$\lambda = \mu_0 I_t / \Psi_t$$

- Ion Doppler temperature increases from 20 eV up to 30 eV.

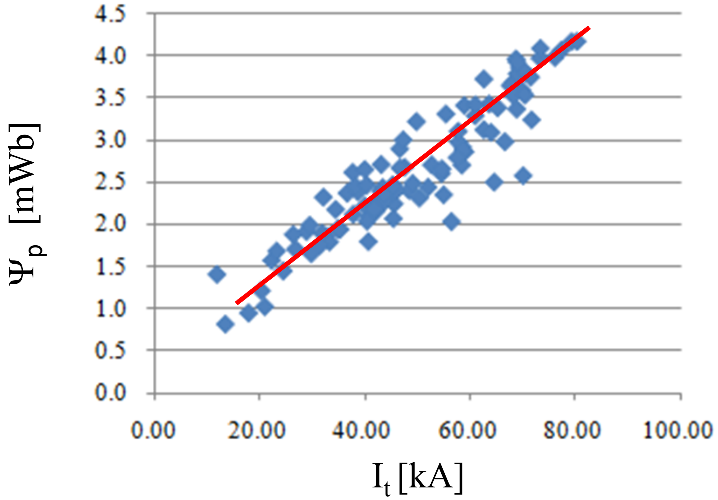
# Flux and current amplification



**High-q ST**

**Poloidal Flux >Bias flux**

$$\Psi_p > \Psi_{p.bias}$$



**Flux Amplification**

$A_\Psi = 4 \sim 5$

$\Psi_{p.bias} \approx 1$ mWb

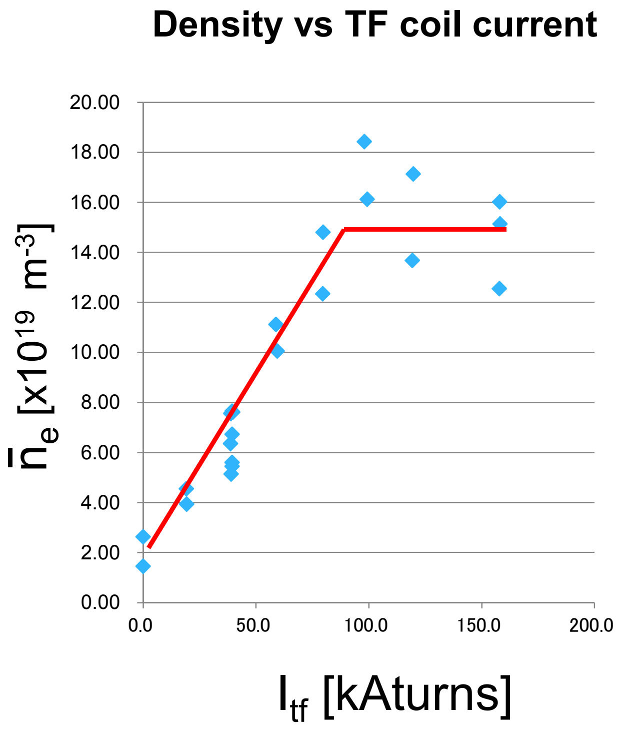
**Current Amplification**

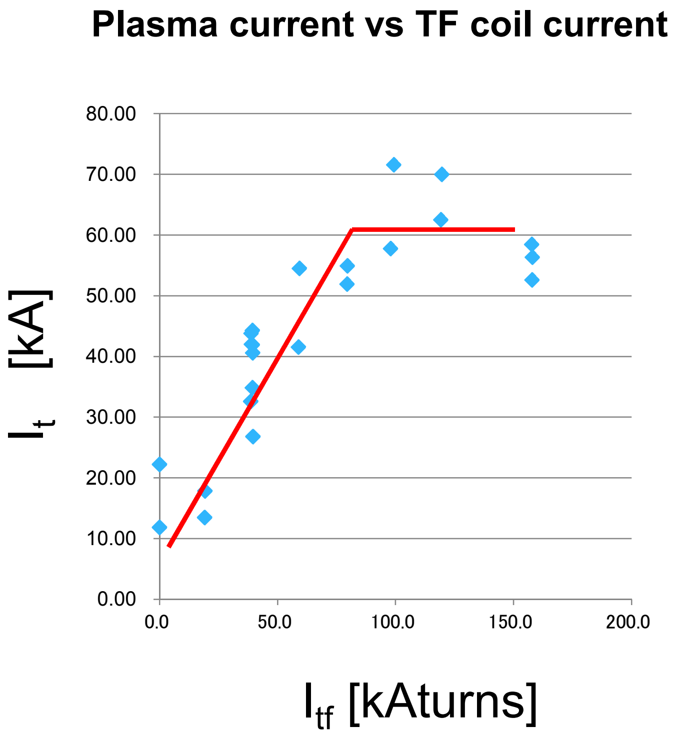
