Extension of High-Beta Plasma Operation to Low Collisional Regime

Satoru Sakakibara
On behalf of LHD Experiment Group

National Institute for Fusion Science
SOKENDAI (The Graduate University for Advanced Studies)
Outline

- Background and purpose of this study
- Experimental Setup
- High-beta experiments
  - Global properties of high-beta operations in low-collisional regime
    - Characteristics of high-beta discharges
      - Multi-pellet operations
      - Quasi-steady state operations with improvement of particle confinement
- Summary
Strategy of high beta experiments

\( <\beta> \) of 5.1 % was achieved in previous experiments

→ verify an ability in high beta plasma production in currentless plasmas

→ Extension of database of non-dimensional parameters \((\beta, S, v^*, \rho^*)\)

Physics Studies
Stability, Plasma confinement in ergodic regime, magnetic island dynamics, transport caused by turbulence etc.

⇒ high \( T \) and high \( \beta \) plasma is required

Goal: \( <\beta> \sim 4 \% \) at 1T
(Final goal of LHD: 5 % at 1T)
Experiments have been done since 1998

All coils are superconductive.

10 pairs of RMP coils

Specification:

\[ R = 3.5 \sim 4.1 \text{ m}, \quad a \sim 0.65 \text{ m} \]

Maximum \( B_t \sim 3 \text{ T} \)

Heating Power:

- \( \text{N-NBI} \quad 15 \text{ MW} \)
- \( \text{P-NBI (perp.)} \quad 10 \text{ MW} \)
- \( \text{ICRF} \quad < 3 \text{ MW} \)
- \( \text{ECH} \quad \sim 2 \text{ MW} \)
$R_{ax}$ is a key parameter for high-beta.

$R_{ax}^v$ (Magnetic axis in vacuum) is important for optimizing characteristics of MHD, transport and heating.

- **Stability:**
  - Hill
  - Well

- **Equilibrium:**
  - Weak dependence

- **Transport:**
  - Increment of helical ripple

- **Heating:**
  - Prompt loss of NB

- **Confinement:**
  - (Experiment)
  - Shafranov shift

Shafranov shift deteriorates transport and heating efficiency, although it is valid for stability.
$R_{ax}^v$ scan experiments for high-beta

- $R_{ax}^v$ scan experiments were done in condition with constant heating power and electron density.

- Core instabilities were excited in the configuration with $R_{ax}^v < 3.55$ m.

$\Rightarrow R_{ax}^v$ of 3.56 m was selected.

Unstable

$B_t = -1$ T

Optimum $R_{ax}^v$ for pellet and gas-puff

$B_t = -1$ T

S.Sakakibara, IAEA-FEC2016, Oct.16-22, 2016, Kyoto
<\beta> of 4.1% was successfully achieved

High beta operation has been extended to low collisional regime

- Multi-pellet injections (Maximum beta)
  \[4.1\% \left( T_{e0} = 0.9 \text{ keV}, n_{e0} = 6 \times 10^{19} \text{ m}^{-3} \right)\]

- Gas puff (Quasi-steady state)
  \[3.4\% \left( T_{e0} = 1.2 \text{ keV}, n_{e0} = 3 \times 10^{19} \text{ m}^{-3} \right)\]

\[R_{ax} = 3.56 \text{ m}, B_t = -1 \text{ T}, A_p = 5.8\]
Low-\(n\) instabilities are suppressed with the increase in \(S\)

Increase in \(S\) suppresses the amplitude of low-\(n\) mode

- The amplitude of low-\(n\) modes depend on the beta and magnetic Reynolds number, \(S\), which is consistent with prediction of linear theory.

- Results of low-\(\nu^*\) (high-\(S\)) experiments emphasize the obtained knowledge.

\[ S = \begin{bmatrix}
  10^9 \\
  10^8 \\
  10^7 \\
  10^6 \\
  10^5 \\
  0 \\
\end{bmatrix}
\]

\[ \frac{\tilde{b}_0}{B_t} = \begin{bmatrix}
  10^{-4} \\
  10^{-5} \\
  10^{-6} \\
  10^{-7} \\
  0 \\
\end{bmatrix}
\]

\[ m/n = 1/1 \]

