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Study of Time Evolution of Toroidal current in LHD

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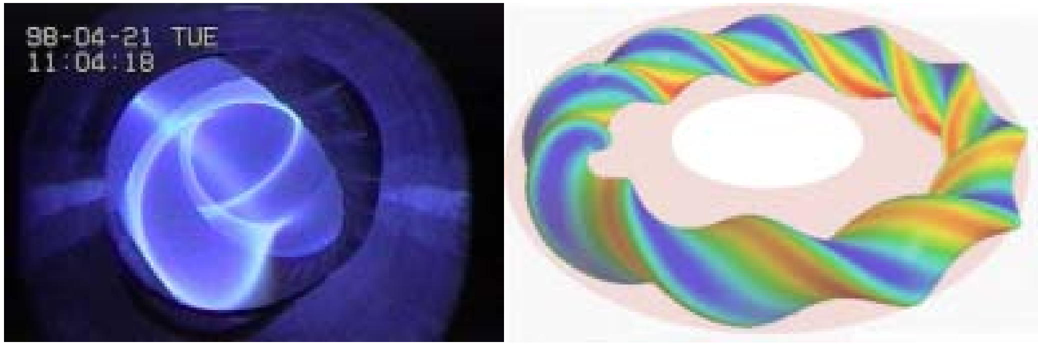


Tangential View of LHD

Toroidal Current --- Observation ---

In principle

Toridal current for plasma confinement is not necessary in Heliotron devices!!

Observation in LHD

In NBI discahrge
More than 100kA of toroidal current is observed.
No active control of one turn voltage

B_0=0.75~2.9T, H_2, R_{ax}^V=3.6/3.75m,
I_p= -30~110kA, $\Delta\iota(a)$ = -0.04~0.1.

Toroidal current affects MHD equilibrium, stability and Transport in Heliotron devices

Determination of Driving Mechanism; ***Important!!***

Candidates of Current Driving Mechanism;
Ohkawa Current & Bootstrap Current

Outline of talk

1. Properties of Bootstrap Current in Heliotron devices
2. Experimental Observation of Bootstrap current in LHD

   (including comparison results between experimental data and theoretical prediction)

3. Observation of MHD activity and rational surface

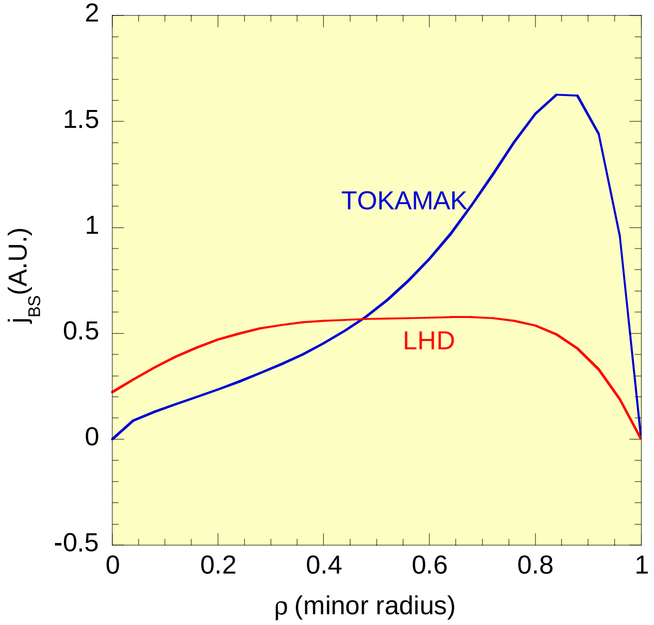
   (A MHD activity indicates information of central rotational transform)

   ➔ Information leads to determination of the current profile

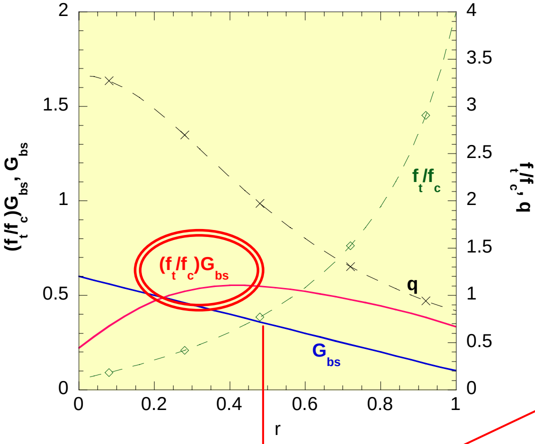
Properties of Bootstrap Current in Heliotron devices (1)

- profile TOKAMAK vs LHD (Heliotron) -

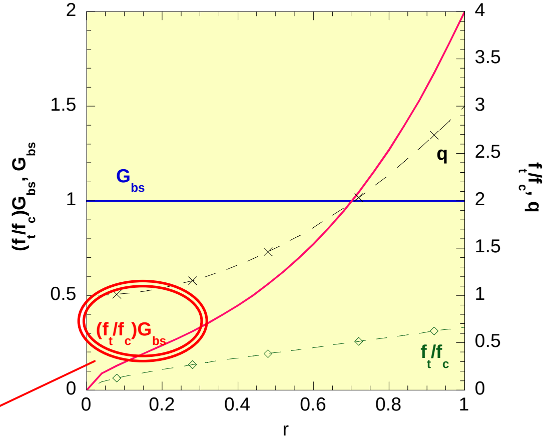
$I_{BSC\text{-}LHD}/I_{BSC\text{-}TOK} \sim 0.5$



