Study of Time Evolution of Toroidal current in LHD

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Tangential View of LHD
Toroidal Current --- Observation ---

**In principle**

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

**Observation in LHD**

In NBI discharge
More than 100kA of toroidal current is observed.

*No active control of one turn voltage*

\[ B_0 = 0.75\text{~T} - 2.9\text{~T}, \ H_2, \ R_{ax} = 3.6/3.75\text{~m}, \]
\[ I_p = -30\text{~kA} - 110\text{~kA}, \Delta t(a) = -0.04\text{~to} -0.1. \]

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) -

$\frac{I_{BSC-LHD}}{I_{BSC-TOK}} \sim 0.5$

- $j_{BS} \sim (f/f_c) * G_{bs} * \frac{dP}{ds}$
  in banana ($1/\nu$)-regime

- BS current profile in LHD is much broader than TOKAMAK
  comes from
  Difference of Radial profile of $q$ and geometrical factor between TOKAMAK and LHD
Properties of Bootstrap Current in Heliotron devices (2)
- Dependence on Magnetic Axis Configuration -

\[ j_{BS} \sim (f/f_c)^* G_{bs} \times P^{*}(n'/n + a_1 T_i'/T_i + a_2 T_e'/T_e) \]
\[ a_1, a_2 \sim O(+0.1), \quad G_{bs}^{tok} = I_p/2\pi \]

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

Note!!
Magnetic Axis goes torus-outwardly =>
Geometric factor significantly decreases and changes the sign.

Geometrical Factor for LHD in 1/ν-regime
Time evolution of toroidal current and the estimation of non-inductive current

\[ R_p I_p = V_{\text{loop}} + R_p I_{\text{NI}} \]

\[ V_{\text{loop}} = -L_p \frac{dI_p}{dt} + \sum_i M_{ip} \frac{dI_i}{dt} \]

- \( I_p \): observed plasma current
- \( I_{\text{NI}} \): non-inductive plasma current
- \( V_{\text{loop}} \): one-turn voltage (self-induced part is dominant in LHD. When \( \frac{dI_p}{dt} = 0 \), \( V_{\text{loop}} \approx 0 \))
- \( I_i \): 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 collisionality dependence in NB balanced injection -

Observed toroidal current
- increases with $W_p$ increasing.
- Collisionality increases
  => Observed current decreases

Probable candidate of current driving mechanism;

**Bootstrap Current**
Comparison result with theoretical prediction
- \( W_p \) dependence -

**Theoretical calculation of BS current**

   - BS current calculation with the consistent MHD equilibrium
   - Connection formula from \( 1/\nu \) to P-S collisional regime
   - BS current is estimated based on momentum method for asymmetric devices proposed by K.C Shaing et al.

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

3. \( Z_{\text{eff}}=2, \ T_e = T_i \) are assumed.

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

\( \nu = 3.75 \text{m}, \ 1.5 \text{T}, \text{Hydrogen} \)
NBI balanced Inj. Total NBI power = 3.5~3.7MW
Experimental result for non-inductive current (2)
- Magnetic axis configuration dependence in NB “balanced” injection -

Observation
- $R_{ax}$ goes torus-outwardly $\Rightarrow$
- Observed toroidal current decreases

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

*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 $\beta=0.33\sim0.41\%$

\[
\begin{align*}
0.8\sim1.9e19 \text{m}^{-3} \text{keV}, \quad T_{e0}=0.8\sim1.6 \text{keV}
\end{align*}
\]

**Observation**
- $R_{ax}$ goes torus-outwardly
  - $\Rightarrow$ toroidal current decreases

- $Cntr-Direction$ current not observed clearly!!

**Theoretically predicted in torus outward magnetic axis shift configuration**
In high beta discharge with high positive toroidal current (0.75T, \( R_{ax} = 3.6m \), \( \beta \sim 2\% \), \( \delta_1(a) \sim 0.04 \) due to \( I_p \))

\( m/n = 2/1 \) (Magnetic fluctuation) suddenly disappears.

MHD activity and rational surface (1)

In LHD “Magnetic axis torus-inward shift” configuration \( (R_{ax} = 3.6m) \),

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

\( m \): Poloidal mode number
\( n \): Toroidal mode number

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

Remark!!
**Theoretical Analysis with Currentless assumption**

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

- \( \iota = 1/2 \) surface exists \((\iota_0 < 0.5)\) 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 \((\iota = 1/2)\) 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** 
  \[ I_p(S,t) = 4\pi S \frac{\partial}{\partial S} \left[ \frac{1}{\sigma} \frac{\partial}{\partial S} (I_p - I_b) \right] \]
  \[ J_p(S,t) = \frac{\partial}{\partial S} I_p, \quad S = \pi r^2 \]

- **Boundary condition**
  \[ I_p(0,t) = 0, \quad \frac{\partial}{\partial S} (I_p - I_b) \bigg|_{S=R_0} = \sigma \frac{1}{2\pi R_0} (V_{loop} - L_{ext} \frac{\partial}{\partial S} I_p \bigg|_{S=R_0}) \]
  \[ L_{ext} = \mu_0 R_0 \left[ \log \frac{8R_0}{a} - 2 \right] \]

- **Initial condition**
  \[ J_p(S,0) = J_0(S) \]

- **Thermal conductivity (applying neoclassical theory in TOKAMAK)**
  \[ \sigma = \sigma_{spitz} \left( 1 - \sqrt{\varepsilon} \right) \left( 1 + 0.039 \sqrt{\varepsilon} \right) \left( 1 + 0.471 \varepsilon \right) \]
  Experimental Data

  \[ \sigma_{spitz} = 1.65 \times 10^{-9} \left( \frac{z_{eff} \ln A}{T_e^2} \right), \quad \ln A = 23 \ln \left( \sqrt{n_e \times 10^{16}} / T_e \times 10^{3} \right) \]

- **Non inductive current**
  \[ I_b = I_{b,sc} (BS-current) + I_{beam} (Ohkawa-current) \]

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

\[ \frac{b}{B_p} \times 10^{-5} \]

\( \frac{m}{n} = 2/1 \) mode

0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3

\( \theta \)

Currentless is assumed

Calc. result with toroidal current

Timing, when \( m/n = 2/1 \) disappears, is close to theoretically predicted timing when \( \theta = 1/2 \) rational surface disappears.

\( 1.2 \text{s} < t < 1.8 \text{s} \)

- peaked current profile due to \( I_{\text{ohkawa}} \)

\( 1.8 \text{s} < t < 2.7 \text{s} \)

- flat current profile (\( I_{\text{ohkawa}} \) decreases, \( I_{\text{BS}} \) increases)

\( \Rightarrow \theta = 1/2 \) surface appears

\( 2.8 \text{s} < t \)

- peaked current profile due to \( I_{\text{BS}} \) (peaked pressure profile) \( \Rightarrow \theta = 1/2 \) surface disappears

Result!
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 ($\beta > 2\%$, $\Delta \tau(a)$ 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 $\tau=1/2$ rational surface disappears based on BS-current and Ohkawa current.