L-H Transition Studies on DIII-D to Determine H-mode Access for Operational Scenarios in ITER

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for

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Background/Motivation

- Can H-mode be achieved in the first (non-nuclear) phase of ITER operations with He (and/or H) plasmas?

- Need to access H-mode in non-nuclear phase of ITER operations
  - Assess machine hardware and systems in higher performance H-mode plasmas e.g. heat loads, fueling, heating, etc.
  - Test ELM mitigation techniques and hardware in ITER environment

- Reduce the large scatter in H-mode power threshold database and large error in scaling predictions
  - Examine physical trends not included in $P_{TH}$ scaling
  - Obtain physics basis for the scaling laws

- Determine methods to reduce the H-mode power threshold and extrapolate to ITER

- Knowledge beyond the L-H transition is important; quality of H-mode performance dependent on input power above threshold power
  - Affects pedestal behavior, ELM characteristics, etc.
H-mode Power Threshold Increases Smoothly from Near Pure D Plasmas to Near Pure He Plasmas

- No sudden change in $P_{TH}$ observed
  - He concentrations exceeding 40% exhibit discernible increase in $P_{TH}$
- D plasmas: $I_p = 1.0$ MA, $B_T = 1.65$ T, $n_e = 2.8-3.0 \times 10^{19}$ m$^{-3}$ with ECH
The Plasma Geometry in Vicinity of Divertor has a Strong Effect on $P_{TH}$

- Decreasing the height of the X-point above the divertor surface significantly decreases $P_{TH}$ (> factor of 2)

- ECH into He plasmas
  - High X-point (138698) $(\kappa=1.66, \delta_{bot}=0.77, \delta_{top}=0.37)$
  - Low X-point (138707) $(\kappa=1.79, \delta_{bot}=0.78, \delta_{top}=0.37)$

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**Graphs:**

- **ECH Power (MW)**
- **Density ($10^{19} \text{ m}^{-3}$)**
- **He II Div. Signal (au)**
- **Time (ms)**

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**Legend:**

- 26 cm height
- 10 cm height
The X-point height has a Strong Effect on the H-mode Power Threshold for H, D and He

- Effect previously observed on DIII-D and other devices
- First systematic study of effect for H, D and He

Preliminary analysis indicates edge neutrals may be affecting the power threshold
The X-point height has a Strong Effect on the H-mode Power Threshold for H, D and He

- Effect previously observed on DIII-D and other devices
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H: 2 T  
D and He: 1.7 T

- **H-mode power threshold scaling for D plasmas**
  - $P_{TH, SCAL08} (D) = 0.049 \, n_e^{0.72} \, B_T^{0.80} \, S^{0.94}$
    (units: $10^{20}$ m$^{-3}$, T, m$^2$)

- **X-point dependence is not included in the power threshold scalings**
  - Results in factor of 2 difference between $P_{TH}$ at low X-point and the scaling prediction

- Preliminary analysis indicates edge neutrals may be affecting the power threshold
Edge $E_r$ Shear and Edge Magnetic Shear Show No Significant Change with X-point Height
Difference in the H-mode Power Threshold Between He and D Plasmas Decreases at Higher Densities

- **He and D plasmas** \((I_p = 1.0 \text{ MA}, B_T = 1.65 \text{ T})\)
  - Balanced NBI (i.e. zero torque) at same ion species as plasma species \((D - \text{NBI} \rightarrow D; \text{He} - \text{NBI} \rightarrow \text{He})\)
  - ECH
  - High X-point location

- **At low densities** \(<3 \times 10^{19} \text{ m}^{-3}\)
  \(P_{TH} (\text{He}) \sim 1.5-2 P_{TH} (\text{D})\)

- **At high densities** \(>3 \times 10^{19} \text{ m}^{-3}\)
  \(P_{TH} (\text{He}) \sim 1-1.5 P_{TH} (\text{D})\)
Difference in the H-mode Power Threshold Between He and D Plasmas Decreases at Higher Densities