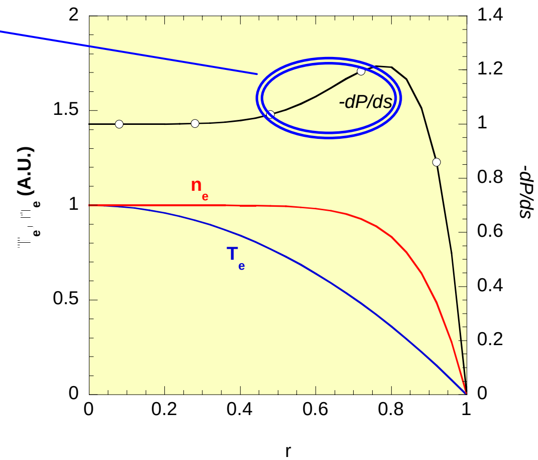
LHD



equiv. *TOKAMAK*



$j_{BS} \sim (f_t/f_c)^*G_{bs}{}^*dP/ds$
in banana(1/ν)-regime



- BS current profile in LHD is much broader than TOKAMAK

  <u>*comes from*</u>

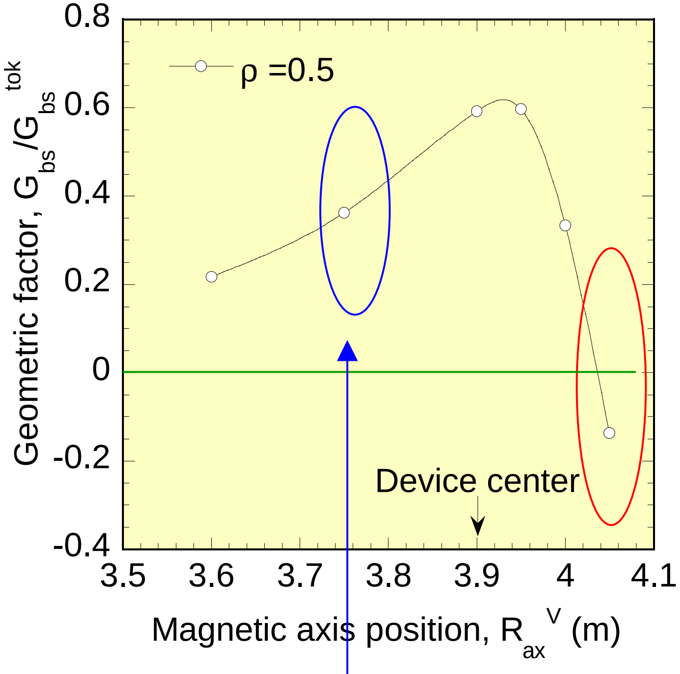
  Difference of Radial profile of q and geometrical facter between TOKAMAK and LHD

Properties of Bootstrap Current in Heliotron devices (2)

- Dependence on Magnetic Axis Configuration -

$$j_{BS} \sim (f_t/f_c)*G_{bs}*P*(n'/n+a_1T_i'/T_i+a_2T_e'/T_e)$$

$$a_1, a_2 \sim O(+0.1),\ G_{bs}^{tok}=I_p/2\pi\iota$$



Geometrical Factor for LHD in 1/ν-regime

Standard configuration

Geometric Factor (BS current) strongly depends on Magnetic Axis Position!!

Note!!

Magnetic Axis goes torus-outwardly =>

Geometric factor significantly decreases and changes the sign.

