H-mode and ELM Dynamics Studies at Near-Unity Aspect Ratio in the PEGASUS Toroidal Experiment and their Extension to PEGASUS-Upgrade

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H-mode Readily Accessed in A ~ 1 \text{ PEGASUS ST}

\begin{itemize}
  \item Low B_T at A \sim 1 \rightarrow \text{low H-mode } P_{\text{LH}}
    \begin{itemize}
      \item P_{\text{OH}} >> P_{\text{ITPA08}} \sim B_T^{0.80} n_e^{0.72} S^{0.94}
      \item Limited or diverted topology
      \item Facilitated by HFS fueling
    \end{itemize}
  \item Standard H-mode features observed
    \begin{itemize}
      \item Unique edge diagnostic access
    \end{itemize}
\end{itemize}

\begin{center}
\begin{tabular}{|c|c|c|}
  \hline
  Wall Type & SS + Ti getter & SS + Ti getter \\
  \hline
  \hline
  \textbf{PEGASUS Toroidal Experiment} & & \\
  A & 1.15 – 1.3 & \\
  R (m) & 0.2 – 0.45 & \\
  I_p (MA) & \leq 0.25 & \\
  B_T (T) & < 0.2 & \\
  \Delta \tau_{\text{shot}} (s) & \leq 0.025 & \\
  \hline
\end{tabular}
\end{center}

\textit{Fast visible imaging, } \Delta t \sim 30 \mu s
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

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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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Full Virial Analysis is Required as $A \to 1$

- Technique gives magnetics based $\beta_p$, $W_K$, and $\tau_e$\(^1\)

\[
\beta_p = \frac{S_1}{2} + \frac{S_2}{2}(1 - R_T/R_0) + \mu
\]

\[
W_K = -\frac{3}{2} \beta_p \frac{B_{pa}^2 \Omega}{2 \mu_0}
\]

\[
\mu_{\text{expt}} = \frac{4\pi B_{T0} R_0 \Delta \phi}{B_{pa}^2 \Omega}
\]

- Model equilibria at varied $A$, $\beta_p$ highlight breakdown of high-$A$ approximations
  - $\beta_{p,\text{circ}} = 1 + \mu$ significantly overestimates $W_K(\tau_e)$ in paramagnetic regime

- Developing fast boundary reconstruction code to provide full treatment at $A \sim 1$

\[^1\] Lao et al., Nucl. Fusion 25, 1421 (1985)
\( P_{LH} \) Measurements Extended to A \( \sim 1.2 \) in PEGASUS

- 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

\[ \text{Limited USN Diverted} \]

\[ \text{SN 73580} \]
\[ t = 0.0248 \, s \]

\[ \text{SN 70914} \]
\[ t = 0.02425 \, s \]

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\( P_{LH} \) Consistent with Global Parametric Scalings—But Differences Arising at Low A

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

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

\( M.W. \) Bongard, ISTW 2015

\(^1\) 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 $A \to 1$
  - \text{PEGASUS} $P_{\text{LH}} / P_{\text{ITPA08}} \geq 10$–$20$
  - Confirms trend from NSTX, MAST

- Discrepancy may hint at additional physics

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1 Maingi \textit{et al.}, Nucl. Fusion \textbf{50}, 064010 (2010)

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• Filament structures observed
  – Coincident with $D_\alpha$ bursts

• 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
  – Can cause H-L back-transition

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• 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

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Results Motivate PEGASUS-U Upgrade Proposal

- New centerstack assembly
  - OH solenoid via PPPL collaboration
    - $\Delta \Phi_{OH}: 40 \rightarrow 170 \text{ mV-s}$
  - TF bundle: $0.15 \rightarrow 0.40 \text{ T}$
  - Pulse length: $15 \rightarrow 50\text{–}100 \text{ ms}$

- Power system, control upgrades
  - New TF power supply
    - $I_{TF} \times 3\text{–}4$
  - Upgraded OH power supply
    - Improved $V_{\text{loop}}$ control

- Comprehensive 3D-Magnetic Perturbation System

- Longer-term: ECH auxiliary heating
  - In discussion with ORNL

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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 Sauter neoclassical bootstrap model

ELM Modification and Mitigation
- Novel 3D-MP coil array
  - LFS array: 12 toroidal $\times$ 7 poloidal
  - Helically-wound HFS coils
- LHI current injectors in divertor, LFS regions

Physics of Local Helicity Injection Startup$^1$
- High $I_p$, long-pulse startup
- Projections to NSTX-U

$^1$ J.A. Reusch, Session O6, Friday
Unique Studies of H-mode Physics at $A \sim 1$

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

- Features unique to low-$A$ emerging
  - Strong $P_{\text{LH}}$ threshold scaling with $A$
  - Insensitivity to magnetic topology

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

- PEGASUS-U planned to address critical physics, technology issues
  - Nonlinear ELM, pedestal physics with local edge diagnostics
  - Comprehensive 3D-MP and $J_{\text{edge}}$ injection for ELM mitigation / control
  - Tests of LHI at NSTX-U relevant field, pulse length
3D-Magnetic Perturbation System Proposed

- Design study, fabrication as proposed work

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

- Uniqueness
  - Wide spectral range
  - Local pedestal plasma response measurements

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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
    • Similar to LHCD on EAST\(^1\)
  – Edge biasing to modify rotation profiles

Pegasus-U LHI Injector Configuration

- Four, large-$A_{\text{inj}}$ injectors
  - $2 \text{ cm}^2 \rightarrow 4 \text{ cm}^2$
  - LFS, HFS locations
  - Modest P/S devel. for long-pulse
    - e.g. cathode-spot quench interrupter circuit

- Supports confinement, scaling studies for NSTX-U

(a) Present injector cross-section; (b) proposed new injector design.

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Ohmic H-mode Plasmas Have Standard Signatures

- Quiescent edge
  - Edge current, pressure pedestals
- Reduced $D_\alpha$ emission
- Large and small ELMs
- Bifurcation in $\phi_D$
  - Correlates with improving $\tau_e$

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