$A_I = 4 \sim 8$

$I_{inj}$=10, 20 kA

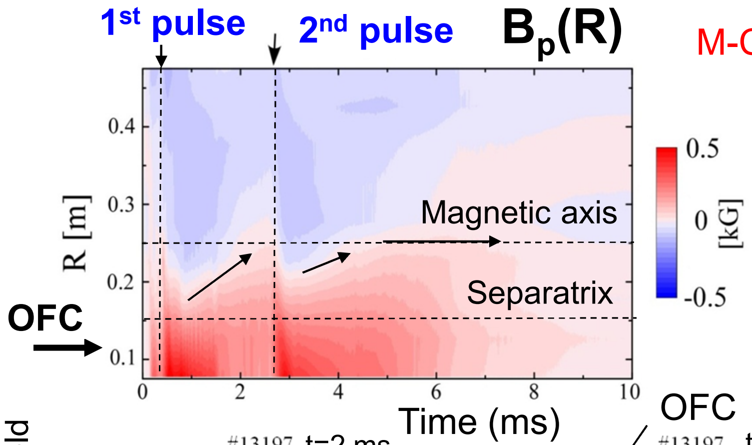
# Note that $A_\Psi$ includes the OFC

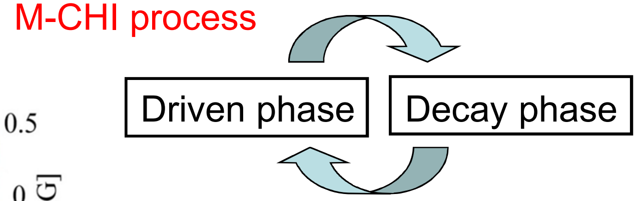
# $I_t$ and $\bar{n}_e$ vs $I_{tf}$ for 2nd pulse



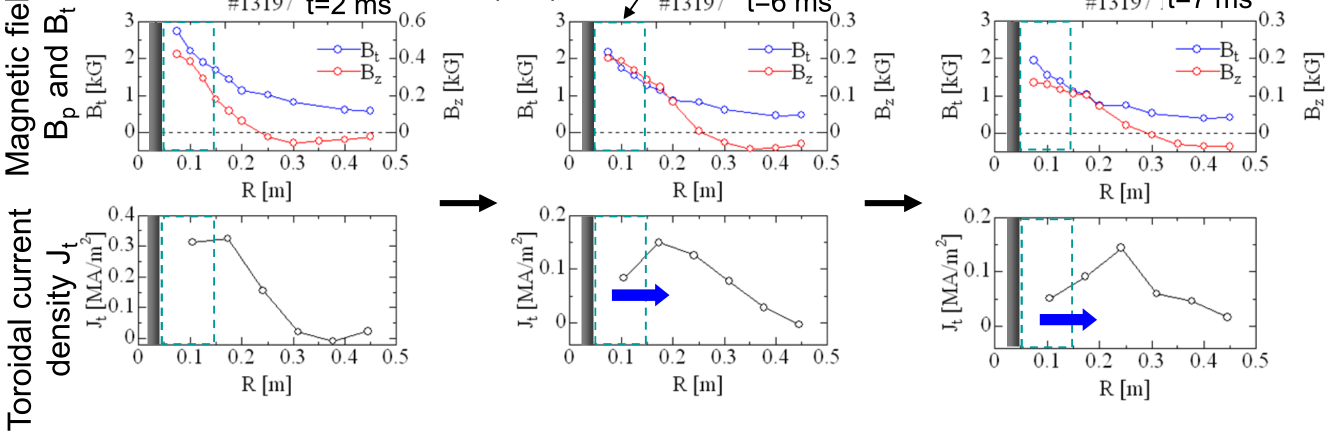


# Internal magnetic field profiles





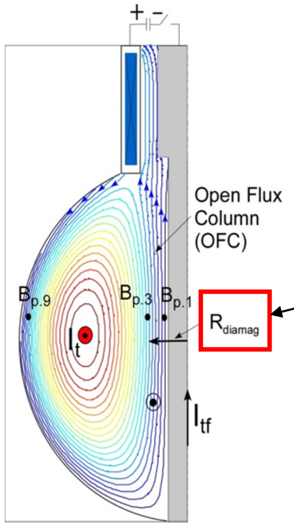
*B*p is enhanced in the OFC.
Magnetic axis moves outwardly.
$J_t$ becomes from a hollow to a peaked profile.



