Initial Investigations of H-mode Edge Dynamics in the PEGASUS Toroidal Experiment

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<table>
<thead>
<tr>
<th>Utilizing Unique Aspects of the ST to Improve Edge Physics Understanding</th>
<th>Pegasus Hall Probe Deployed to Measure J</th>
<th>Peeling Modes Accessed via Skin Current, Match Empirical and Theoretical Expectations</th>
<th>H-mode Plasmas Routinely Obtained in Pegasus</th>
<th>Two Distinct ELM Types Observed in H-mode</th>
<th>Type III Jedge ELM Dynamics Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pegasus is a Compact, Ultralow-A ST</td>
<td>J(R,t) Calculable Directly from Ampere’s Law</td>
<td>Peeling Modes Have Low-n, High-m Structure</td>
<td>Edge Current Pedestal Observed in H-Mode</td>
<td>ELMs Have Distinct Magnetic Signatures</td>
<td>Type I Jedge ELM Dynamics Measured</td>
</tr>
<tr>
<td>Edge Stability Critical to Next-Step Fusion Devices</td>
<td>Direct J(R) Profiles Obtained in Pegasus</td>
<td>Peeling Mode Onset Consistent with Ideal MHD</td>
<td>Local Helicity Injection Startup Compatible with Consequent High-Quality OH H-mode</td>
<td>Pegasus ELM Spectra Similar to NSTX</td>
<td>Low-A Regime Provides Environment for Unique Tests of Edge Stability Theory</td>
</tr>
<tr>
<td>Validated, Predictive Theory Needed to Mitigate ELMs</td>
<td>High Temporal Resolution Resolves Nonlinear Peeling Mode Jedge Dynamics</td>
<td>Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport</td>
<td>Divertor Coils Activated to Access Standard Separatrix-Limited H-modes</td>
<td>Disruptive Type I ELM Occurs at High Input Power</td>
<td>Type I ELM Filament Ejection Coincides with Jedge Current-Hole Generation</td>
</tr>
</tbody>
</table>

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**ELM Precursor Components Grow on MHD Timescales**

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Utilizing Unique Aspects of the ST to Improve Edge Physics Understanding

• Low A ST operation offers ready access to AT physics
  – Low H-mode $P_{th}$; strong neoclassical effects at low $T_e$
  – Peeling, peeling-balloonning mode edge physics
  – Simplified diagnostic access $\rightarrow$ unique $J_{edge}(t)$ measurements

• Peeling mode characterized in L-mode via skin current drive
  – Edge-localized, low-n, ideal MHD mode; onset consistent with ideal MHD
  – Nonlinear $J_{edge}$ dynamics: Filament generation, expulsion, and propagation

• Extension to H-mode: Measurements of pedestal, ELM dynamics
  – Ohmic H-mode routinely accessed; limited and diverted magnetic topologies
  – Two ELM regimes suggested to date with differing toroidal mode spectra
  – $J_{edge}(R,t)$ measured throughout ELM crash

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PEGASUS is a Compact, Ultralow-A ST

**Equilibrium Field Coils**

**High-stress Ohmic heating solenoid**

**Vacuum Vessel**

**Toroidal Field Coils**

**Ohmic Trim Coils**

**New Divertor Coils**

**Local Helicity Injectors**

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**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.15 – 1.3</td>
<td>1.12 – 1.3</td>
</tr>
<tr>
<td>R(m)</td>
<td>0.2 – 0.45</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤ .23</td>
<td>≤ 0.30</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6 – 14</td>
<td>6 – 20</td>
</tr>
<tr>
<td>RB_t (T-m)</td>
<td>≤ 0.06</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>κ</td>
<td>1.4 – 3.7</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>τ_{shot} (s)</td>
<td>≤ 0.025</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>β_t (%)</td>
<td>≤ 25</td>
<td>&gt; 40</td>
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</tbody>
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Edge Stability Critical to Next-Step Fusion Devices

- Future fusion devices will operate in H-mode
  - Edge Localized Modes (ELMs) of concern

- Peeling-balloonning theory believed to underlie most damaging Type-I ELM
  - Pressure, current density gradients in edge drive ideal MHD instabilities
  - Detailed $J_{edge}$ measurements needed

\[ \propto \frac{qRJ_\parallel}{B} \]

\[ \rho_\text{ped} \propto \alpha/\alpha_c \]


***: Snyder, Phys. Plasmas 12, 056115 (2005); Hegna, Phys. Plasmas 3, 584 (1996)

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Validated, Predictive Theory Needed to Mitigate ELMs

- **Peeling-ballooning model**
  - Competing ideal MHD instabilities cause ELM onset
  - Current-driven peeling modes
  - Pressure-driven ballooning modes

- **Nonlinear dynamics**
  - More complete physical models
  - Evolution of P-B mode structures
  - Heat flux deposition projections

- **Detailed measurements required to validate theory**
  - $P_{\text{edge}}, J_{\text{edge}}(R,t)$ on ELM timescales*