- He and D plasmas ($I_p = 1.0 \text{ MA}, B_T = 1.65 \text{ T}$)
  - Balanced NBI (i.e. zero torque) at same ion species as plasma species (D-NBI $\rightarrow$ D; He-NBI $\rightarrow$ He)
  - ECH
  - High X-point location

- At low densities ($<3 \times 10^{19} \text{ m}^{-3}$) $P_{TH} (\text{He}) \sim 1.5-2 P_{TH} (\text{D})$

- At high densities ($>3 \times 10^{19} \text{ m}^{-3}$) $P_{TH} (\text{He}) \sim 1-1.5 P_{TH} (\text{D})$

- Lowering the X-point will move all curves significantly downwards with respect to the scaling
Application of Strong Resonant n=3 RMP Fields Increase $P_{TH}$ in Helium Plasmas

- n=3 resonant magnetic perturbations (RMPs) applied by in vessel coils (I-coils)
- Stronger resonant components lead to higher $P_{TH}$
- Similar effect observed with ECH
Resonant Magnetic Perturbations Increase the H-mode Power Threshold (Helium Plasmas)

- n=3 resonant magnetic perturbations (RMPs) applied by in-vessel coils (I-coils) to be resonant at specific values of q₉₅ (=3.4)

- 3 He plasma discharges with
  - No I-coil at q₉₅ = 3.4
  - I-coil current = 2 kA at q₉₅ = 3.4
  - I-coil current = 2 kA at q₉₅ = 4.0

- Application of I-coil current = 2 kA
  - Resonant field at q₉₅ = 3.4 remained in L-mode at up to Pₑᶜʰ = 3.5 MW
  - H-mode achieved again with non-resonant RMP fields (q₉₅ = 4.0)

- Careful timing of I-coil activation required after L-H transition, but before first type I ELM
Application of Strong Resonant n=3 RMP Fields Increase $P_{TH}$ for Both ECH and Balanced H-NBI Heating (Helium Plasmas)

- n=3 resonant magnetic perturbations (RMPs) applied by in vessel coils (I-coils)

![Graph showing P_{TH} vs \frac{\delta B}{B_T} for He Plasmas.]

He Plasmas
1.0-1.2 MA, 1.65 T, $n_e = 3.0-3.6 \times 10^{19}$ m^{-3}
Balanced H-NBI: $q_{95} = 3.5$, $q_{95} = 4.1$
ECH: $q_{95} = 3.4$, $q = 3.4$, L-mode, $q_{95} = 4.0$
For D Plasmas, there is a Minimum Required RMP Field Before $P_{TH}$ Increases

- Effect on $P_{TH}$ observed for $\delta B/B_T > \sim 3 \times 10^{-4}$
- Determined for both ECH and balanced D-NBI (plasma shape different to He plasma study)
The H-mode Power Threshold is Unaffected by the TBM

- Test Blanket Module (TBM) magnetic ripple replicated using mock up coils on DIII-D
  - Results are for TF + TBM local ripple ~3.1% (expected TF + TBM local ripple in ITER ~1.3%)

- Determined for ECH, balanced D-NBI and co D-NBI in D plasmas
The TBM has no Significant Effect on the H-mode Power Threshold

- TBM magnetic ripple replicated using mock up coils on DIII-D
  - Results are for TF + TBM local ripple ~3% 
    (expected TF + TBM local ripple in ITER ~1.3%)
- Determined for ECH, balanced D-NBI and co D-NBI in D plasmas
Summary

- Strong dependence of $P_{TH}$ on the X-point height at the divertor for H, D and He plasmas (not included in $P_{TH}$ scaling)

- The difference between the H-mode threshold power ($P_{TH}$) for He and D plasmas decreases at higher densities

- Resonant magnetic perturbations (n=3) increase $P_{TH}$ in He and D
  - Threshold in RMP field for effect on $P_{TH}$ in D
  - Requires appropriate timing of RMP coil activation after L-H transition

- Local magnetic ripple from test blanket module mockup coils have no significant effect on $P_{TH}$ in D plasmas
  - TBM not expected to significantly affect $P_{TH}$ in ITER

- Need to include certain dependences (e.g. X-point) and determine underlying physics of all known effects for reliable predictions by H-mode power threshold scalings

DIII-D

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