# Diamagnetic properties of Open Flux Column

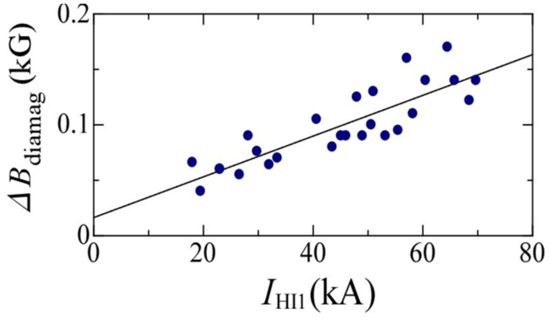
**The toroidal field $B_t$ in the OFC is decreased from the vacuum field.**

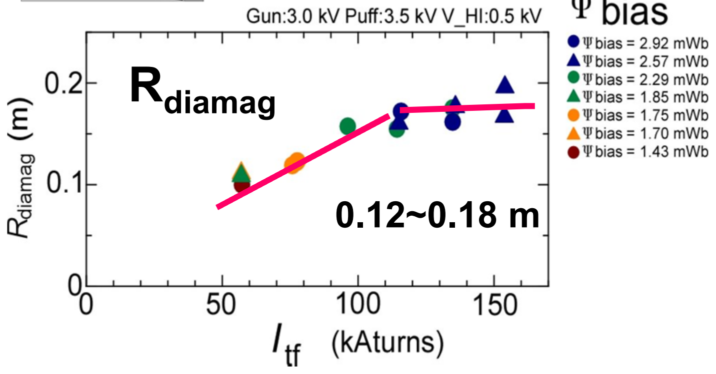
**“diamagnetic”**

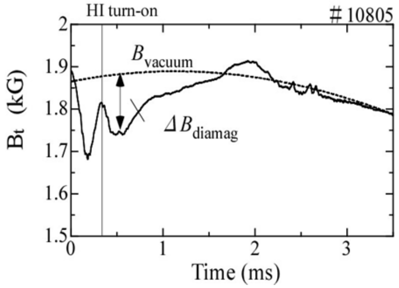


**OFC radius ~ $R_{diamag}$**

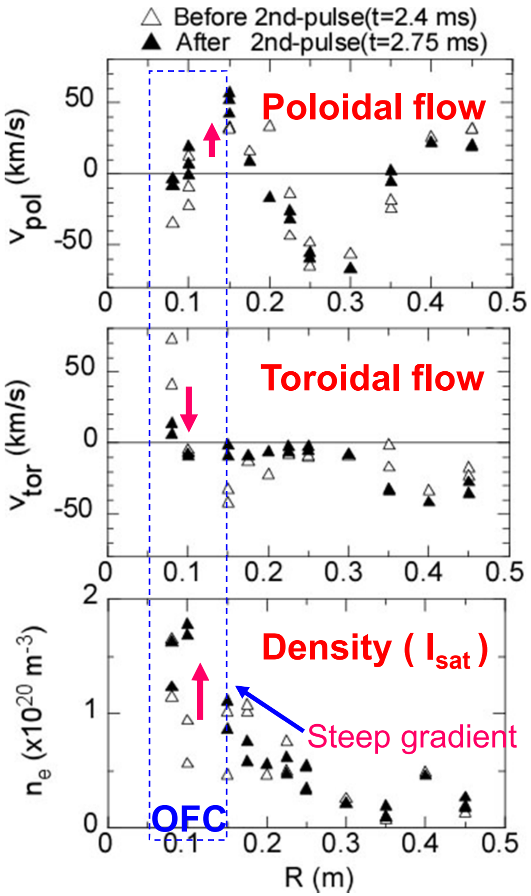
**Separatrix position**







# Flows and density profiles



$$v_p = \frac{E_r \times B_t}{B^2} - \boxed{\frac{\nabla p_i \times B_t}{enB^2}}$$

