Effect of Aspect Ratio on H-mode and ELM Characteristics

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Motivation I

H-mode Characteristics I

H-mode Characteristics II

Power Threshold

ELMs

Future Work

Motivation II

Energy Confinement Improves in H-Mode

Pegasus Hall Probe Deployed

Noise Shielding in Pegasus

Large Type I and II ELMs observed

Pressure correlation with MHD fluctuations

Pegasus

Pegasus has the ability to produce current and pressure pedestal

J \( (R,t) \) calculated from Ampere’s Law

Simplified LP Circuit/Grounding Scheme

Hall Probe Observes Large ELM dynamics through discharge

Pressure profiles suggest existence of edge pedestal

H-mode Upgrades

\( P_{\text{LH}} \) dependence upon Aspect Ratio

Direct J Profiles obtained in Pegasus

Triple Probe Theory

Closer Inspection of \( J \) edge reveals complex behavior

Future experiments with low MHD are needed

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H-mode Studies Across Physics Regimes Crucial

- ITER will operate in H-mode
- Parameter variations critical to validate theories of H-mode and ELM behavior
- Toroidal aspect ratio $A$ changes H-mode access, equilibrium, and stability
- Low-$A$ H-mode differences
  - Fueling location importance
  - $P_{\text{LH}}$ and ELM characteristics
  - Magnetic configuration effects

$A \geq 4, q_\psi \geq 4$

$A \geq 1.25, q_\psi \geq 12$


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\( A \sim 1 \rightarrow \text{high } I_p \text{ at very low } B_T \)
- Excitation of peeling modes without \( J_{BS} \)
- Easy access to H-mode regime and ELMs
- Neoclassical effects (resistivity enhancement)

Modest-sized plasma and relatively low \( T_e \)
- Allows diagnostic access to pedestal
- Pedestal \( J_\phi(R, t), p(R, t), \) and \( v_\phi(R, t) \) via probes

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PEGASUS Provides H-mode Plasmas at Ultralow-A

Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.15 – 1.3</td>
</tr>
<tr>
<td>R (m)</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤ 0.25</td>
</tr>
<tr>
<td>B_T (T)</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Δt_shot (s)</td>
<td>≤ 0.025</td>
</tr>
<tr>
<td>Z_eff</td>
<td>~ 1</td>
</tr>
<tr>
<td>Recycling</td>
<td>&lt; 0.7</td>
</tr>
</tbody>
</table>

High-stress Ohmic Heating Solenoid

Local DC Helicity Injectors

Divertor Coils

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Recent Upgrades for H-mode Studies

- **High-field-side (HFS fueling)**
  - Two valves (top and bottom)
  - Improved density control

- **Augmented divertor coils**
  - New external divertor set
  - Allows SN, DN operation

- **Radial field coils**
  - Vertical position control
H-mode Readily Accessed at Near-Unity $A$

- $A \approx 1 \rightarrow \text{low } B_T \rightarrow \text{low } P_{\text{LH}}$

$$P_{\text{LH}} \sim n_e^{0.717} B_T^{0.803} S^{0.941}$$

- H-mode achieved
  - HFS neutral fueling
    - Similar to other STs
  - Limited or diverted plasmas

Fast visible imaging, $\Delta t \sim 30 \mu s$

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Standard Signatures Observed in OH H-mode

- Quiescent edge
  - Edge current and pressure pedestals

- Reduced $D_\alpha$

- Large and small ELMs

- Bifurcation in $\phi_D$
  - At $A \sim 1$, indicates current redistribution

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Energy Confinement Improves in H-mode

• Equilibrium reconstructions yield $\tau_e$

$$\tau_e = \frac{W_k}{P_{in} - dW/dt - P_{RAD}}$$

  - Challenges: short pulse, MHD, $I_{wall}(t)$
  - Significant $dW/dt$

• $W_k (\tau_e)$ increases after L-H transition
  - $H_{98}$ increases from 0.5 to 1.0

• Ongoing: Virial analysis for fast $\tau_e$

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• Provides magnetics based $\beta_p$, $W_k$, and $\tau_e$\(^1\)

• High-$A$: $\beta_{p,\text{circ}} \approx 1 + \mu$
  - Overestimates $\beta_p$, $W_k$ at low-$A$
  - $\mu = 4\pi B_{T0} R_0 \Delta \Phi / B_{pa}^2 \Omega$