Based on [Sakakibara PPCF2008]
### Comparison between Pellet and Gas-puff

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<tr>
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<th>Pellet discharge</th>
<th>Gas-puff discharge</th>
</tr>
</thead>
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<tr>
<td>Achieved $\langle \beta \rangle$</td>
<td>4.1 %</td>
<td>3.4 %</td>
</tr>
<tr>
<td>Duration time</td>
<td>&lt; 0.1 s</td>
<td>&gt; 0.5 s (limited by heating)</td>
</tr>
<tr>
<td>$T_{e0}$</td>
<td>0.9 keV</td>
<td>1.2 keV</td>
</tr>
<tr>
<td></td>
<td>(0.2 keV at $B_t = 0.425$ T)</td>
<td>(&lt; 0.5 keV at $B_t = 0.425$ T)</td>
</tr>
<tr>
<td>$n_{e0}$</td>
<td>$6 \times 10^{19}$ m$^{-3}$</td>
<td>$3 \times 10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>$P$ Profile</td>
<td>Peaked profile</td>
<td>Broaden profile</td>
</tr>
<tr>
<td>$R_{ax}$ shift</td>
<td>$\sim 0.44$ m</td>
<td>$\sim 0.29$ m</td>
</tr>
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<td>Improvement of particle confinement</td>
<td>Unclear (short duration)</td>
<td>Clear</td>
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<td>Stability</td>
<td>Core instability</td>
<td>Edge instability</td>
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<tr>
<td>subjects</td>
<td>Long time duration</td>
<td>Stability control</td>
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<tr>
<td></td>
<td></td>
<td>Fueling to core</td>
</tr>
</tbody>
</table>
High-beta discharge with pellet injections

✓ Pellets were injected in NB and ICRF plasma
  → Peaked $n_e$ and $T_e$ profiles were formed
✓ Central beta ~ 7%
✓ Shafranov shift $\Delta R$ : ~ 0.44 m

![Graph showing $n_e$ and $T_e$ profiles with time evolution](image)

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Appearance of Core MHD mode
- Pellet Discharge -

✓ Peaking of pressure profile leads to destabilization of core mode
→ no profile flattening
→ Increase in beta can stabilize the mode by Shafranov shift?

✓ No significant edge instability

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Quasi steady-state high beta discharge with more than 3% - Gas-puff -

Transition phenomenon appears in quasi-steady state operation

✓ Strong fluctuation appears ⇒ limits the increase in beta
✓ Density fluctuation correlates with magnetic one

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Particle flux to divertor reduces after the transition

- Ion saturation current and density reduce after the transition.
- Hα starts to decrease with IS current before transition.
Changes of plasma profiles before and after transition

Increment of edge density after the transition [Toi, FST2010]

- No change of core density
- Extension of confinement region

⇒ Magnetic field structure is changed?
Confinement region is extended to the outward

- Long $L_c$ around $\nu/2\pi = 2 \Rightarrow$ extension of confinement region
- New edge MHD instability is excited $\Rightarrow$ limits the increase in $\beta$
Radial structures of the modes measured with CO$_2$ interferometer

Observed modes are localized near edge

Transition

\[ \nu/2\pi = 2.0 \]

\[ \nu/2\pi = 1.5 \]

\[ m/n = 1/2 \]

\[ m/n = 2/3 \]
Change of dominant mode with beta

Resonance of the dominant mode: $\frac{1}{2\pi} = \frac{3}{2} \rightarrow 2/1$

Extension of confinement region leads to appearance of new resonant surface.

- Dominant MHD mode is changed from inner region to outer one when $\beta$ is increased.

[A. Komori, POP2004]
### Experimental observation
- The transition with the spontaneous increase in $<\beta>$ is found in high-beta regime, which is caused by the increase in peripheral electron density
- After the transition, particle flux to divertor plate is obviously reduced
- Plasma boundary is shifted to the outward (Thomson scattering)
- Edge MHD instabilities are abruptly excited

### Speculations
- **Extension of plasma boundary**
  magnetic field structure with short-Lc is changed to that with long-Lc (HINT2 calculation) $\rightarrow$ confinement region is extended $\rightarrow$ good particle confinement
- **Excitation of Edge MHD instabilities**
  $\rightarrow$ Appearance of new rational surface due to extension of long-Lc region
  Change of magnetic topology is a key ($v^*$, $\beta$, configuration etc.)

[S.Sakakibara NF2013, PPCF2013]
High-beta experiments have been done in order to extend operation regime to low collisional one.

✓ Volume-averaged beta value of 4.1% was achieved at 1 T by multi-pellet injections, and 3.4% could be maintained for a long time by gas-puff fueling.

✓ Strong instability excited in the core was observed in multi-pellet discharges, which is expected to be stabilized by magnetic well formation due to the increase in beta.

✓ Maximum beta in steady-state discharge (gas-puff) is realized by improvement of particle confinement. The reduction of particle flux to divertor is obviously observed after the transition.

