Edge Current Profile Measurements of Peeling-like Modes at High $J_{\text{edge}}/B$ in PEGASUS


51st Annual APS-DPP
Atlanta, GA
November 3, 2009
• University-scale, Low-A ST
  – $R_0 \leq 0.45 \text{ m}, a \sim 0.40 \text{ m}$

• Physics of High $I_p/I_{TF}$
  – Expand operating space of the ST
  – Study high $\beta_t$ plasmas as $A \to 1$
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• Non-Solenoidal Startup
  – Point Source DC Helicity Injection (“Plasma Guns”)
  – Addressing critical ST physics of plasma initiation, growth

\[ I_p, I_{inj} (\text{kA}) \]
\[ \text{ms} \]

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• Edge Stability Physics
  – Peeling modes at high $\langle j_{edge}/B \rangle$
**PEGASUS: ELM-like Structures Observed**

- ELMs take form of filamentary, field-aligned structures
  - Peeling-ballooning theory: trigger mechanism

- **PEGASUS**: L-mode edge assumed
  - Peeling instability candidate mechanism

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Snyder, Phys. Plasmas 12, 056115, 2005;  
see also Hegna, Phys. Plasmas 3, 584, 1996
Near-unity A: Naturally Strong Peeling Drive

\[ \sqrt{1 - 4D_M} > 1 + \frac{2}{2\pi q'} \int \frac{\mu_0 j_\parallel B}{R^2 B_p^3} \, dl \sim \frac{Rq}{s} \left( \frac{\mu_0 j_\parallel}{B} \right) \]


- \( j_{\text{edge}}/B \) is a figure of merit for quantifying peeling drive

- 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
Near-unity A: Naturally Strong Peeling Drive

<table>
<thead>
<tr>
<th>Device</th>
<th>$J_{\text{edge}}$ (MA/m$^2$)</th>
<th>$B_{\phi,0}$ (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

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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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Peeling-like 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 $\rightarrow$ 4 km/s over 60 $\mu$s

- MAST*: Type-I ELM filaments accelerate radially


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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
Peeling-like Filaments Are Low-n, High-m

- 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 $O(50 \mu s)$ fast imaging results

- 2-point $m$ ID: $m \sim -36$
  - Consistent with reconstructed $q_a \sim 18$

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• Diagnostic Capability: $B_z(R,t)$
  – 16 Sypris SH-410 Hall detectors
  – 7.5 mm channel spacing
  – C armor: Low-Z PFC

• Good Temporal Resolution
  – Frequency response: $\leq 25$ kHz

• Negligible plasma perturbation

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Hall Probes Constrain $J(\psi)$

- Strong constraint over full $\psi_N$ possible
  - Constraint locations vary in time due to evolution of plasma over fixed location of probes

- Polynomial parameterization inadequate to accurately fit internal data
  - Additional parameterizations in development

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Improving Models to Determine $J_{\text{edge}}(\psi)$

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

*Sontag, A, Nuclear Fusion, 48, 095006, 2008

- $I_p = 157 \text{ kA}$
- $R_0 = 0.30 \text{ m}$
- $a = 0.24 \text{ m}$
- $A = 1.2$
- $\kappa = 2.2$
- $\ell_i = 0.25$
- $\beta_p = 0.10$
- $\beta_t = 0.02$
- $q_0 = 6.1$
- $q_{95} = 17$

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Filament Appearance Consistent with Peeling Stability Criterion

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

- Peeling calculated unstable at all times (not observed)
  - However, peeling phase is least stable of all phases

- Future: Detailed comparison with peeling-ballooning theory
  - Stability analysis via DCON, ELITE

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Summary

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

• Measurement capabilities deployed to directly constrain $j(\psi)$
  – Demonstrated capability to measure internal $B_z(R,t)$
  – Initial analysis with relatively smooth $j(\psi)_{\text{edge}}$ 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
See Also

*Later This Session:*
- A.J. Redd, JO4.00012
  - Point-source helicity injection for ST plasma startup in PEGASUS

*Poster Session PP8, Wednesday PM:*
- R.J. Fonck, PP8.00085
  - The PEGASUS Toroidal Experiment Program
- D.J. Schlossberg, PP8.00086
  - Non-solenoidal startup and low-\(\beta\) operations in PEGASUS
- E.T. Hinson, PP8.00087
  - Edge current and pressure measurements of plasma equilibrium and stability properties in PEGASUS

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