Time evolution of toroidal current and the estimation of non-inductive current

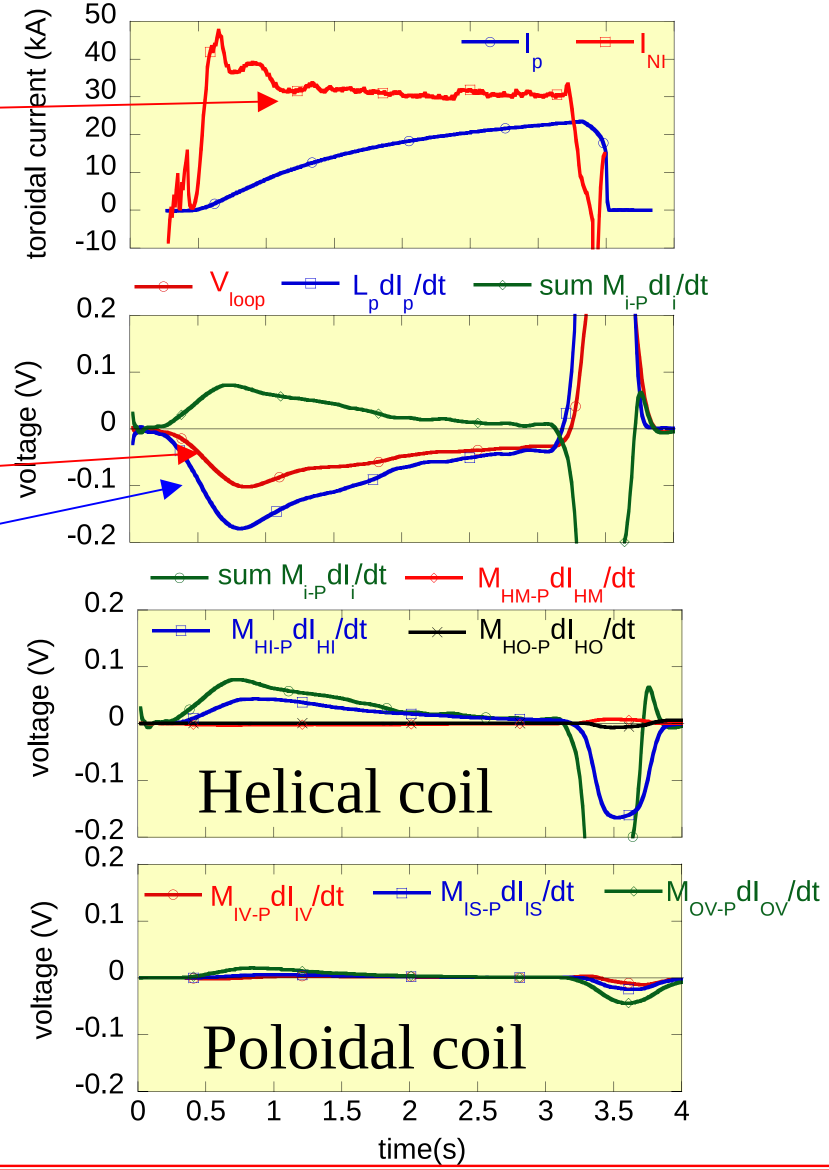
Calculate

$$R_p I_p = V_{loop} + R_p I_{NI}$$

$$V_{loop} = -L_p \frac{\mathrm{d}I_p}{\mathrm{d}t} + \sum_i M_{iP} \frac{\mathrm{d}I_i}{\mathrm{d}t}$$

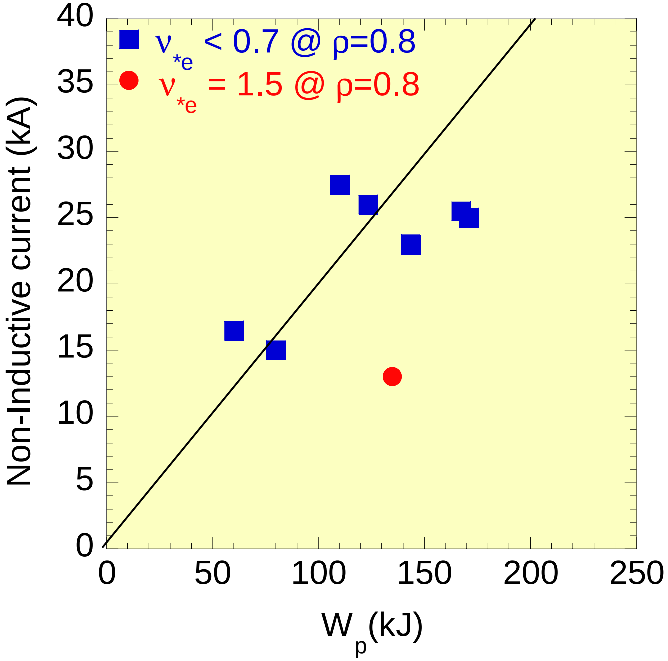
Measure

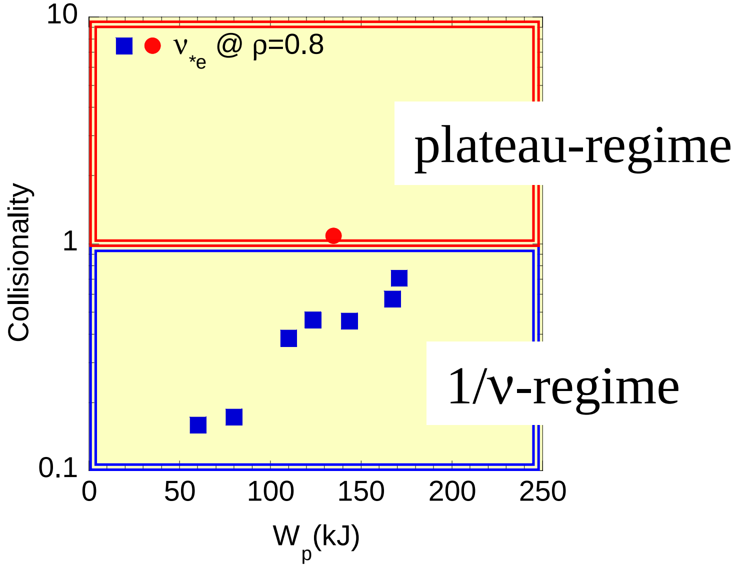
I_p: observed plasma current
I_{NI}: non-inductive plasma current
V_{loop}: one-turn voltage
(self-induced part is dominant in LHD. When $\mathrm{d}I_p/\mathrm{d}t=0$, $V_{loop}\sim 0$)
I_i: increment of current in helical coils, vacuum vessel and so on.
M_{ip}: Mutual inductance between i-component and plasma.
L_p: self-inductance of Plasma
R_p: resistance of plasma
(Tokamak neoclassical used here)



Experimental result for non-inductive current (1)

- W_p and collionality dependence in NB balanced injection -





R_{ax}^{V}=3.75m, 1.5/1.52T, Hydrogen

NB balanced Inj. Total NBI power = 2~3.7MW

$\Delta\iota(a)$~0.02(20kA@1.5T)

Observed toroidal current
increases with W_p increasing.
Collisionalty increses
=> Observed current decreases

