Equilibrium and Stability Properties of Pegasus Edge Plasmas

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ELM-like filamentary edge instabilities are observed under conditions of high $j_{\parallel}/B \geq 1$ MA/m$^2$T) in Pegasus. Their properties include: a high-$m$, low-$n$ (1-5) electromagnetic signature, consistent with $m/n \approx q_a$; characteristic frequencies $< 100$ kHz; high poloidal coherence; rotation; and, explosive filament detachment followed by accelerating outboard radial propagation. Presently, these modes’ dependence on the peeling instability parameter $j_{\parallel}/B$ is being systematically studied through variation of $dI_p/dt$ and $I_{TF}$. To date, all data indicate these instabilities lie in the peeling regime. The modest edge $T_e$ and short pulse lengths of Pegasus afford direct diagnostic access to the edge via internal magnetic and Langmuir probe measurements. A novel edge probe utilizing a radial array of Hall-effect sensors* measures $B_z(R, t)$ with high spatial and $\sim 50$ μs temporal resolution, and provides strong experimental constraint on equilibrium reconstructions on ELM-relevant timescales. Initial magnetic equilibrium reconstructions and ideal stability analysis with DCON imply instability when edge filamentation occurs.


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Overview and Motivation

- Edge stability critical to next-step devices
  - Edge localized mode (ELM) heat loads will damage plasma facing components
  - Validation of ELM physics necessary to devise effective mitigation techniques

- PEGASUS: ELM-like instabilities consistent with peeling modes
  - Edge localized, filamentary, field-aligned perturbations
  - High poloidal coherence
  - Intermediate n, high-m electromagnetic signature
  - Filament detachment, accelerating outboard radial propagation

- Systematic study conducted with respect to edge peeling drive
  - New edge current profile diagnostics measure $J_{\text{edge}}$ dynamics
**PEGASUS: A Mid-Size, 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>≤ .22</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6 – 12</td>
</tr>
<tr>
<td>ℓ_i (MA/m-T)</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>≤ 0.025</td>
</tr>
<tr>
<td>β_l (%)</td>
<td>≤ 25</td>
</tr>
<tr>
<td>P_HHFW (MW)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Diagram Illustration**

- Equilibrium Field Coils
- High-stress Ohmic heating solenoid
- Vacuum Vessel
- RF Heating Antenna
- Toroidal Field Coils
- Ohmic Trim Coils
- Plasma Limiters

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ELM-like Structures Observed in PEGASUS

- ELM bursts take form of field-aligned filaments
  - Transient degradation of H-mode pedestal
  - Peeling-ballooning theory: trigger mechanism

PEGASUS

PEGASUS: L-mode edge assumed

- Peeling instability candidate mechanism

NSTX

MAST

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Candidate Instability: The Peeling Mode

- Peeling-balloonong theory is a proposed mechanism for ELMs
  - Localized MHD edge instability
  \[ \propto \frac{q R j_\|}{B} \]

- Ballooning
  - \( p' \) drive from H-mode pedestal

- Peeling
  - Edge current, current gradient drive

- Qualitative guide: analytic peeling stability criterion*

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

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

Improved $J_{\text{edge}}$ Measurements Desirable

- $p(\psi)$ typically constrained via multichannel Thomson Scattering
  - PEGASUS system under design; see Schlossberg, CP9.00071

- Edge $J(\psi)$ equally important to validate theory*; rarely measured
  - Extremely challenging measurement on high-temperature ATs
  - Results to date: DIII-D Li beam polarimetry**

- Typical alternative: compute $J$
  - Calculates $J_{\text{BS}}$ given experimental $p(\Psi)$
  - Questionable assumptions in edge

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*: Maggi, Nucl. Fusion 50, 066001, 2010
**: Thomas, Phys. Plasmas 12, 056123, 2005

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Near-unity A Enhances Peeling Drive

<table>
<thead>
<tr>
<th>Device</th>
<th>$J_{\text{edge}}$ (MA/m$^2$)</th>
<th>$B_{\varphi,0}$ (T)</th>
<th>$J_{\text{edge}}/B$</th>
<th>$R_0$ (m)</th>
<th>$q_{95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEGASUS</td>
<td>~ 0.1 – 0.2</td>
<td>0.1</td>
<td>~ 1</td>
<td>~ 0.45</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>DIII-D</td>
<td>1 – 2*</td>
<td>2</td>
<td>0.5 – 1</td>
<td>~ 1.50</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

*: Thomas, Phys. Plasmas 12, 056123 2005

- **PEGASUS** operations at $A \rightarrow 1$ lead to naturally high $J_{\text{edge}}/B$

- However, *source of $J_{\text{edge}}$ differs*
  - Large machines: H-mode $p' \rightarrow J_{\text{BS}}$
  - PEGASUS: Large $dI_p/dt$ ($\leq 50$ MA/s) $\rightarrow$ transient skin current

