H-mode and Edge Physics on the PEGASUS ST: Progress and Future Directions

M.W. Bongard

57th Annual Meeting of the APS
Division of Plasma Physics

Savannah, GA
November 18, 2015
H-mode Readily Accessed in A ~ 1 PEGASUS ST

- Low $B_T$ at $A \sim 1 \rightarrow$ low H-mode $P_{LH}$
  - $P_{OH} >> P_{ITPA08} \sim B_T^{0.8} n_e^{0.72} S^{0.94}$
  - Limited or diverted topology
  - Facilitated by HFS fueling

- Standard H-mode features observed
  - Quiescent edge, improved $\tau_E$, ELMs

PEGASUS Toroidal Experiment

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>1.15 – 1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>0.2 – 0.45</td>
<td></td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>$\leq$ 0.25</td>
<td></td>
</tr>
<tr>
<td>$B_T$ (T)</td>
<td>$&lt; 0.2$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \tau_{shot}$ (s)</td>
<td>$\leq 0.025$</td>
<td></td>
</tr>
<tr>
<td>Wall Type</td>
<td>SS + Ti getter</td>
<td></td>
</tr>
</tbody>
</table>
Edge Pedestals Present Between ELMs in H-mode

- Short pulse, low edge $T_e$ permit detailed edge measurements
  - $J_\phi(R,t)$ via multichannel Hall probe$^{1,2}$
    - High spatial, temporal resolution
  - $p(R)$ via triple Langmuir probe
    - Single point, high temporal resolution

- Clear current pedestal observed
  - $L \rightarrow H$ scale lengths: 4 $\rightarrow$ 2 cm

- Multi-shot Langmuir probe scans indicate pressure pedestal
  - Some edge distortion present from MHD

---

1 Bongard et al., Rev. Sci. Instrum. 81, 10E105 (2010)
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

- Virial analysis ongoing for $\tau_E$ database

M.W. Bongard, APS-DPP 2015
• 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$^{-3}$
    • Inner wall limited
    • Diverted: USN (favorable $\nabla B$)

• $P_{LH,\text{exp}} = P_{OH} - dW/dt$
  – $dW/dt$ from magnetic reconstructions
  – $\sim 30\%$ correction
$P_{\text{LH}}$ Consistent with Global Scalings—But Low-A Differences Arising

- $P_{\text{LH}}(n_e)$ consistent with ITPA scaling
  - FM$^3$ model$^1$: minimum $P_{\text{LH}}(n_e) \sim 1 \times 10^{18}$ m$^{-3}$

- Magnetic topology independence
  - Diverted, limited edge topology similar
  - FM$^3$: $P_{\text{LH}}^{\text{LIM}} / P_{\text{LH}}^{\text{DIV}} \sim (q_{\psi}^{\text{LIM}} / q_{\psi}^{\text{DIV}})^{-7/9}$

$^1$ Fundamenski et al., Nucl. Fusion 52, 062003 (2012)
At Low $A$, $P_{\text{LH}} \gg P_{\text{ITPA08}}$

- $P_{\text{LH}}$ increasingly diverges from expectations as $A \rightarrow 1$
  - PEGASUS $P_{\text{LH}} / P_{\text{ITPA08}} \geq 10$–20
  - Confirms trend from NSTX, MAST

- Discrepancy may hint at additional physics

---

Multi-Machine $P_{\text{LH}} / P_{\text{ITPA08}}$ Comparison

1 Maingi et al., Nucl. Fusion 50, 064010 (2010)
• Filament structures accompany ELMs

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

• Large ("Type I") ELMs infrequent, violent
  – $P_{OH} \gg P_{LH}$
  – Intermediate $n$

• ELM magnetic structure varies with $A$
  – Type III: $A$-dependent
    • Pegasus, NSTX: $n \leq 4$
    • $A \sim 3$: $n > 8$
  – Type I: $A$ independent, but ST’s report lower $n$ in range
  – Strong peeling drive in ST $\rightarrow$ lower $n$
Details of Nonlinear ELM Behavior Emerging

- Simultaneously unstable toroidal modes present during ELM
  - Detectable only within ~ cm of LCFS
  - Nonlinear energy exchange

- Complex, multimodal $J_{\text{edge}}(R, t)$ collapse
  - High $\Delta t \sim 6 \mu s$ through single large ELM
  - Current filament ejection

- **Challenge:** studies of nonlinear ELM dynamics at Alfvénic timescales
Results Motivate PEGASUS-U Upgrade Proposal

- **Centerstack upgrade: new capabilities at \( A \approx 1.2 \)**
  - \( B_T \) increases \( 2-5 \times \)
  - Pulse length \( \approx 100 \) ms
  - \( V\)-s increases by \( > 4 \times \) (PPPL collaboration)

- **Focused Physics Mission**
  - Nonlinear pedestal and ELM studies
    - Simultaneous measurement of \( p(R,t), J(R,t), v_\phi(R,t) \)
    - New edge diagnostics (probe arrays, DNB)
  - ELM Modification and Mitigation
    - Novel 3D-MP coil array
    - LHI current injectors in divertor, LFS regions
  - Physics of Local Helicity Injection Startup
    - High \( I_p \), long-pulse startup
    - Projections to NSTX-U
Unique Studies of H-mode Physics at $A \sim 1$

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

- Low-A $P_{LH}$ features emerging
  - $P_{LH}$ threshold strongly increases as $A \to 1$
  - Insensitivity to magnetic topology

- Operating regime allows detailed ELM studies
  - Nonlinear ELM dynamics on Alfvénic timescales

- PEGASUS-U addresses critical physics, technology issues
  - Nonlinear ELM, pedestal physics with local edge diagnostics
  - Comprehensive 3D-MP and $J_{\text{edge}}$ injection for ELM control
  - Tests of LHI at NSTX-U relevant field, pulse length

Supporting Posters This Meeting
R.J. Fonck, GP 12.00114
K.E. Thome, GP 12.00115
D.M. Kriete, GP 12.00120