H-mode Power Threshold, Pedestal and ELM Characteristics and Transport in Hydrogen Plasmas in DIII-D

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Motivation

Operations

• First (non-activated) operational phase in ITER is planned to be with hydrogen and/or helium plasmas
  – Important phase for developing control hardware and techniques (e.g. for ELMs NTMs, etc)
  – Determine the interaction with plasma facing components (e.g. divertor heat loads and erosion, etc)
  – Dependent on obtaining H-mode plasmas

Physics

• Dependence of the pedestal width on $\beta_{\theta}^{\text{ped}}$ or $\rho_{i\theta}$
  – Mass dependence can resolve this issue
The Injected Torque was Controlled by Careful Selection of the DIII-D Neutral Beams

- **Experiments performed with**
  - NBI (H°) → H⁺ plasmas
  - NBI (D°) → D⁺ plasmas

- **Capability for performing simultaneous co-current and counter-current NBI**
  - Provides independent control of torque and power
For D Plasmas with D-NBI, the H-Mode Power Threshold Varies Strongly with the Applied Beam Torque

- Factor of ~3 increase in $P_{TH}$ for discharges with unfavorable ion drift
- Factor of ~2 increase in $P_{TH}$ with favorable ion drift

![Diagram showing favorable and unfavorable ion drift with corresponding graphs for $P_{TH}$ vs Torque (Nm).]
Hydrogen Plasmas: The H-mode Power Threshold with Counter-NBI is at Least a Factor of 2 Lower Than with All co-NBI

- **NBI(H⁰) → H⁺ plasmas**
- With co-NBI: stays in L-mode at medium target density ($3 \times 10^{19} \text{ m}^{-3}$)
- Hydrogen purity (H/H&D) was above 90% in L-mode
The H-mode Threshold Power Increases With Injected Torque in Hydrogen Plasmas (Similar to Deuterium Plasmas)

- Hydrogen threshold power is twice that for deuterium at zero torque
The H-mode Power Threshold is Dependent on the Location of the Plasma X-point From the Divertor Surface

- Threshold power lowered by 20\%–40\% by reducing height of X-point above lower divertor from 26 to 10 cm
- Trend of increasing threshold power with increasing torque still present

\[ \text{Deuterium} \]
- \( \text{NBI (2.25x10^{19} \text{ m}^{-3})} \)

\[ \text{Hydrogen} \]
- \( \text{NBI (2.3x10^{19} \text{ m}^{-3})} \)
- \( \text{NBI (Lowered X-point, 3.6x10^{19} \text{ m}^{-3})} \)

\[ P_{TH} (\text{MW}) \]

\[ \text{Inj. Torque (N*m)} \]
Application of ECH lowers the required threshold power slightly (~15%) compared to the NBI discharges.

The graph shows the relationship between the threshold power ($P_{TH}$) and the injection torque ($N*m$). The data points are categorized by hydrogen and deuterium, with different symbols and markers indicating the use of NBI alone or combined with ECH. The graph includes error bars to indicate the variability in the measurements.
Comparing the pedestal widths in D and H plasmas provides an opportunity to break the degeneracy:

- $\rho_{i\theta}$ scales with ion mass as $\sqrt{M_i}$
- $\beta_{\theta}^\text{ped}$ has no explicit mass dependence

- $\sqrt{\beta_{\theta}^\text{ped}}$ scaling: $\Delta^H_p / \Delta^D_p = 1$
- $\rho_{i\theta}$ scaling: $\Delta^H_p / \Delta^D_p = 0.7$

- Actual $\Delta^H_p / \Delta^D_p = 1.15$
  - Consistent with $\sqrt{\beta_{\theta}^\text{ped}}$ scaling
Conclusions

- The net power required to access the H-mode increases with applied torque
  - For both hydrogen and deuterium
  - Hydrogen threshold power is twice that for deuterium at zero torque
  - Trend with torque is favorable for ITER where low input torque is expected
  - The threshold power is sensitive to the plasma geometry; specifically, to the X-point height above divertor surface

- Present power threshold scaling studies do not include torque, plasma rotation or plasma geometry effects
  - May explain the large range/error in prediction for present and future fusion devices

- The pedestal width is consistent with a $\sqrt{\beta_{\text{ped}}}$ scaling