“MHD Properties in high-β plasma and recent results from LHD” by Watanabe et al. Transparencies follow…

1. Summary of achieved parameters; confinement

\[ T_e \approx T_i \approx 10 \text{ keV} \]
\[ \langle \beta \rangle_{\text{MAX}} = 4\%, \beta_0 = 6\% \]
\[ n_e = 2.2 \times 10^{20} \text{ m}^{-3} \]

No “significant” degradation of confinement with increasing \( \beta \)

2. Discussion of high-\( \beta \) results in light of comparisons with TERPSICHORE

- Core & edge predicted unstable to Mercier modes
- Stability to ideal low-n modes calculated w/ TERPSICHORE
  - Pressure gradient in core region skirts low-n unstable region
  - Edge is deep in unstable low-n unstable region

3. Changed magnetic configuration to obtain higher aspect ratio at \( R_{\text{AXIS}} = 3.6 \text{ m} \) by slightly changing effective pitch of helical coils (?)

- Better beam-ion confinement, higher power density
- Achieved \( \langle \beta \rangle_{\text{DIA}} = 4\% \); no detailed analysis yet
Recent status of LHD experiments

- Stored energy has reached 1.3MJ comparable to big tokamaks.
- Electron temperature: 10 keV
- Ion temperature: 9.8 keV (Ar)
- Beta: 4% (based on Diamag./ central beta ~ 6%)
- Density: $2.2 \times 10^{20} \text{ m}^{-3}$
- Pulse length: 756 s (ECH)
Outline of talk

1. Background of high beta exp. in LHD
2. Results
   (1) Global confinement property in high beta
   (2) Typical behavior of fluctuation observed in LHD
   (3) Relationships between the prediction of linear MHD stability criteria and experimentally achieved plasma parameter
   (4) Recent topic of high beta exp. in LHD
3. Summary
Background of high beta exp. in LHD

*LHD high beta operation is done in low magnetic field and with only NBI heating.*

*Low-n ideal MHD unstable region in $\beta-R_{ax} V$ diagram*

LHD
(R$_{ax}$=3.6m)
Rotational Transform

NBI heating power loss due to direct loss depends on $R_{ax}$ and B.

**Torus Inwardly Shifted Conf.**
($R_{ax}$;small)
Good NB Heating Efficiency in high $\beta$ (low field)

*Torus Inwardly Shifted Conf. with $R_{ax} V$=3.6m;* selected as a standard config. of high $\beta$ experiment in LHD
Transport Properties in LHD High $\beta$ Discharges

$\langle \beta_{\text{dia}} \rangle$, $H_{\text{ISS-eff}}$; based on diamagnetic flux measurements.

$H_{\text{ISS-eff}}$: taking NB heating power loss due to the direct orbit losses into account.

**NB heating power loss** due to the direct orbit losses;
38% in $B_0=0.5T$, 14% in $B_0=0.75T$, and 7% in $B_0=1T$ in $\langle \beta_{\text{dia}} \rangle \sim 2\%$, $n_e=2.5\times10^{19}m^{-3}$.

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*Clear degradation of global energy conf. time has not been observed below $\beta \sim 3.2\%$*
Properties of magnetic fluctuation and pressure gradient in LHD

Dependence of mag. fluct. and P-grad. on beta at typical resonant mag. surf.

Core

Edge

B=0.5-1.5T/R_{ax}=3.6m

Core region
# β -gradients;
- Saturated with β (1%<β<1.8%)
- Increases as β (1.8%<β)
# Magnetic Fluctuation;
- In Mercier stable region, resonant fluctuation (low-n) mode is not observed.
- Amplitude increases as β gradients

Edge region
# β -gradients;
- Increases as β
# Magnetic Fluctuation;
- Even in Mercier stable region, resonant fluctuation (low-n) mode is observed.
- Amplitude increases as β and β -gradients
Role of low-n ideal MHD mode in R_{ax}=3.6m configuration (I)

Compare between observed pressure gradient and low-n unstable region based on linear ideal MHD mode analysis by TERPSHICORE code in d\(\beta\)/d\(\rho\)-\(\beta\) diagram

**Core region**
Gradient seems to avoid low-n unstable region.

# Gradient does not care
Mercier unstable in core regions!!

One final goal of this work is to obtain a criterion (parameter) that low-n mode is effective by using on D_{I} or \(\gamma\).
Role of low-n ideal MHD mode in \( R_{ax}=3.6m \) configuration (II)

Compare between observed pressure gradient and low-n unstable region based on linear ideal MHD mode analysis by TERPSHICORE code in \( d\beta/d\rho-\beta \) diagram

- **Experiment**

  ![Graph showing pressure gradient and low-n unstable region](image)

  - \( \rho=0.9 \) (\(~1\)~)
  - low-n unstable (\( \gamma>10^{-2}\omega_A \))
  - \( \gamma \sim 1.5\times10^{-2}\omega_A \)

**Edge region**

The achieved pressure gradients exhibit slight saturation with the increase in \( \langle\beta_{dia}\rangle \).
However, they are more deeply in the low-n mode unstable region compared with results in the core.