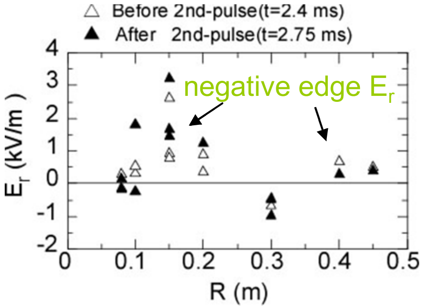
⇩

**Poloidal shear flow**

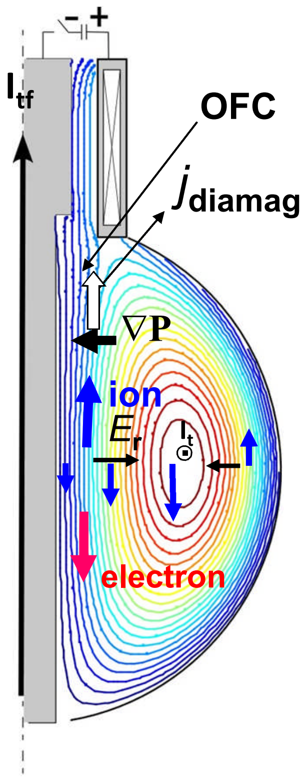
**Diamagnetic current**

⇨ Diamagnetic properties of OFC

**Radial electric field $E_r$**



$$E_r \approx \frac{\nabla p_i}{e n_i Z_i} \boxed{-(v_p B_t} - v_t B_p)$$



# Two-fluid dynamo effects

## Generalized Ohm's law

$$\eta\,\boldsymbol{j} = \boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} - \boldsymbol{j}\times\boldsymbol{B}\,/en + \nabla\, p_{\mathrm{e}}/en$$

$$\downarrow$$

$$\eta\,\boldsymbol{j}_0 - \boldsymbol{E}_0 = (\boldsymbol{v}_0\times\boldsymbol{B}_0) + <\tilde{\boldsymbol{v}}\times\tilde{\boldsymbol{B}}> - (\boldsymbol{j}_0\times\boldsymbol{B}_0)\,/en - <\tilde{\boldsymbol{j}}\times\tilde{\boldsymbol{B}}>/en$$

$$\downarrow$$

$$\boldsymbol{\eta j}_{\parallel 0} - \boldsymbol{E}_{\parallel 0} = <\tilde{\boldsymbol{v}}\times\tilde{\boldsymbol{B}}>_{\parallel} - <\tilde{\boldsymbol{j}}\times\tilde{\boldsymbol{B}}>_{\parallel}/en \approx -<\tilde{\boldsymbol{v}}_{\mathrm{e}}\times\tilde{\boldsymbol{B}}>_{\parallel}$$

**MHD dynamo** **Hall dynamo** **Electron dynamics**

$$\tilde{\boldsymbol{v}}_{\mathrm{e}\perp} = \tilde{\boldsymbol{v}}_{\perp} - \tilde{\boldsymbol{j}}_{\perp}/en \approx \frac{\tilde{\boldsymbol{E}}_{\perp}\times\boldsymbol{B}_0}{B^2} + \frac{\nabla_{\perp}\,\tilde{p}_{\mathrm{e}}\times\boldsymbol{B}_0}{enB^2}$$

Electron-ion decoupling

**ExB drift** **Diamagnetic drift**

# Diamagnetic dynamo term does not appear explicitly in the parallel mean-field Ohm's law

Diamagnetic dynamo $\dfrac{<\nabla\tilde{p}_{\mathrm{e}}\cdot\tilde{B}>_{\parallel}}{\mathrm{en\,B}}$

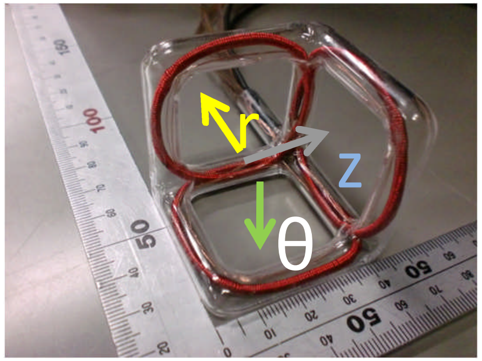
# Diamagnetic current $\mathbf{j}_{\mathrm{diamag}}$ due to electron and ion diamagnetic drift contributes on Hall dynamo term

$$\tilde{\boldsymbol{j}}_{\mathrm{e}\perp} \approx \frac{\boldsymbol{B}_0\times\nabla\,\tilde{p}_{\mathrm{e}}}{B_0^{\;2}} \qquad \tilde{\boldsymbol{j}}_{\mathrm{i}\perp} \approx \frac{\boldsymbol{B}_0\times\nabla\,\tilde{p}_{\mathrm{i}}}{B_0^{\;2}}$$

