Edge Stability Studies at High $\langle J_{\text{edge}}/B \rangle$
in the PEGASUS Toroidal Experiment


University of Wisconsin-Madison

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PEGASUS Toroidal Experiment
Outline

• Introduction

• Filamentary Edge Instabilities in PEGASUS: Peeling Modes

• Characterization of Filaments
  – High-speed imaging
  – Magnetic, electrostatic measurements

• Experimental Current Profile Constraint via Hall Probes

• Summary / Conclusions
**PEGASUS: A University Scale, Ultralow-A ST**

### Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>To Date</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>≤ 0.21</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6 – 12</td>
</tr>
<tr>
<td>ℓ_i</td>
<td>0.2 – 0.5</td>
</tr>
<tr>
<td>κ</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>τ_{shot} (s)</td>
<td>≤ 0.25</td>
</tr>
<tr>
<td>(β_t) (%)</td>
<td>≤ 25</td>
</tr>
<tr>
<td>P_{HHFW} (MW)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*M.W. Bongard, 15th ST Workshop, Madison, WI 10/09*
**PEGASUS: ELM-like Structures Observed**

- Filamentary, field-aligned structures
  - Found under conditions of high $j_{\text{edge}}/B$

- Unlike ELMs, L-Mode edge assumed
  - However, may be same instability

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**NSTX**

Maingi, Phys. Plasmas 13, 092510, 2006

**MAST**


Scannell, Plas. Phys. Controlled Fus. 49, 2007

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Two Distinct Filament Classes Observed

- **Peeling-like (a)**
  - EM signature: high m, low n
  - Coherent spatial structure
  - Filament rotation
  - Detachment, radial propagation

- **MHD Quiescent L-mode (b)**
  - No EM signature
  - Electrostatic turbulence: short-lived filaments observable when \( \tau_{\text{exp}} \leq 20 \, \mu s \)

- **Separated by n=1 internal tearing phase (c)**

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Candidate Instability: The Peeling Mode

- Peeling-balloonning theory is a proposed mechanism for ELMs
  - Localized MHD edge instability
- Ballooning
  - \( p' \) drive from H-mode pedestal
- Peeling
  - Edge current, current gradient drive

- Qualitative guide: analytic peeling stability criterion*

\[
2\sqrt{-D_I} = \sqrt{1 - 4D_M} > 1 + \frac{2}{2\pi q'} \int \frac{\mu_0 j_{||} B}{R^2 B_p^3} dl
\]

*Snyder, Phys. Plasmas 12, 056115, 2005; see also Hegna, Phys. Plasmas 3, 584, 1996

Near-unity A Maximizes Peeling Drive

<table>
<thead>
<tr>
<th>Device</th>
<th>$J_{\text{edge}} \text{ (MA/m}^2\text{)}$</th>
<th>$B_{\phi,0} \text{ (T)}$</th>
<th>$J_{\text{edge}}/B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEGASUS</td>
<td>$\sim 0.1 – 0.2$</td>
<td>0.1</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>DIII-D*</td>
<td>$1 – 2$</td>
<td>2</td>
<td>$0.5 – 1$</td>
</tr>
</tbody>
</table>

*: Thomas, Phys. Plasmas 12, 056123 2005

- **PEGASUS** operations at A $\rightarrow$ 1 lead to naturally high $j_{\text{edge}}/B$
  - Comparable to larger machines in H-mode

- However, *source* of peeling drive different
  - Large machines: H-mode $p' \rightarrow j_{BS}$
  - PEGASUS: Large $dI_p/dt \leq 50 \text{ MA/s}$ $\rightarrow$ transient skin current

- Low-A geometry enables ITER-relevant research

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Peeling-like Filaments Observed During Periods of High $<j_{\text{edge}}/B>$

- Spatially coherent
- High-m structure visible over majority of poloidal cross-section

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- Poloidal filamentary structures grow and decay simultaneously
- Mean lifetime ~ 55 μs

- Bulk filament rotation appears to be in ion diamagnetic drift direction

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Edge Perturbation Scale, Amplitude
Decrease with Increased B

\[ I_{TF} = 192 \, \text{kA} \]
\[ B_{\phi,0} \sim .15 \, \text{T} \]

\[ I_{TF} = 244 \, \text{kA} \]
\[ B_{\phi,0} \sim .20 \, \text{T} \]

\[ I_{TF} = 288 \, \text{kA} \]
\[ B_{\phi,0} \sim .23 \, \text{T} \]

- Modes more virulent at reduced \( B_\phi \)
  - \( \frac{dI_p}{dt} \), shape, \( V_\ell \), fueling held constant to identify B dependence

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Peeling Filaments Accelerate Radially

- Filaments detach from edge, propagate radially outboard

- Significant $a_r$ measured
  - $a_r = 2.8 \times 10^7$ m/s$^2$
  - $v_r$: 1 → 4 km/s over 60 μs

- MAST*: Type-I ELM filaments accelerate radially

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Peeling-like Filaments are Electromagnetic