Probable candidate of current driving mechanism;
Bootstrap Current

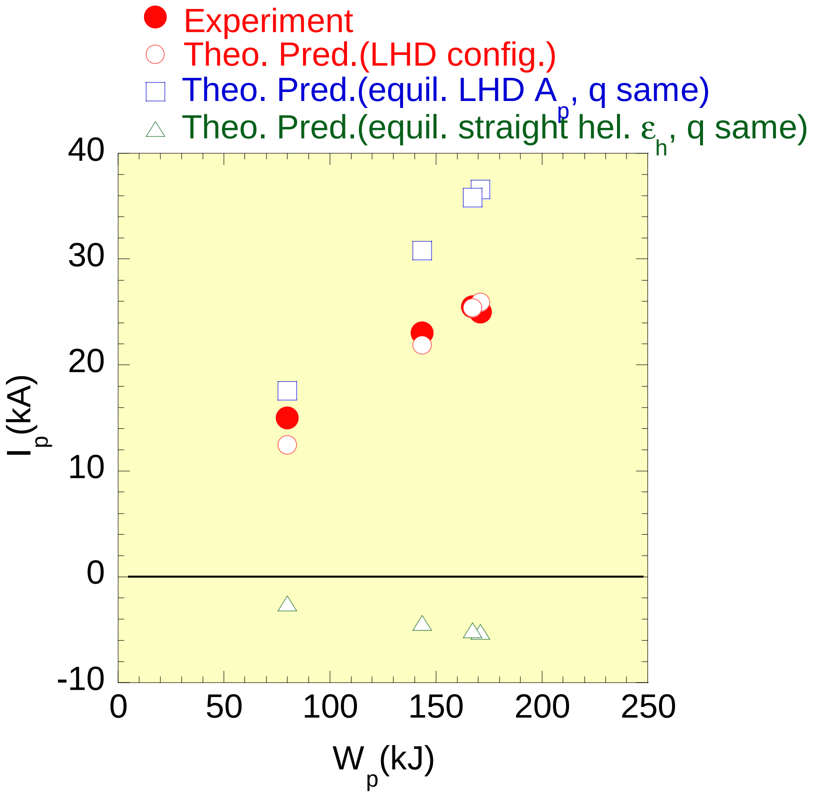
Comparison result with theoretical prediction
- W_p dependence -

Theoretical calculation of BS current

1. *SPBSC* code (ref K.Y.WATANABE et al, Nuclear Fusion 35 (1995) 335)
   - BS current calculation with the consistent MHD equilibrium
   - Connection formula from 1/ν to P-S collisional regime
   - BS current is estimated based on momentum method for asymmetric devices proposed by K.C Shaing *et al*. (Phys. Fluids 26(1983)3315, Phys. Fluids 29(1986)521)

2. $n_{e\text{-bar}}$ and T_e are used by measurement. n_e profile is assumed as ~$(1-\rho^8)$

3. Z_{eff}=2, $T_e = T_i$ are assumed.



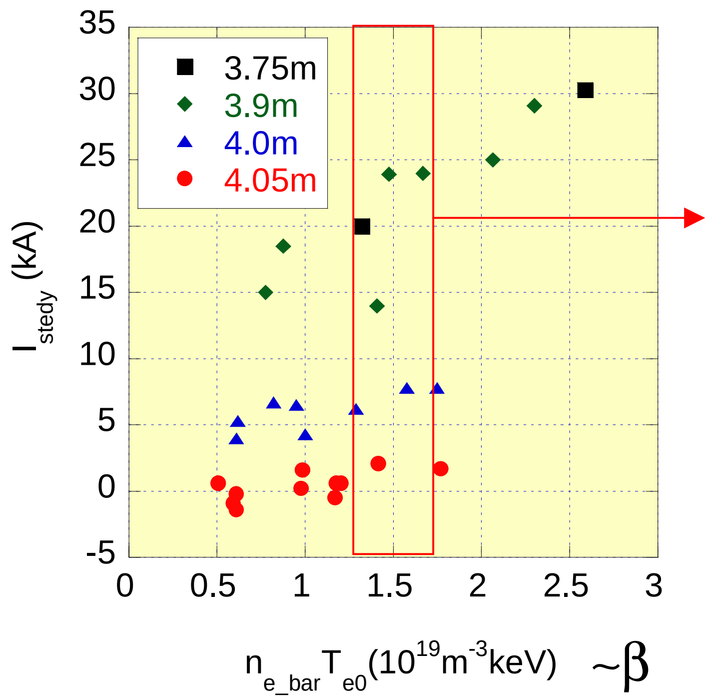
R_{ax}^V=3.75m, 1.5T, Hydrogen

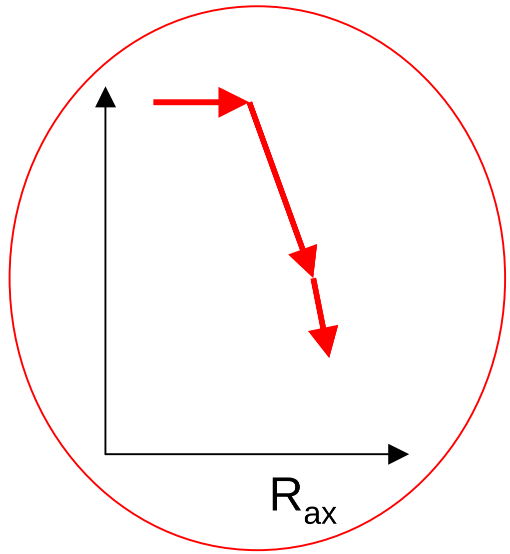
NBI balanced Inj. Total NBI power = 3.5~3.7MW

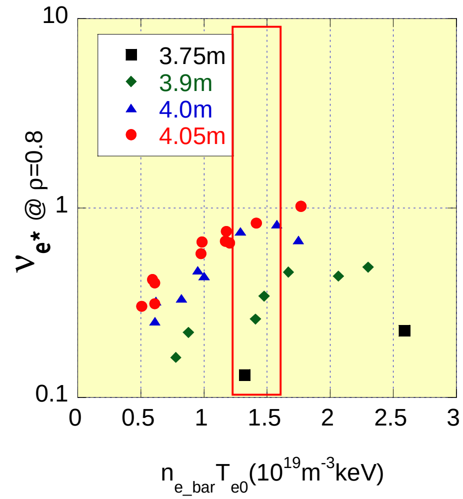
- Calculated result agrees with experimental data in W_p dependence.
- Direction and Amplitude of theoretical prediction also agrees.