- **Additional geometric effects**: modest drive from $R_{q_{a}}$ possible
  - Increased edge shear competes with this effect

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Two Distinct Filament Classes Observed

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

- **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)**
Peeling 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 interpretation of electrostatic L-mode turbulence

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Peeling Filaments Accelerate Radially

- Filaments detach from edge, propagate radially outboard

- Significant $a_r$ measured
  - $a_r = 2.8 \times 10^7 \text{ m/s}^2$
  - $v_r$: 1 $\rightarrow$ 4 km/s over 60 $\mu$s

- MAST*: Type-I ELM filaments accelerate radially


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• **PEGASUS edge**, SOL compatible with probes
  - Low $T_e$, short $\tau_{\text{pulse}}$
  - Locations variable on shot-to-shot basis

• **External Probes**
  - Single-point Mirnov
    - $dB_r/dt$, $dB_z/dt$
  - Toroidal $B_z$ array
    - Int. to high-$n$

• **Internal Probes**
  - Hall Probe
    - $B_z(R, t) \rightarrow J(R, t)$
  - Langmuir Probes
    - $n_e, T_e \rightarrow p_e$
J Determined by $B(R, t)$

- Internal $B$ constrains $J$ through Ampere's law: \( \frac{1}{\mu_0} \nabla \times B = J \)
  - Requires spatially localized measurements
  - Edge stability theory validation demands time resolution $\sim \tau_{ELM} \leq 100 \, \mu s$

- $J(\psi)$ must be obtained through equilibrium reconstruction

- Successful approaches to measuring $J(R,t)$ employ $B_p(R,t)$
  - Beam-based methods: Localized, but poor- to moderate time resolution
    - Motional Stark Effect spectroscopy: core $J$
    - Li beam polarimetry: edge $J$
  - Faraday rotation polarimetry: good time response, but chordal
  - Direct probes: Localized, good time response, but incompatible with high $T$ plasmas
Hall Arrays Provide Local B(t) in Tokamaks

- **TEXTOR**
  - External B$_R$, B$_z$ fluctuations

- **HBT-EP**
  - dB$_z$/dt, internal B$_z$

- **CASTOR**
  - External B$_z$ → plasma position

- **PEGASUS**
  - Internal B$_z$ → J(R), J(ψ)


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PEGASUS Hall Probe Deployed

- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5 mm radial resolution
- Slim C armor as low-Z PFC
  - Minimizes plasma perturbation
- 25 kHz bandwidth

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• High spatial, good temporal resolution
  – Sensor size: few mm
  – Bandwidth ~ 10–30 kHz

• Simple operation
  – Control current $I_c \sim \text{mA}$

• Provides $V_H = G_H I_c B_\perp$
  – $G_H$ combines all Hall physics effects; determined by calibration

• Weak variance in $G_H$ possible
  – Hall semiconductor, $T_{\text{sensor}}$, $B_{\parallel}$
  – Calibration corrects these effects

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Initial Tests Yield Precision $B_z$ Measurements

- Internal probing yields no measurable plasma perturbation, according to:
  - $I_p$ evolution / sustaining $V_{\text{loop}}$
  - Achieved shape ($\ell_i$ evolution)
  - SPRED impurity spectroscopy

- Compares favorably with external Mirnov coils
  - $n = 1$ MHD well-resolved

- Full array yields spatially resolved $B_z(R,t)$
\( \mu_0 J_\phi = (\nabla \times \mathbf{B})_\phi = \frac{\partial B_R}{\partial Z} - \frac{\partial B_Z}{\partial R} \)

- 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 \( J(R) \)

*: Petty, et al., Nucl. Fusion 42, 1124, 2002
Application to J(R) in PEGASUS

• Computational method:
  – Obtain Hall Probe $B_z(R,t)$
  – Construct interpolated $B_z(R)$ with smoothing spline*
  – Compute $dB_z/dR$ from spline
  – Compute $J_\phi(R,t)$ given geometry

• $J(R,t)$ show features of $I_p$, MHD evolution

• Radial span extendible with multi-shot averaging
  – Requires mild time averaging; MHD is out-of-phase in general

*: Reinsch, C., Numerische Mathematik 10, 177, 1967
Peeling Instability Drive Scan Conducted

- Peeling drive varied systematically in $I_p$ ramp
  - Shape well-matched

- Experimental proxies:
  - $\frac{dI_p}{dt} \sim J_{\text{edge}}$; $I_{\text{TF}} \sim B$

- Uniform edge diagnosis
  - Hall, edge magnetic probes
  - 27 kHz fast imaging

- 11 combinations $\frac{dI_p}{dt}$, $I_{\text{TF}}$
  - $I_{\text{TF}} = \{144, 192, 240, 288\}$ kA
  - $\frac{dI_p}{dt} = \{30, 15, 10\}$ MA/s