✓ Edge MHD instabilities excited after the transition limit the achieved beta.
Reference Materials
✓ HINT2 predicts extension of stochastic regime

Plasma is confined in stochastic regime

Disturbance of magnetic field line

Pressure profile

$\frac{1}{2\pi}$

Magnetic field structure

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$A_p = 6.6$ and $5.8\, (R_{ax} = 3.56\text{m}, 1\text{T})$

- Comparison of discharges -

Beta value before transition is almost the same in both cases

- The transition is observed only in $A_p = 5.8$

- Shafranov shift in $A_p = 6.6$ is smaller than that in $A_p = 5.8$
No transition and strong instabilities in core and edge at $A_p = 6.6$

Excited modes are quite different despite $\beta$ and $P$-profile are almost the same

- $A_p = 6.6$: core and edge instabilities are unstable
- $R_{ax} = 3.56$ m configuration is not suitable for high-beta plasma production
$A_p = 6.6$ and $5.8 (R_{ax} = 3.56m, 1T)$

- MHD Equilibrium -

$P_0$ and pressure profile are almost the same

- $A_p = 6.6$: $\nu_a/2\pi \sim 2$, $A_p = 5.8$: $\nu_a/2\pi \sim 3$

Before transition

After transition

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Fluctuation at divertor synchronizes with MHD mode

- Fluctuation of ion saturation current is enhanced during the transition
- Strong correlation with $m/n = 2/3$ MHD mode

Fluctuation of ion saturation current

Magnetic Fluctuation

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Shielding by magnetic island?

Increment of density is observed only in periphery

✓ Magnetic island appears around $\nu/2\pi = 1$
surface after the transition

→ suppress influx of particles to core?
MHD equilibria before and after transition

$\frac{m}{n} = \frac{1}{2}$

$\frac{m}{n} = \frac{2}{3}$
Change of MHD activities with $\beta$

Suppression of $i/2\pi < 1$ modes

Suppression of $i/2\pi \leq 1$ modes

Suppression of $i/2\pi \leq 2$ modes

$\langle \beta_{\text{dia}} \rangle$, $n_e$

$\frac{i}{2\pi} = 1/2$

$\frac{i}{2\pi} = 1$

$\frac{i}{2\pi} = 3/2$

$\frac{i}{2\pi} = 2$

$\frac{i}{2\pi} = 5/2$
Magnetic configuration was decided based on $R_{ax}^\gamma$ scan experiments with constant $P_{NBI}$ and $n_e$.

- $A_p = 6.6$ in previous high-$\nu^*$ exp.
- $A_p = 5.8$ in recent low-$\nu^*$ exp.

$$A_p = 6.6$$

$$A_p = 5.8$$
Global Energy Confinement property

Inward shift of $R_{ax}^v$ recovers confinement property ($A_p = 5.8$)

- $A_p = 5.8$: Improvement of particle confinement is one of reasons for recovery of global energy confinement property
- $A_p = 6.6$: The confinement property is almost the same (No improvement of particle confinement, strong instabilities...)

- $A_p = 6.6$ (Prev. high-$\beta$)
- $A_p = 5.8$ (Recent high-$\beta$)
Negative electric field is formed after the transition

Profile of electric field is clearly changed after the transition

- $E_r$ is significantly changed at $R > 4.4$ m
Excitation of edge MHD mode \((m/n = 1/2, 2/3)\) just after the transition

⇒ Extension of confinement region leads to appearance of new resonant surface.
- Resonance of dominant mode is changed from inner region to outer one

[A.Komori et al., POP2004]
Change of dominant mode with beta

Resonance of the dominant mode: $\nu/2\pi = 3/2 \rightarrow 2/1$
- Consistent with extension of plasma confinement region

Ion saturation current

$m/n = 2/3$ mode

$m/n = 2/3$

$m/n = 1/2$

No excitation

$m/n = 1/2$

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High beta operation has been realized by two scenarios

**Standard scenario (broaden P-profile)**
- High $A_p$ configuration for optimizing heating efficiency, transport and MHD
- $\langle \beta \rangle$ of 5.1 % was obtained at low-field

**Super Dense Core scenario (peaked P-profile)**
- Peaked P profile by multi-pellet injections
- High density ($> 10^{20} \text{ m}^{-3}$)
- Central $\beta$ of 10 % was realized at high-field

- Steady-state high-beta discharge was realized in optimized configuration

$\rightarrow$ Verification of ability in high beta plasma production in heliotron

**Graph**:
- Standard Scenario
- SDC Scenario
- $A_p = 6.6$ (2005~)
- $A_p = 5.8$ (~2003)

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