Experimental result for non-inductive current (2)

- Magnetic axis configuration dependence in NB “balanced” injection -







Co-Injected power is larger by 20% than Cntr-one.
Co/ 2.0MW, Cntr/ 1.6MW

Observation

- R_{ax} goes torus-outwardly =>
- Observed toroidal current decreases

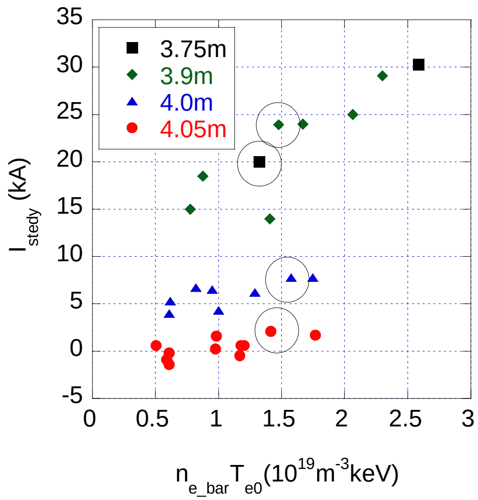
- *NB injection Condition*

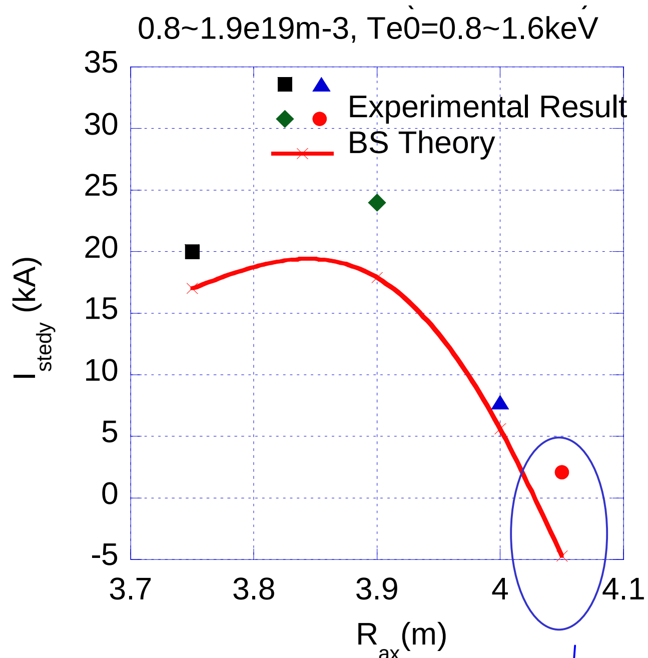
keeps *same during above experiment sequence* in magnetic axis changing.

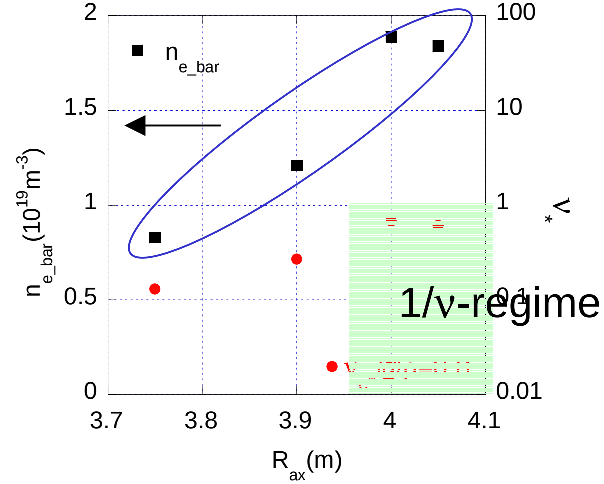
Comparison result with theoretical prediction

- Magnetic Configuration dependence -

Pick up data with almost same beta value β=0.33~0.41%







Observation

• R_{ax} goes torus-outwardly
=> toridal current decreases

=> • Agrees with BS behavior predicted in theory.

• Cntr-Direction current not observed clearly!!

Theoretically predicted in torus outward magnetic axis shift configuration

MHD activity and rational surface (1)

<u>*In LHD "Magnetic axis torus-inward shift" configuration*</u> (R_{ax}=3.6m),

Even in low beta regime (**β>0.3%),**
m/n=2/1(Magnetic fluctuation)
is observed <u>*generally*</u>.