# Gradient does not care Mrecier unstable in edge regions!!
Summary of relationships between achieved beta and low-n ideal MHD instability

In LHD $R_{ax} = 3.6\,\text{m}$ config.:
Good fast ion confinement property.
Good accessibility to "2nd stability regime for the core low-n modes".

=> High beta discharge with more than 3% can be achieved.

Effect of global MHD modes on global confinement in more than beta 3.5%??

# Local transport analysis
# Extension of comparison between a theoretical prediction and the observed pressure gradients to various magnetic configurations in LHD.
Recent topic of LHD high beta experiments

Heating capability (*NBI 9=>12MW*) and a new mag. conf. (with *a high aspect ratio*, \(\gamma=1.22\)) enables exploration of MHD studies in the \(\beta\) range up to 4%. The central beta value has reached about 6%.

\[
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\end{align*}
\]

Achieved beta value based on Diamag. flux for various magnetic configurations

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\end{align*}
\]

\[
\begin{align*}
\gamma; \text{ pitch parameter of helical coil winding}; \text{ decreases; plasma aspect ratio increases.}
\end{align*}
\]

Reason of increase of achieved beta value;
Reduction of NBI power loss due to prompt loss, Expansion of plasma confinement region, and so on (Under investigation)

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\]

A new mag. conf. is more favorable for fast ion confinement, but is worse for MHD stability than the standard conf.
Geometrical characteristics of the new mag. conf. with high aspect ratio

\( R_{ax} = 3.6 \text{m}, B_q = 100\% [\beta = 0\%] \)

\( \gamma = 1.25 \) (standard)

\( \gamma = 1.22 \) (high aspect ratio)

\( V_p \) of \( \gamma = 1.22 \) is smaller by 20\% than \( \gamma = 1.25 \).

*Shafranov shift* of \( \gamma = 1.22 \) is smaller.

\( \Rightarrow \) Better fast ion confinement in high \( \beta \).

Low-n *MHD stability* property of \( \gamma = 1.22 \) is worse.
Summary and future subjects

1. A volume averaged beta values of over 3% are achieved without disruptive phenomena nevertheless fluctuation signals are observed. They generally increase as beta increases.

2. Clear degradation of global energy conf. time has not been observed below $\beta \sim 3\%$

3. Relationships between the prediction of linear low-n MHD stability criteria and experimentally achieved pressure gradients are analyzed.
   (1) In the core plasma region, the achieved pressure gradient seems to avoid a low-n linear ideal MHD mode unstable region.
   (2) In the edge region, the achieved pressure gradients exhibit slight saturation with the increase in $<\beta_{\text{dia}}$. However, they are more deeply in the low-$n$ mode unstable region compared with results in the core.
   (3) In order to make clear whether global ideal MHD modes limit the pressure gradients in the edge, extension of comparison between a theoretical prediction and the observed pressure gradients to various magnetic configurations, and local transport analysis are necessary. This is one of our future subjects.
3. (4) High m (n) interchange modes (localized modes) does not look to affect the achieved pressure gradients, which does not care Mercier criteria in both the core and the edge region.

4. As recent progress in high beta study, a heating capability (NBI 9=>12MW) and a new magnetic configuration (with a high aspect ratio) enables exploration of MHD studies in the $\beta$ range up to 4%.
“Results from H-1”, by Blackwell et al
  Number of new 2-D tomographic measurement capabilities implemented
  Visible Emission Doppler Spectroscopy for configuration mapping

  TERPSICHERE studies of kink stability show beta limit near 3% at low density
  - Kink stability strongly dependent on rotational transform profile at edge
HINT Calculation for Reference Config. (2b32)

- HINT code calculates free-boundary MHD equilibrium without assuming nested magnetic surfaces.
- Clear magnetic surfaces are kept at $\langle \gamma \rangle = 3.3\%$ with external vertical field and no net toroidal current.
- Equilibrium calculation with bootstrap current has now been progressing.
Global Mode Calculation by TERPSICHCORE

- Resonant modes with rotational transform from 0.3 to 0.8 and coupling with equilibrium mode number \((m,n)= (1,2)\) are considered up to \(n \leq 7\).
- 81 perturbation modes are included for \(N=1\) family.
- Wall stabilization effect is excluded. (Conducting wall is placed far enough.)
The value of edge rotational transform (especially 0.5) is crucial in triggering external kink instability (m/n=2/1 mode).