Improved performance in long-pulse ELMy H-mode plasmas with internal transport barrier in JT-60U


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Introduction

AT plasmas (high $f_{BS}$ & $\beta_N$) based on ITB plasmas
contribution to “hybrid scenario” in ITER

Larger neutron fluence per ITER pulse
Extension of burning plasma longer than 1000s
• substantial fraction of $I_p$ is sustained by BSC and NBCD

Q~5 for >1000s: $H_H=1$, $\beta_N$~1.9-2.3 with $f_{NI}$~42-52%
  (B.J. Green PPCF 45 (2003) 687)
Q=11 for 1550s: $H_H=1.2$, $\beta_N$~2.1 with $f_{NI}$~44%

High confinement and high $\beta$ plasmas with large non-inductive current should be sustained longer than $\tau_R$.
Sustainability of ITB, which drives significant BS current, should be understood in actual long-pulse plasmas ($\sim \tau_w$).
● Introduction
● Advantages of ripple reduction by FSTs especially for long-pulse plasmas with ITB
  – Reduction of toroidal field ripple and fast ion losses
● Improvement of ELMy H-mode performance
  – Extension of sustained time duration of high $\beta_N$
  – Improvement of thermal confinement property
  – Importance of particle control for ITB performance
● Summary
Advantages of ripple reduction by FSTs

Installation of FSTs

With FSTs

Without FSTs

=> Reduction of fast ion losses by 1/2~1/3 at 1.6T

- Larger $P_{\text{abs}}$ at given $P_{\text{in}}$
  => smaller required NB units for given $\beta_N$
  => better flexibility in NBI combination
  => better flexibility of torque profile

- Smaller inward $E_r$
  => less ctr-rotation (M. Yoshida EX/P3-22)
\( \beta_N > 2.3 \) has been sustained for 28.6s

- Steady current profile (q profile) much longer than \( \tau_R \) was sustained

\[ \begin{align*}
\beta_N &= 2.3 \\
H_H &\sim 1.1, \quad \beta_N \sim 2.5 \\
P_{NBI} &\sim 8\text{MW}, \quad \beta_p \sim 1.4 \\
n_e/n_{GW} &\sim 0.48, \quad \tau_R \sim 2\text{s} \\
\delta &\sim 0.32, \quad \kappa \sim 1.4 \\
q_{95} &\sim 3.3, \quad f_{BS} \sim 43\% \\
\end{align*} \]

Enhanced recycling in latter phase (t>23s) => ITB degraded

Increased \( P_{NBI} \) by stored energy FB sustained \( \beta_N > 2.3 \) => \( H_H \) decreased
Thermal confinement is much improved

Sustained time duration of $\beta_N=2.3$ has been extended from 22.3s to 28.6s

Peaked pressure profile can be sustained without large sawtooth and NTMs by smaller heating power

8.3MW in E44092 (5u+NNB+EC) $\Rightarrow H_H=0.82$

6.7MW in E45436 (4.5u) $\Rightarrow H_H=1.1$
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Both better confinement and larger $P_{abs}$ contribute to reduce required NB units, which help to extend the sustained duration
Larger thermal component sustained by improved ITB gives higher $H_H$

Similar achieved $\beta_N$, but higher $H_H$ for a given density

$Y2004$ (w/o FSTs) $W_{th} \leq W_{beam}$

$Y2006$ (with FSTs) $W_{th} > W_{beam}$

pedestal contribution was small
β_N H_H > 2.2 has been sustained for 23.1s (~12τ_R) at q95~3.3

\[ β_{NH}/q_{95}^2 > 0.20 \]

\[ β_{N89}/q_{95}^2 > 0.42 \]

f_{BS}~36-45%, τ_{R}~2s
downarrow
candidate for ITER
Hybrid scenario

What parameters do limit the sustained time duration?

Y2004: limited by P_{NBI} and its duration
Y2006: limited by confinement degradation

Not P_{NBI} limit
- No help from higher P_{NBI}

Not MHD limit
- No NTMs appeared

V_T was unchanged
Broad $n_e$ profile caused smaller $p_{th}$ through pedestal <-> core interplay

$n_{e,\text{ped}}$ increased by $\sim 30\%$

$\Rightarrow T_{i,\text{ped}}$ decreased by $\sim 30\%$

$\Rightarrow$ core $T_i$ also decreased by $\sim 30\%$ (stiff profile)

But, $n_e$ became broader!
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$P_{\text{NET}}$

$6.7\text{MW} \Rightarrow 8.7\text{MW}$

$\tau_{E,\text{th}}$

$0.15\text{s} \Rightarrow 0.11\text{s}$
Higher edge density due to high recycling prevented peaked pressure profile

Long-pulse plasma in different wall condition

\[ T_i \text{ follows same line in both cases} \Rightarrow \text{const. } \nabla (\ln T_i) \]

But, achieved \( T_i \) was smaller in high recycling case due to higher edge \( n_e \)
Higher edge density due to high recycling prevented peaked pressure profile

Long-pulse plasma in different wall condition

Similar recycling with similar $Q_{abs}$ => similar $p(r)$

Limited capability of pumping cased enhanced recycling
Summary

- Reduction of fast ion losses by 1/2~1/3 provides higher heating power together with better flexibilities of NBI combinations and torque input profile.

- Sustained duration of $\beta_n=2.3$ has been extended to 28.6s, where smaller heating power kept peaked $p(r)$.

- $\beta_n H_H > 2.2$ with $f_{BS}=36-45\%$ was sustained for 23.1s ($\sim 12\tau_R$) at $q_{95} \sim 3.3$. These long-pulse plasmas are possible candidates for ITER hybrid operation scenario.

These long-pulse plasmas close to $\tau_w$ reveal following issues for further development of AT plasmas

- higher edge $n_e$ prevented peaked pressure profile
- long sustainment of high performance plasmas with active particle control