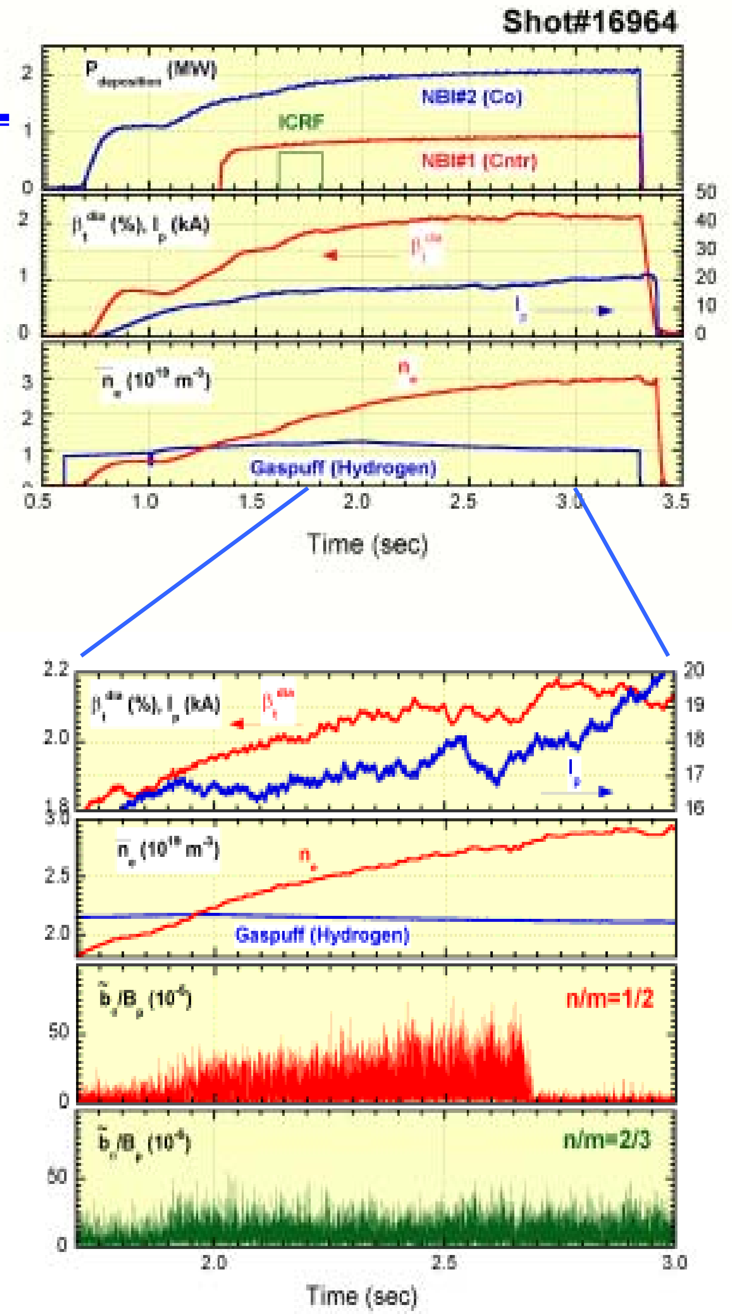
<u>*m: Poloidal mode number*</u>
<u>*n: Toroidal mode number*</u>

Rational surface of ι=1/2 is located at ρ=0.5 in R_{ax}=3.6m config.(vacuum).

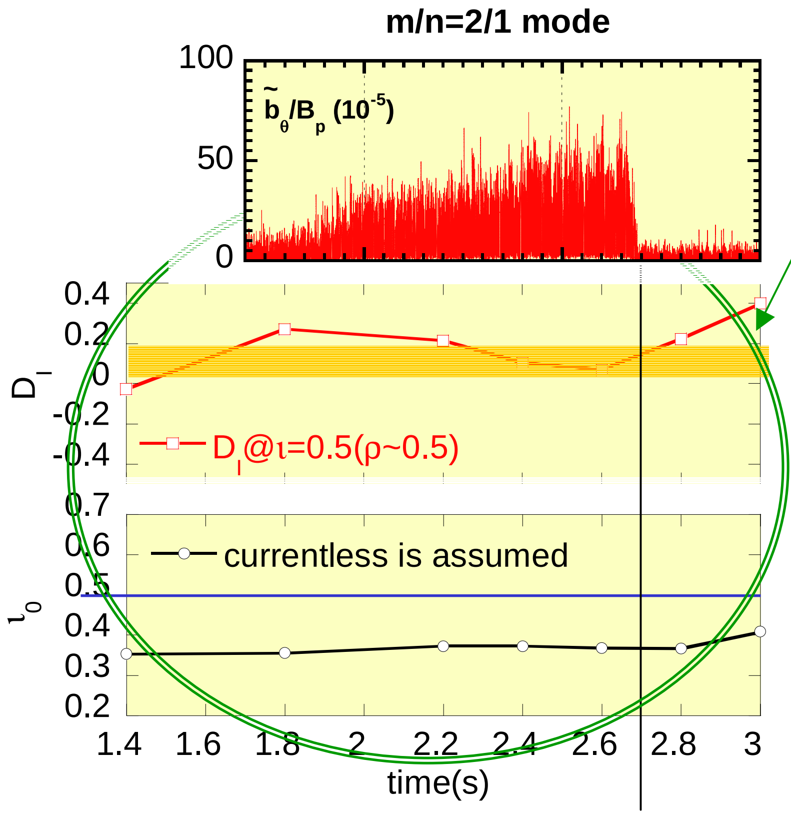
Remark!!

<u>*In high beta discharge with high positive toroidal current*</u>
(**0.75T, R_{ax}=3.6m, β~2%, δι(a)~0.04 due to I_p**)

<u>m/n=2/1(Magnetic fluctuation)</u>
suddenly disappears.



MHD activity and rational surface (2)



Theoritical Analysis with Currentless assumption

(MHD equilibrium is calculated using pressure profile obtained by measurement)

- *iota=1/2 surface exists* ($ι_0$<0.5) *both before and after disappearance of 2/1 mode.*
- *The plasma after disappearance of 2/1 mode is more Mercier unstable than that before disappearance of 2/1 mode*

Most probable explanation of 2/1 mode disappearance

- Rational Surface (ι=1/2) disappears.