* Private communication with Dr. K. McCollam

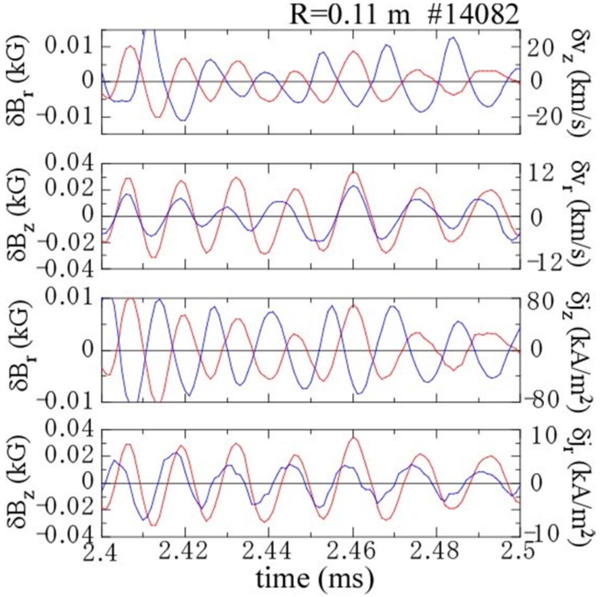
# Hall and MHD dynamo measurement

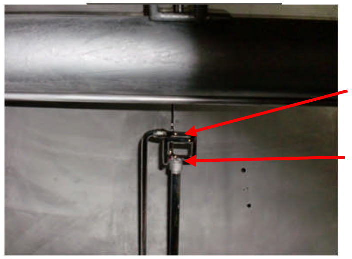
Measurement of three components of fluctuating velocity, current density and magnetic field at a radial position



**Hall dynamo probe** (50x50x50 mm)

Incorporating Rogowski loop and flux loop





**Hall dynamo probe**

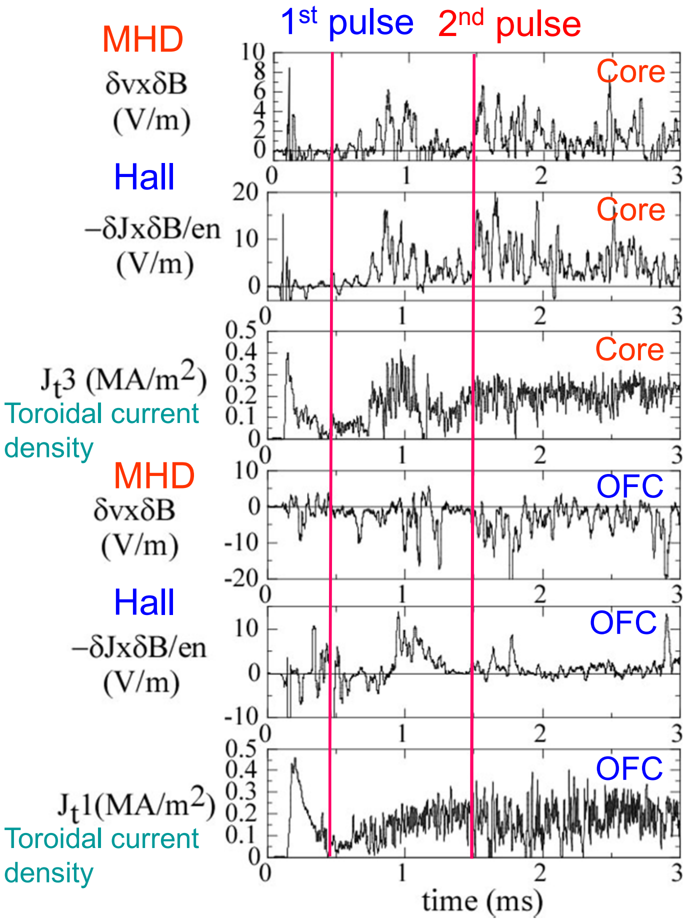
**MHD dynamo probe**

$$E_{t0} = <\delta \boldsymbol{v}\times\delta\boldsymbol{B}>_t = <\boxed{\delta \boldsymbol{v}_z\cdot\delta \boldsymbol{B}_r} - \boxed{\delta \boldsymbol{v}_r\cdot\delta \boldsymbol{B}_z}>$$