• Low-$A$: $\beta_p = S_1/2 + S_2/2(1 - R_T/R_0) + \mu$
  - Full treatment accurately determines $\beta_p$, $W_k$

• In progress: fast boundary reconstruction code for full treatment at $A \sim 1$

\(^1\) Lao et al., Nucl. Fusion 25, 1421 (1985).
Ti and Te Increase in H-mode

- OH plasmas: $T_i \ll T_e$

- Impurity $T_i$ doubles

- Increasing $T_e(0)$
  - Increasing, peaking CV emission observed in H-mode
Thomson Scattering Indicates Higher H-mode $T_e$

- Initial measurements
  - Grating optimized: $T_e \leq 100$ eV

- L-mode: $T_e(0) \sim 150$ eV

- H-mode: $T_{e, H}(0) > T_{e, L}(0)$
  - Spectrum broadened off low $T_e$ grating
  - Comparable $n_e$, but lower peak emission

- Diagnostic upgrades improve spatial and $T_e$ resolution
  - Alternate grating: $T_e \leq 1$ keV

*See posters 118 and 119 for more detail*
Strengthened Core Rotation in H-mode

- No external momentum input — intrinsic rotation
- Chordally-integrated velocity profiles show low rotation in L-mode
Edge Pedestals Measured with Probes

- A $\sim 1$: very low $B_T \rightarrow$ low $T_e$
  - Unique pedestal access with probes

- Inter-ELM current pedestal formation
  - Measured with Hall probe array$^{1,2}$
  - Scale length: 4 $\rightarrow$ 2 cm L to H

- Pressure pedestal observed
  - Multi-shot scan with triple Langmuir probe
  - Edge distortion effects removed
  - See poster 120 for more information

Extends $P_{LH}$ to $A \sim 1$ regime

Vary $P_{OH}$ with power scan
- Transition time from $\phi_D$ bifurcation
- Wide parameter range
  - $P_{OH} = 0.1 - 0.6$ MW
  - $n_e = 0.5 - 4 \times 10^{19}$ m$^{-3}$
  - Limited: Centerstack
  - Diverted: USN (favorable $\nabla B$)

$P_{LH,exp} = P_{OH} - \frac{dW}{dt}$
- $\frac{dW}{dt}$ by magnetic reconstruction
- $\sim 30\%$ correction
$P_{\text{LH}}$ Shows Strong Density Dependence

- Survey of L and H-mode plasmas at different $P_{\text{OH}}$ and $n_e$

- $P_{\text{LH}}$ increases with $n_e$
  - $n_e$ dependence consistent with scalings
  - Density minimum not apparent

- Topology independent
  - Diverted and limited $P_{\text{LH}}$ similar

Threshold Power vs. Density

$P_{\text{LH}}_{\text{exp}} \sim 0.7P_{\text{OH}}$

$P_{\text{OH}}/(B_T^{0.803}S^{0.941}) [\text{MW/T.m}^2]$

$\bar{n_e} [10^{20} \text{ m}^{-3}]$

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At low $A$, $P_{\text{LH}} \gg P_{\text{ITPA08}}$

- $P_{\text{LH}}$ increasingly diverges from expectations as $A \to 1$
- Discrepancy may hint at additional physics

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1 Maingi et al., Nucl. Fusion, 50, 064010 (2010).
Some $P_{\text{LH}}$ Results Consistent with FM$^3$ Model

- FM$^3$ model reproduces $P_{\text{ITPA08}}$ scaling

- FM$^3$: $P_{\text{LH}}(n_e)$ minimum $\sim 1 \times 10^{18}$ m$^{-3}$
  - $n_e/n_G << 0.1$, inaccessible due to runaways

- $P_{\text{LH}}$ topology independence
  \[ \frac{P_{\text{LH}}^{\text{lim}}}{P_{\text{L-H}}^{\text{div}}} \approx \left( \frac{q_{*}^{\text{lim}}}{q_{*}^{\text{div}}} \right)^{-7/9} \]
  $\gg 1$ @ $A \sim 3$
  $\rightarrow 1$ @ $A \sim 1$

- Strong $P_{\text{LH}}(A)$ not understood
  - Multi-machine $P_{\text{LH}}$ studies in progress/proposed (NSTX-U, PEGASUS, DIII-D)