Compare between time trace of central rotational transform based on calculation and MHD activity

Basic Equation for Time Evolution Analysis of toroidal current profile

■ ***Diffusion equation of toroidal current*** $I_p(S,t)$

$$\mu_0 \frac{\partial I_p}{\partial t} = 4\pi S \frac{\partial}{\partial S}\left[\frac{1}{\sigma}\frac{\partial}{\partial S}(I_p - I_b)\right], \quad J_p(S,t) = \frac{\partial}{\partial S} I_p, \quad S = \pi r^2$$

■ ***Boundary condition***

$$I_p(0,t) = 0, \quad \left.\frac{\partial}{\partial S}(I_p - I_b)\right|_{S=\pi a^2} = \sigma \frac{1}{2\pi R_0}\left(V_{loop} - L_{ext}\dot{I}_p\big|_{S=\pi a^2}\right), \quad L_{ext} = \mu_0 R_0\left[\log\frac{8R_0}{a} - 2\right]$$

■ ***Initial condition***

$$J_p(S,0) = J_0(S)$$

■ ***Thermal conductivity (applying neoclassical theory in TOKAMAK)***

$$\sigma = \sigma_{spitz}\left(1-\sqrt{\varepsilon}\right)\left(1+0.039\sqrt{\varepsilon}\right)/\left(1+0.471\sqrt{\varepsilon}\right),$$

Experimental Data

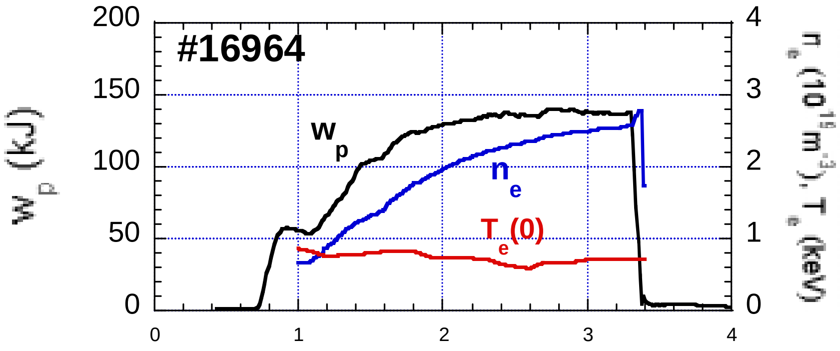
$$\sigma_{spitz}^{-1} = 1.65\times 10^{-9} z_{eff} \ln \Lambda / T_e^{3/2}, \quad \ln \Lambda = 23 - \ln\left(\sqrt{n_e \times 10^{-6}} / T_e \times 10^{-3}\right)$$

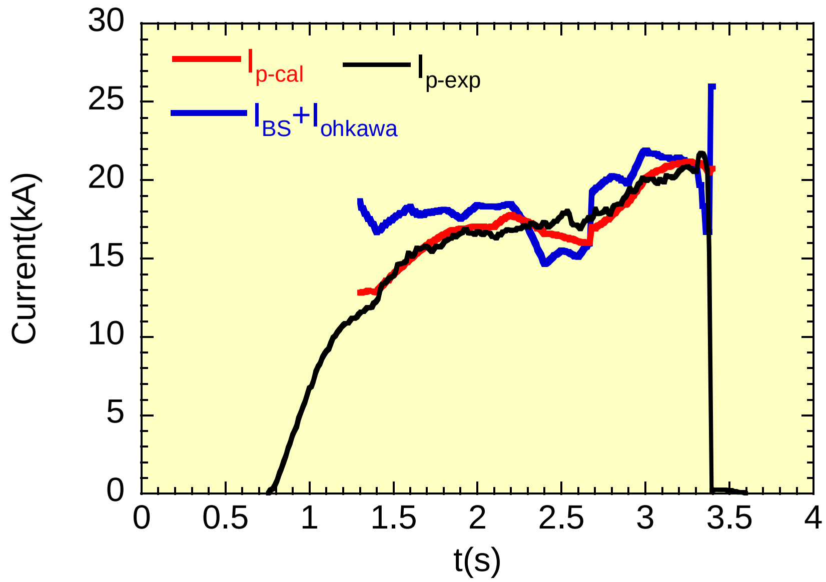
■ ***Non inductive current*** I_b

$$I_b = I_{bsc}\,\textit{(BS-current)} + I_{beam}\,\textit{(Ohkawa-current)}$$

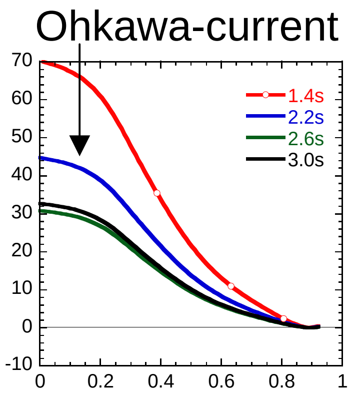
BS current; calculated by SPBSC code
Ohkawa current; cal. by MCNBH code (considering orbit and CX loss)

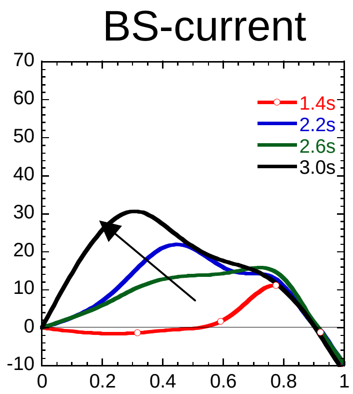
Calculation result of toroidal current evolution