$$E_{t0} = <\delta \boldsymbol{j}\times\delta\boldsymbol{B}>_t = <\boxed{\delta \boldsymbol{j}_z\cdot\delta \boldsymbol{B}_r} - \boxed{\delta \boldsymbol{j}_r\cdot\delta \boldsymbol{B}_z}>$$

out of phase in phase

# Dynamo balances Ohm’s law



**Parallel mean-field Ohm's law**

$$\boxed{\eta j_{\parallel 0}} - \boxed{E_{\parallel 0}} = \underbrace{\boxed{<\tilde{\boldsymbol{v}} \times \tilde{\boldsymbol{B}}>_{\parallel}}}_{\text{MHD dynamo}} - \underbrace{\boxed{<\tilde{\boldsymbol{j}} \times \tilde{\boldsymbol{B}}>_{\parallel} /e\overset{\uparrow}{n}}}_{\text{Hall dynamo}}$$

$I_{sat}$

$$\boxed{E_{\parallel 0}(r) = V_{\parallel g}/L - \frac{\partial \Psi_p(r)}{\partial t\, 2\pi r}}$$

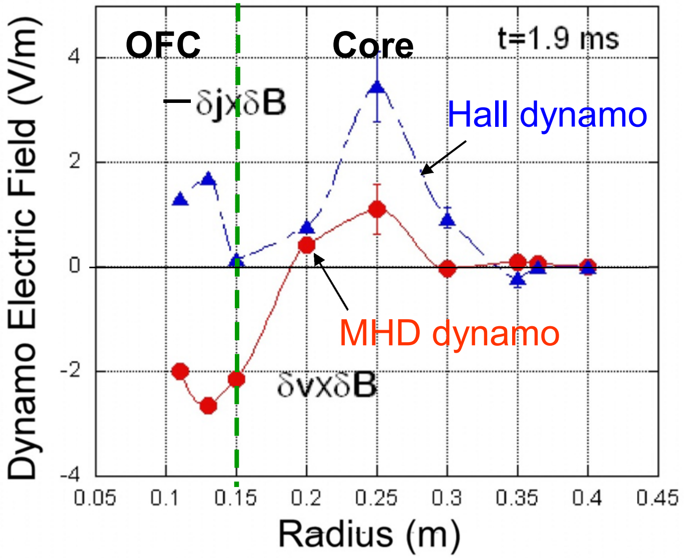
$$\boxed{\eta_{\text{spitzer}} = \eta_{\parallel} = 5.22 \times 10^{-5}\, Z_{\text{eff}}\, (kT_e)^{-3/2} \ln \Lambda}$$

$$\eta_{\parallel} \approx 2 \sim 6 \times 10^{-5} \quad \Omega\text{m}$$

| OFC region | Core region |
|---|---|
| $V_{\parallel g} \approx 100 \sim 200$ V<br>$E_{\parallel 0} \approx 10 \sim 20$ V/m<br>$\eta j_{\parallel 0} \approx 3 \sim 9$ V/m | $V_{\parallel g} \approx 0$ V<br>$E_{\parallel 0} \approx -2$ V/m<br>$\eta j_{\parallel 0} \approx 4 \sim 12$ V/m |
| $<\tilde{\boldsymbol{v}} \times \tilde{\boldsymbol{B}}>_{\parallel} - <\tilde{\boldsymbol{j}} \times \tilde{\boldsymbol{B}}>_{\parallel}/en \approx$ | |
| $\approx -1$ V/m | $\approx 6 \sim 14$ V/m |

# Radial profile of dynamo electric field

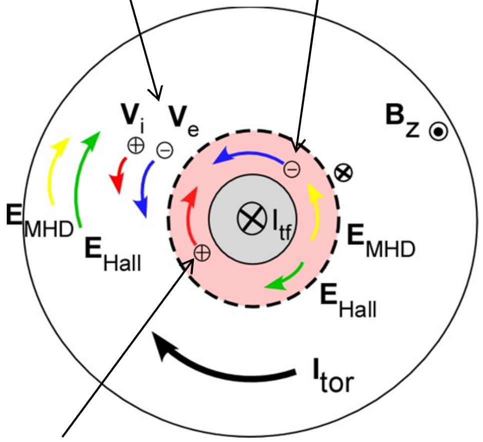
$$<\tilde{v}\times\tilde{B}>_{\parallel} - <\tilde{j}\times\tilde{B}>_{\parallel} /en$$



**Anti-MHD dynamo**

Collisional drag of electrons on the ions accelerates the ions in the core.