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*S: Maggi, Nucl. Fusion **50**, 066001 (2010)
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**PEGASUS Hall Probe Deployed to Measure J**

- Precision $B_z(R, t)$ measurements
  - 16 solid-state InSb Hall sensors
  - 7.5 mm radial resolution
  - 25 kHz large-signal bandwidth

- Carbon Armored
  - Compatible with L, H-mode to date

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\[ \mu_0 J_\phi = (\nabla \times \mathbf{B})_\phi = \frac{\partial B_R}{\partial Z} - \frac{\partial B_Z}{\partial R} \]

- Simplest test follows from \( B_R(Z) \) or \( B_Z(R) \) measurements

- Petty* solves for an off-midplane \( B_Z(R) \) measurement set and an elliptical plasma cross-section:

\[
\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R - R_0)} \left( 1 - \frac{Z^2 R_0}{\kappa^2 R (R - R_0)^2} \right) - \frac{dB_Z}{dR} \left( 1 + \frac{Z^2}{\kappa^4 (R - R_0)^2} \right)
\]

- Does not make assumptions on shape of \( J(R) \)

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Direct $J_\phi(R)$ Profiles Obtained in PEGASUS

- Straightforward J estimation
  - Obtain Hall Probe $B_z(R,t)$
  - Compute $dB_z/dR$ using interpolated smoothing spline*
  - Compute $J_\phi(R,t)$ given geometry

- Resultant $J_\phi(R,t)$ consistent with $I_p$, MHD evolution

- Radial span extendible with multi-shot averaging

- Higher-order shaping effects negligible within errors

* Reinsch, Numerische Mathematik 10, 177 (1967)
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High Temporal Resolution Resolves Nonlinear Peeling Mode $J_{\text{edge}}$ Dynamics

- Pure peeling modes accessed in L-mode via transient skin current drive
- Radially-propagating filaments form from initial “current-hole” $J_{\text{edge}}$ perturbation*
  - Validates formation mechanism hypothesized by EM blob transport theory**
- Filaments carry current $I_f \sim 100$-220 A
  - $I_f < 0.2\%$ of $I_p$, similar to MAST ELMs


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Peeling Modes Accessed via Skin Current; Match Empirical and Theoretical Expectations

- Short lifetimes with high poloidal coherence
- Detachment, radial propagation of filaments
- High-\(m\), low-\(n\) structure
- Mode amplitude increases with measured \(J/B\) theoretical drive

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Peeling Modes Have Low-n, High-m Structure

- Dominant toroidal \( n \leq 3 \) strictly observed
  - Only detectable near edge
  - \( n = 2 \) depicted here

- Lower limit on \( m \) via cylindrical mode analysis
  - Poloidal cross-phase: \( m_{\text{lab}} \approx 41 \)
  - P8 Radial decay rate: \( m_{\text{lab}} \approx 42 \)

- More accurate \( m \) via straight field line mapping
  - PEST transform large at \( A \sim 1 \)
  - \( m \sim 3-7 \) \( m_{\text{lab}} \) for this case
Peeling Mode Onset Consistent with Ideal MHD

- High-performance discharge with peeling activity analyzed
  - $\langle I_\phi \rangle_{edge}(\psi) \sim 500 \text{ kA/m}^2$ from reconstruction with Hall data

- Analytic peeling criterion*, DCON stability analysis indicate instability

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Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport

- Trajectory of detached peeling filament tracked with 275 kHz imaging

- Magnetostatic repulsion* plausibly contributes to dynamics
  - Current-hole $\mathbf{J} \times \mathbf{B}$ drives $a_R$
  - Transition at ~ 35 μs comparable to healing time of current-hole

- Measured $V_R$ comparable to available EM blob models**
  - $V_R \sim 4$ km/s; $V_{R,IB} \sim 8$ km/s
  - Agrees to O(1) accuracy of theory


H-mode Plasmas Routinely Obtained in PEGASUS

- Obtained with centerstack fueling
  - Ohmically heated
  - Limited or diverted topology

- Standard H-mode signatures
  - Quiescent edge
  - Reduced D_α emission
  - T_e, T_i increase
  - Large, small ELMs suggested
  - Bifurcation in Φ_D
  - Toroidal flow reversal

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Edge Current Pedestal Observed in H-Mode

- Internal B measurements from Hall array* yield local $J_\phi(R,t)$**
  - Map to $\psi_N$ only approximate

- Current gradient scale length reduced in H-mode

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Local Helicity Injection Startup Compatible with Consequent High-Quality OH H-mode

- High-\( I_p \), long-pulse H-mode plasmas desirable for PEGASUS goals
  - Confinement and edge stability studies; attaining high \( \beta_T \) regime

- \( V \)-s savings provided by LHI support H-mode research
  - \( I_p > 150 \) kA, limited and diverted; highest H-mode \( I_p \) to date
  - No fundamental obstacle to H-mode access from LHI physics

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*: Battaglia et al., Nucl. Fusion 51, 073029 (2011)
Divertor Coils Activated to Access Standard Separatrix-Limited H-modes