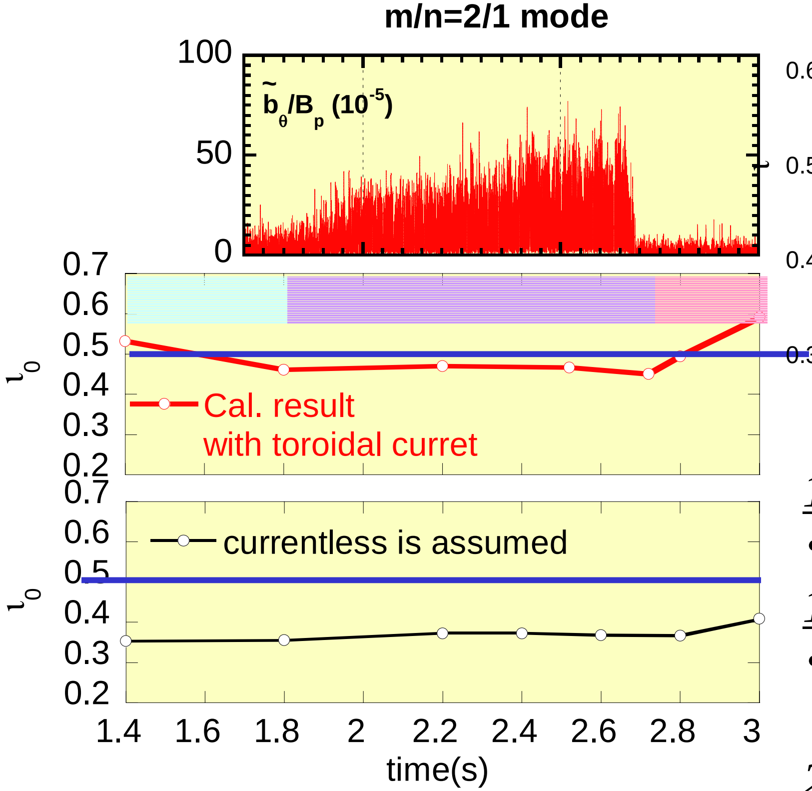


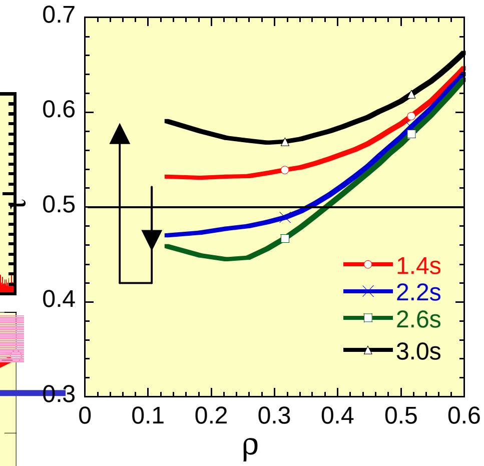
- Co dominant-NB Injected
- *Non inductive current is almost same with time.*
- ***Ohkawa current is decreasing***
  n_e gradually increases
- ***BS current is increasing with time***.
  W_p gradually increases,
  central n_e profile hollow => flat
  central T_e profile => peaked

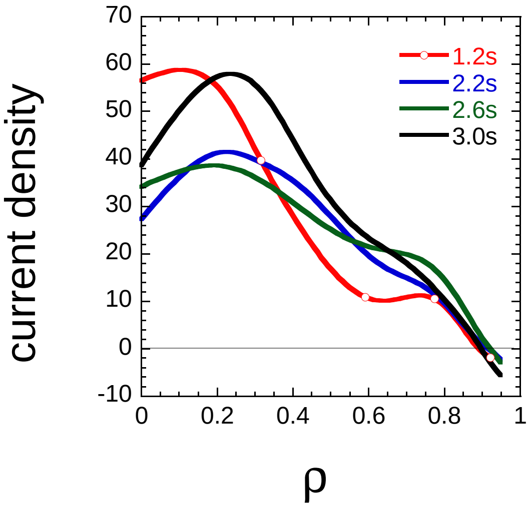




Comparison between time traces of m/n=2/1 magnetic fluctuation and calculated central rotational transform







<u>*1.2s<t < 1.8s*</u>

- peaked current profile due to I_{ohkawa}

<u>*1.8s < t <2.7s*</u>

- flat current profile (I_{ohkawa} decreases, I_{BS} increases) => ι=1/2 surface appears

<u>*2.8s < t*</u>

- peaked current profile due to I_{BS} (peaked pressure profile) => ι=1/2 surface disappears

Result!

Timing, when m/n=2/1 disappears, is close to theoretically predicted timing when ι=1/2 rational surface disappears.

Summary

We analyze the non-inductive toroidal current in LHD experiments with balanced NB-Injection.

1. We experimentally obtain the dependence of non-inductive current on W_p and R_{ax}.
2. W_p and R_{ax} dependence agree with theoretical prediction based on BS current for Heliotron devices.

We analyze the MHD activity behavior in high beta LHD experiment with high toroidal current (β>2%, $\Delta\iota$(a) due to I_p > 0.05) and time evolution of toroidal current profile.

1. The possibility of determination of current profile (central rotational transform) by measuring existence of m/n=2/1 in LHD.
2. Timing, when m/n=2/1 disappears, agrees with theoretically prediction when ι=1/2 rational surface disappears based on BS-current and Ohkawa current.