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Peeling Instability Mitigated via Lower Drive

- High-n Toroidal Probe Array used to characterize filament EM signature
- Observed dB/dt signal onset concurrent with edge filament detachment
- Peeling suppression achieved at lowest dI_p/dt
- Mitigation effectiveness increases with reduced J/B
  - Reduced virulence; delayed onset

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J(R) Structure Strongly Influenced by $\frac{dl_p}{dt}$

- Data supports hypothesis of skin current drive

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Diagnosis of Peeling EM Signatures

- High-m, low-n EM signature found in peeling phase

- n determined by standard cross-phase analysis

- High-m found in dedicated experiments with high-n probe array and a poloidally separated probe
  - Case shown: $m \approx -29 \pm 3$

- Data set used to benchmark new m estimation technique
m Also Approximated via Radial Decay Rate

\[ |m| \approx -\frac{\log A_2/A_1}{\log R_2/R_1} = -2\frac{\log \hat{P}_2/\hat{P}_1}{\log R_2/R_1} \]

for fluctuation amplitudes \(A\), power spectral density \(P_{1,2}(f)\) at \(R_{surf} < R_1 < R_2\)

- MHD vacuum perturbation amplitude decays with \(R\), \(m^*\)
  - Approximately as \((R-R_{surf})^{-|m|}\)

- High-n probe array has two coils separated purely by \(R\)

- Power spectral density ratio allows course estimation of \(m\)
  - This case: \(m \approx 25 \pm 2\) at 20 kHz

- Technique allows estimation of \(m\) with probe array alone

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*: Wesson, Tokamaks, 3rd Ed., 6.7
Filament MHD Has Peeling Characteristics

- Toroidal mode analysis, m estimation performed on peeling signatures from \( \frac{dl_p}{dt} \), \( I_{TF} \) scan
  - Low \( n \), high \( m \) observed
    - \( n < 3 \); 1–2 typical
    - \( m \geq 10 \) for most modes
  - \( m/n \sim q_a \), implying edge localization

- Fluctuation power strongly increases with \( J/B \)

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J \text{edge} Dynamics Resolved on ELM Timescales

- J(R) evolution tracked over filament burst
- Filament carries $|J_{\text{edge}}|$ prior to instability outward
- Outboard $\delta J$ acceleration, radial localization

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Edge Dynamics Consistent with ELM models

• Tracking $J_{\text{max}}(R,t)$ allows determination of filament velocity, acceleration

• This particular filament has
  – $v_{r,0} \sim 600 \text{ m/s}$, $a_r \sim 1.7 \times 10^7 \text{ m/s}^2$
  – Fast imaging results comparable

• Filament / Hole creation, propagation qualitatively consistent with ELM dynamics models*
  – Current-carrying ELM filaments repelled by magnetostatic forces

Equilibrium and Stability Analysis

- Equilibrium analysis of peeling unstable shots is challenging

- Peeling instability when wall currents dominate internal B(R,Z)
  - Peeling unstable $I_p \sim 50$–$80 \text{ kA} < \sum I_{\text{wall}} \sim 150 \text{ kA}$
  - Typical PEGASUS reconstructions attained when $I_p \geq \sum I_{\text{wall}}$

- Wall modeling and equilibrium code improvements underway
  - Recalibration of wall resistance distribution
  - Exploring minimization of weighted $\chi^2$ functional to emphasize Hall data
  - Applying direct $J_\varphi(R)$ estimates as experimental fit constraint

- Due to low-$n$ nature of observed modes, ideal stability analysis with DCON is appropriate means to test theory
  - If future experiments find intermediate $n > 5$, ELITE becomes applicable
Future Investigative Directions

• Equilibrium, stability studies with internal profile constraints
  – Hall Probe for $J(\psi)$
  – Thomson Scattering for $p(\psi)$
  – Enhancements to KFIT to accommodate diagnostic capabilities

• Investigation of $J(R, t)$ in non-inductively produced plasmas

• Planned machine upgrades to enable diverted operations, feedback control
  – Affords investigation of shear effects on edge stability
  – Possibility of H-mode access
Summary

• Edge instabilities in PEGASUS consistent with peeling modes
  – Present under conditions of naturally high $J_{\text{edge}}/B$ as $A \to 1$
  – Low-n, high-m electromagnetic signature with $m/n \sim q_a$
  – Edge detachment, radial outboard acceleration
  – MHD virulence correlated with peeling drive

• New Hall probe allows diagnosis of $J_{\text{edge}}$ dynamics
  – Precision, internal $B_z(R,t)$ obtained without plasma perturbation
  – Radially accelerating filaments qualitatively consistent with ELM model

• Peeling stability to be evaluated with DCON as reliable edge reconstructions are obtained
  – Present challenge: accurate reconstruction in presence of large wall currents
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http://pegasus.ep.wisc.edu/Technical_Reports