Electrons become slow down due to anti-dynamo $E_{MHD}$



Ions are accelerated due to $E_{Hall}$ in the direction of the current in the OFC.

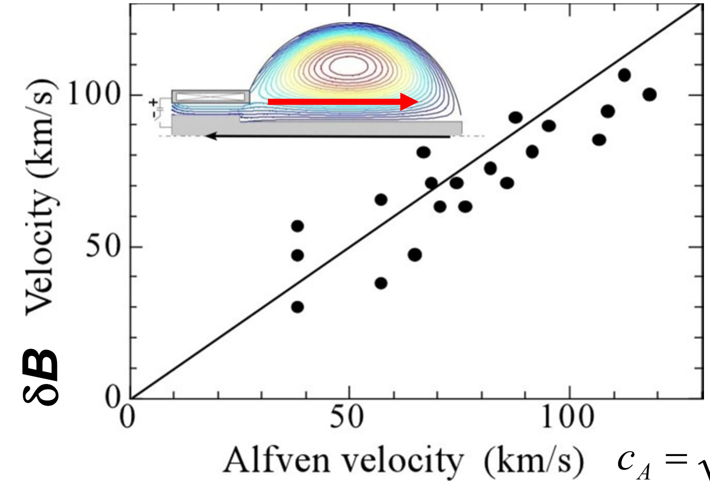
- Hall dynamo driven current in the OFC is the same direction as the mean current.
- MHD anti-dynamo electric field in the OFC reduces the mean current.

⇨ Electron locking model [1]

$$\delta\omega_{ce}\tau_{ie} > \delta/R$$

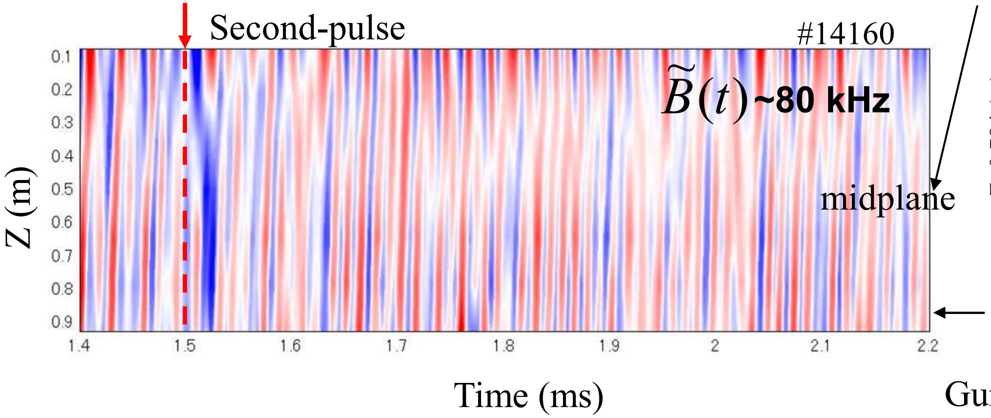
[1] T.R. Jarboe *et al*., Nucl. Fusion **51** 063029 (2011).

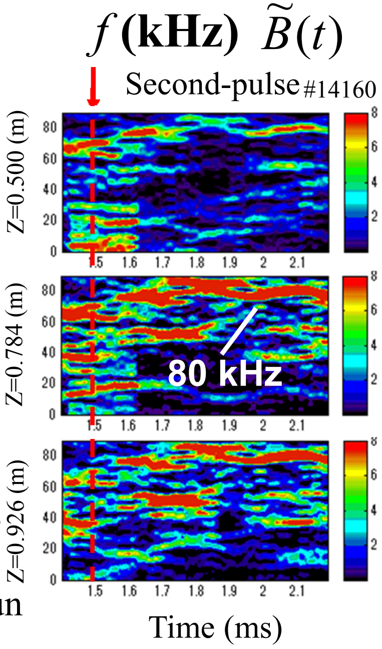
# Axial propagation of magnetic fluctuation



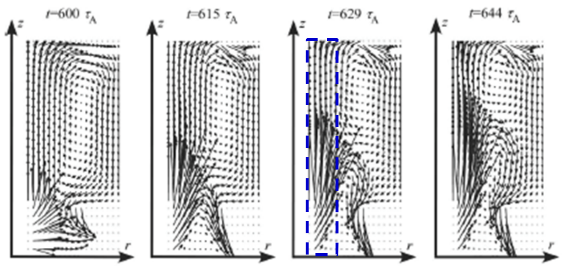
$c_A = \sqrt{B^2/\mu_0 m_i n}$

- Propagation of by Alfven speed
- Alfven wave is excited by the magnetic reconnection around the X-point.