1 Fundamenski et al., Nucl. Fusion 52, 062003 (2012).
• Filament structures observed
  – Coincident with $D_\alpha$ bursts

• Small (“Type III”) ELMs ubiquitous, less perturbing
  – $P_{OH} \sim P_{LH}$

• Large (“Type I”) ELMs infrequent, violent
  – $P_{OH} \gg P_{LH}$
  – Can cause H-L back-transition
• Edge Mirnov array measures ELM toroidal mode spectrum
  – $n \leq 20$ resolved by cross-phase analyses

• Type III: $A$ dependent
  – $A \leq 1.4$: $n \leq 1 – 4$
    • PEGASUS and NSTX\textsuperscript{1}
  – $A \sim 3$: $n > 8$\textsuperscript{2}

• Type I: $A$ independent
  – Intermediate-$n$\textsuperscript{2,3}
  – Low-$A$ devices have lower $n$

• Increased peeling drive at low-$A$
  – Higher $J_{\text{edge}}/B \rightarrow$ lower $n$

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\textsuperscript{1} Maingi et al., Nucl. Fusion \textbf{45}, 1066 (2005).
\textsuperscript{3} Perez et al., Nucl. Fusion \textbf{44}, 609 (2004).
Nonlinear ELM Precursors Observed

- Magnetic signature of ELMs have multiple $n$ components
  - Simultaneously unstable modes

- Modes show different time evolutions
  - Isolated with bandpass filter
  - $n = 8$ grows continuously
  - $n = 6$ fluctuates prior to crash

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• Challenge: study nonlinear ELMs at Alfvénic timescales

• Complex behavior with current-filament ejection
  – Time-averaged data qualitatively similar to JOREK$^1$

Results Motivate Proposed PEGASUS-Upgrade

<table>
<thead>
<tr>
<th></th>
<th>PEGASUS</th>
<th>PEGASUS-U</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi_{\text{SOL}}$ (mWb)</td>
<td>40</td>
<td>138 / 170</td>
</tr>
<tr>
<td>$B_{T,\text{max}}$ (T) at $R_0$</td>
<td>0.14</td>
<td>~ 0.4</td>
</tr>
<tr>
<td>$I_{p,\text{max}}$ (MA)</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>$\Delta t$ (ms)</td>
<td>15</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>$A$</td>
<td>1.15</td>
<td>1.22</td>
</tr>
</tbody>
</table>

- **Nonlinear pedestal and ELM studies**
  - Simultaneous measurements of $p(R,t)$, $J(R,t)$, $v_\phi(R,t)$
    - New edge diagnostics (probe arrays, DNB)
  - Tests of neoclassical physics

- **ELM Modification and Mitigation**
  - Novel 3D-MP coil array
  - LHI current injectors in divertor, LFS regions
• Full design study planned  
  – Proposal includes initial tests

• Comprehensive 3D-MP system  
  – LFS coils, spaced with ~equal-PEST angle  
    • 12 toroidal x 7 poloidal array  
    • Initial DC power systems for n=3 control  
  – HFS 4-fold helical coil set

• Uniqueness  
  – Wide spectral range  
  – Measure internal plasma response

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• Local helicity injection system provides 3D SOL current injection
  – $I_{\text{inj}} \leq 5 \text{ kA}$, $J_{\text{inj}} \sim 1 \text{ kA/cm}^2$

• LHI use with H-mode studies
  – Pulse extension and J(R) control

• LHI system affects edge plasma
  – Strong 3D edge current perturbation
  – Edge biasing to modify rotation profiles
  – Similar to LHCD on EAST\(^1\)

Unique Studies of H-mode Physics at A~1

- H-mode achieved in plasma with pedestal diagnostic access
  - Standard characteristics: pedestal; low $D_\alpha$; increased $\tau_e$; $H_{98}\sim 1$; etc.

- $P_{LH}$ features unique to low-$A$ emerging
  - Strong $P_{LH}$ threshold scaling with $A$
  - Little to no difference between limited and diverted H-modes

- Operating regime allows detailed studies of ELMs
  - ELM mode numbers at low-$A$ systematically lower than high-$A$
  - Nonlinear ELM dynamics measured at Alfvénic timescales

- Upgrade allows detailed study of nonlinear ELMs, pedestal physics
  - Complements experiments on larger fusion facilities
  - Detailed measurements can elucidate more limited results on larger facilities