- Magnetic, Langmuir probes placed at edge of plasma

- Coherent electromagnetic signature present in $I_p$ ramp
  - Anticorrelated with electrostatic LP fluctuation measurements

- No EM signature in MHD quiescent phase
  - Consistent with electrostatic L-mode turbulence

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• High-resolution magnetic probe array placed at edge ($R_a + 3$ cm)

• $n = 2$ mode helicity measured during $I_p$ ramp
  - $n < 5$ commonly present

• 20 kHz peak spectral power consistent with $O(50 \text{ } \mu\text{s})$ fast imaging results
• Peeling cross-power spectral peak vanishes rapidly from edge

• 2-point m identification: \( m \sim -36 \)
  - Approximate; need full magnetic geometry correction for accurate \( m \)
  - Consistent with reconstructed \( q_a \sim 18 \)

\[ n = 2 \text{ reference} \]
\[ 45418, 53.0 \text{ cm, 4 kHz BW} \]
\[ f_{\text{peak}} = 20 \text{ kHz; 18.5 - 19.5 ms} \]

\[ m \Delta \theta = -105.6^\circ \]
\[ m = \text{round}[(m \Delta \theta)/\Delta \theta] = -36 \]

P7; \( \Delta Z = 1 \text{ cm} \)
\[ \Delta \theta = 2.9^\circ, \Delta \phi = 7.8^\circ \]

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Stability Analysis Requires Local Measurements

- Utilization of experimental equilibria in stability analysis depends crucially on accuracy of reconstructions
  - E.g. Peeling-ballooning: edge $p(\psi), j(\psi)$ profiles

- **PEGASUS**: Operating conditions allow for direct measurement of internal $B_z$
  - New diagnostic capability provides strong experimental constraint on $j(\psi)$
In-situ Hall Probe Arrays Constrain J(\psi)

- Solid-state magnetic sensors afford an excellent means to sample B with good spatial and temporal resolution
  - \( V_H = I_c G_H B \sin \phi \), where \( G_H \) is primarily determined by sensor material
  - Very small size; O(mm)

- Deployed on several tokamaks:
  - TEXTOR*: ext. \( B_z \) fluctuations
  - HBT-EP**: \( dB_z/dt \), internal \( B_z \)
  - PEGASUS: Internal \( B_z \rightarrow j(\psi) \)

*: Đuran et al., Rev. Sci. Instrum. 73, 10, 3482, 2002
**: Liu et al., Rev. Sci. Instrum. 76, 093501, 2005
1st Generation Hall Probe Deployed

- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5mm center-center spacing
- C armor as low-Z PFC
- Slim profile minimizes plasma perturbation

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Initial Hall Probe Data Obtained

- Cross-calibration performed using existing Mirnov coils
  - Weak dependence on $G_H(T)$ observed

- Frequency response: $\leq 25$ kHz
  - Suitable for equilibrium reconstructions
HP Can Strongly Constrain $J(\psi)$

- **Strong constraint over full $\psi_N$ possible**
  - Constraint locations (●) can vary in time due to evolution of plasma over fixed spatial location of probes

- **Simple polynomial parameterization insufficient to represent full internal detail**
  - Additional parameterizations in development
Initial Internally Constrained Equilibrium

• 5-knot cubic spline parameterization using KFIT* Grad-Shafranov solver

\[ I_p \quad 157 \text{ kA} \]
\[ R_0 \quad .30 \text{ m} \]
\[ a \quad .24 \text{ m} \]
\[ A \quad 1.2 \]
\[ \kappa \quad 2.2 \]
\[ \ell_i \quad .25 \]
\[ \beta_p \quad .10 \]
\[ \beta_t \quad .02 \]
\[ q_0 \quad 6.1 \]
\[ q_{95} \quad 17 \]

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Filament Appearance Consistent with Peeling Stability Criterion

- Connor’s peeling stability criterion computed from initial equilibria
  - KFIT spline fits coupled to DCON

- Peeling appears unstable at all times
  - Not observed; however, peeling phase is least stable of all phases

- Future: Rigorous comparison with peeling-ballooning theory
  - Numeric stability analysis of accurate j(ψ) equilibria via DCON, ELITE

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Summary

• Localized filamentary edge instabilities present in PEGASUS consistent with peeling drive
  – Triggered during conditions of naturally high $<j_{edge}/B>$
  – Electromagnetic signature with low n, high m
  – Nonlinear phase: radial propagation, acceleration

• Low-A, modest plasma parameters of PEGASUS afford unique laboratory to confront key ELM-relevant physics

• Measurement capabilities deployed to directly constrain $j(\psi)$
  – Demonstrated capability to measure internal $B_z(R,t)$
  – Initial analysis with relatively smooth $j(\psi)_{edge}$ model: strongest peeling drive when observed in experiment
  – Improvements to equilibrium parameterization and coupling to DCON, ELITE will provide more rigorous comparison with peeling theory