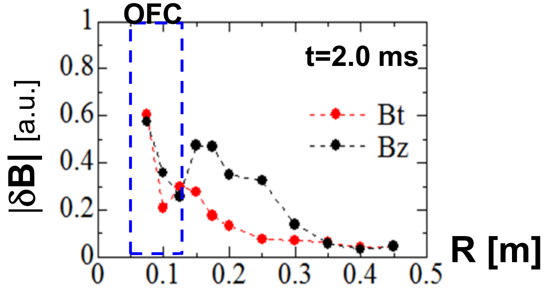


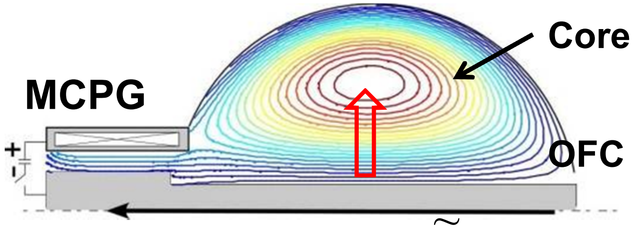


# Radial propagation of magnetic fluctuation



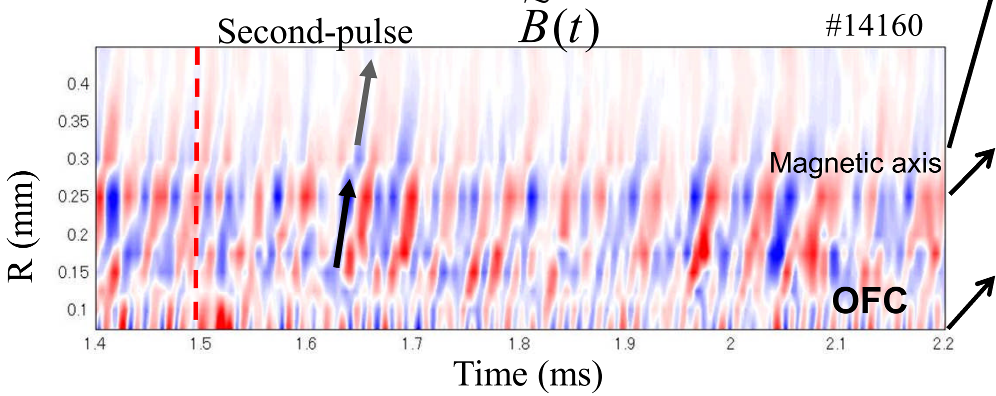
3D MHD simulation for High-q ST

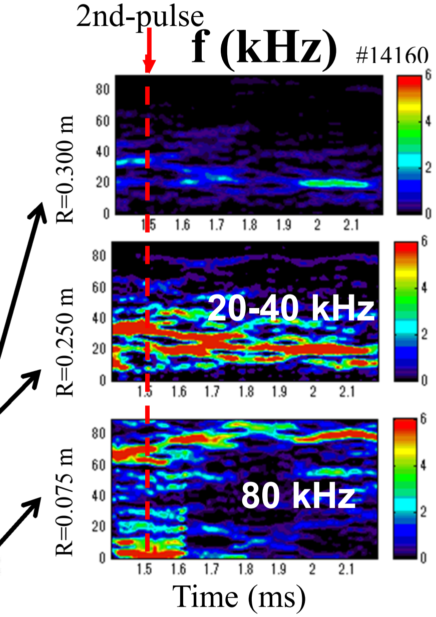




80 kHz
+
20~40 kHz

80 kHz





# Summary

- The HIST device has been developed towards high-β and quasi-steady-state sustainment of high-q and low-q ST plasmas by Multi-pulsing CHI method. We have successfully demonstrated the flux/current amplification and sustainment of the plasmas in the double gun pulse experiment. We have investigated the characteristics of the double CHI driven ST plasmas. Muti-pulsing CHI experiments are planned for the future work.

- We have observed the poloidal flow shear between the OFC region and the closed flux region. The ion diamagnetic drift due to a steep density gradient observed there could account for it.

- It has been the first time to measure simultaneously the Hall and MHD dynamo spatial profile for the ST. The relative contributions of the different dynamo electric field on the driven current have been investigated to verify mean Ohm's law balance. Two-fluid Hall dynamo is essential to the CHI current drive mechanisms.