Non-diverted: Centerstack Limited

Diverted: Separatrix Limited

- Initial results show no significant difference between topologies

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Two Distinct ELM Types Observed in H-mode

- Conventional identification complicated by lack of $P_{aux}$ and modest pulse length
  - Large, Type I-like ELMs are infrequent and violent
    - Can cause H-L back-transition
    - Occur at high $P_{OH}$
  - Small, Type III-like more ubiquitous, less perturbing
    - Occur at lower $P_{OH}$

- Temporally coincident with $D_{\alpha}$ bursts

- Standard filamentary structures observed during ELM crash

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ELMs Have Distinct Magnetic Signatures

- High-n Mirnov coil array placed at edge
  - Resolves $n < 20$ without phase wrapping
- $n$ spectra imply different MHD modes at play
  - $n$ manifold used to tentatively classify ELMs

Large "Type I:" Peeling-Ballooning?

Small "Type III:" Peeling-like?
PEGASUS ELM Spectra Similar to NSTX

- **PEGASUS**: ELM types have distinct $n$
  - Large (“Type I”): intermediate $5 < n < 15$
  - Small (“Type III”): low $n \leq 3$

- Similar $n$ ranges reported for NSTX*
  - Type I: intermediate $5 \leq n \leq 8$
  - Type III: low $n \leq 3$

- Differences in machines’ ELM toroidal mode spectra attributable to $A$ effects?
  - Conventional AT Type I ELMs at higher $n$**
    - But, at low $\nu^*$ ($\rightarrow$ higher $J_{BS}$) $n$ can fall
  - ST’s naturally provide strong peeling drive
    - Toroidal field utilization $I_p/I_{TF} \sim J_{\parallel}/B$

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* Maingi et al., Nuclear Fusion 45, 1066 (2005)
**: Example: Perez et al., Nuclear Fusion 44, 609 (2004)
Disruptive Type I ELM Occurs at High Input Power

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- Large Type I ELM after quiescent period
  - Large ELM induces back-transition, terminates discharge
  - Similar to large tokamaks with auxiliary heating

Spiraling heat deposition on lower divertor plate from large ELM

• Magnetic signature of ELMs have multiple n components
  – Simultaneously unstable modes

• Example: Large ELM signature
  – Immediately prior to $D_\alpha$ rise

• Bandpass-filtered Mirnov components: different growth rates present
  – Timescale: $< 10$’s $\mu$s
  – Dominant $n = 8$ grows continuously
  – $n = 6$ component grows and decays prior to crash

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Type III J$_{\text{edge}}$ ELM Dynamics Measured

- $J(R,t)$ profiles measured throughout single Type III small ELM
  - $n = 1$ precursor

- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in PEGASUS

- Rapid recovery of H-mode pedestal

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Type I $J_{\text{edge}}$ ELM Dynamics Measured

- $J(R,t)$ profiles resolved throughout single Type I ELM cycle
  - No clear EM precursor

- $J_{\text{edge}}$ builds to $\sim 2x$ pre-ELM value

- Crash phase resembles L-mode
  - Reduction in gradient scale length
  - Intermediate $n = 6 – 9$ MHD present

- Filament generation suggested
  - Post-ELM $J_{\text{edge}}$ attained by current-hole expulsion

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**J_{\text{edge}} Structure Reflected in B_{z} Measurements**

**Type I Peak**

**Type I Mid-Crash**

**Filament Expulsion**

**Graphs**

- Type I Peak: Graph showing $J_{\phi}$ [kA/m$^2$] vs. R [m] with data points and error bars.
- Type I Mid-Crash: Similar graph with data points and error bars, showing a transition phase.
- Filament Expulsion: Graph showing Hall $B_{z}$ [mT] vs. R [m], with data points and error bars, indicating filament expulsion.

**Data Points**

- Type I Peak: 65676, 24.3910 ms
- Type I Mid-Crash: 65676, 24.4080 ms
- Filament Expulsion: 65676, 24.4260 ms

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Type I ELM Filament Ejection Coincides with $J_{\text{edge}}$ Current-Hole Generation

- Outwardly-propagating filament observed with high-speed visible imaging in ELM crash

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Low-A Regime Provides Environment for Unique Tests of Edge Stability Theory

• Peeling mode characteristics consistent with theory
  – Onset, spatial structure, MHD virulence consistent with ideal MHD
  – Nonlinear dynamics: filament creation / propagation from $J_{\text{edge}}$ current-hole

• Ohmic H-mode routinely accessed at $A \rightarrow 1$
  – Standard features observed in limited and diverted topologies
  – Compatible with non-solenoidal local helicity injection startup

• Two ELM regimes identified with differing toroidal mode spectra
  – Large, Type I-like: intermediate $n$
  – Small, Type III-like: low $n$
  – Observations similar to NSTX results

• $J_{\text{edge}}$ dynamics measured throughout ELM crash
  – $J_{\text{edge}}$ pedestal present in H-mode
  – $J_{\text{edge}}(R,t)$ current-hole perturbations and current-carrying filament expulsion

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