Probe Measurements in the H-mode Pedestal Region in the Pegasus Toroidal Experiment

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Title Banner

Introduction

Pegasus Toroidal Experiment

Pegasus Power Threshold Predictions

Ohmic H-Mode in Pegasus

Impurity Measurements in Edge Transport Barrier

Energy Confinement Improves in H-Mode

Pegasus has the ability to produce current and pressure pedestal

P_{LH} dependence upon Aspect Ratio

Theory needed to Mitigate ELMs

Pegasus Hall Probe Deployed

J (R,t) calculated from Ampere’s Law

Direct J Profiles obtained in Pegasus

Langmuir Probe Design

Noise Shielding in Pegasus

Simplified LP Circuit/Grounding Scheme

Current Pedestal using Hall Probe Array

Large Type I and II ELMs observed

Hall Probe Observes Large ELM dynamics through discharge

Smoothing of raw LP signal required

Pressure correlation with MHD fluctuations

Pressure profiles suggest existence of edge pedestal

Future experiments with low MHD are needed

Closer Inspection of J_edge reveals complex behavior

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Introduction

- H-mode is the presumed operating regime of ITER.

- An edge transport barrier is formed in H-mode. This barrier drives the ELM instability.

- No first-principles model currently exists for H-mode or ELMs. Thus, understanding the H-mode plasma edge is crucial to developing a model.

- A current pedestal is routinely measured on Pegasus using a Hall Probe.

- A Triple Langmuir Probe was implemented on Pegasus in order to investigate the feasibility of an edge profile measurement.
PEGASUS is a Compact, Ultralow-A ST

**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.15 – 1.3</td>
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<tr>
<td>R(m)</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤ 0.25</td>
</tr>
<tr>
<td>K</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>Δτ_{shot} (s)</td>
<td>≤ 0.025</td>
</tr>
<tr>
<td>β_t (%)</td>
<td>≤ 25</td>
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</tbody>
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**Major research thrusts:**

- Tokamak physics at small aspect ratio
- Non-inductive startup and growth
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\(^1\)

\(^1\)Maggi, Nucl. Fusion 50, 066001 (2010)
H-mode Readily Accessible at Near-Unity $A$

- H-mode accessed when $P_{OH} > P_{LH}$

- $P_{LH}$ scalings strongly depend on $B_T$
  \[ P_{LH} \sim n_e^{0.7} B_T^{0.7} S \]
  - Low $A$, $B_T$: $P_{LH}$ is low

- Magnetic profile similar in limited and diverted at $A \approx 1$
  - Edge shear equivalent between limited and diverted

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1 Nucl. Fus., 47, S82 (2007)


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Ohmic H-mode Plasmas have Standard Signatures

- H-mode achieved via HFS fueling
- Quiescent edge
- Reduced $D_\alpha$, Increased $\nabla D_\alpha$
- Large and small ELMs
- Bifurcation in $\phi_D$
  - Transport equilibrium not attained
• Impurity $T_i(0)$ doubles
  – CV only seen in core H-mode plasmas
  – Transport equilibrium not attained

• Chordally-integrated velocity profiles show increased shear in the outer region in H-mode
  – Indirect evidence of $E_r$ well
Energy Confinement Improves in H-mode

- $\tau_e$ from time-evolving magnetic reconstructions

- L-mode: $\tau_e \sim 1.5$ ms, $H_{98} \sim 0.5$

- H-mode: $\tau_e \sim 3$ ms, $H_{98} > 1$
  - Due to short pulse — not in transport equilibrium

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$P_{LH}$ Increasingly Diverges from Expectations as $A \to 1$

- $P_{LH}$ studied by varying $P_{OH}$, $n_e$
  - $n_e$ dependence observed
  - Near-diverted $P_{LH}$ similar to limited

- $P_{LH}/P_{ITPA08} \approx 10$

- $P_{LH}/P_{ITPA08}$ continues to increase as $A \to 1$
  - Similar to dependence with $q_{edge}$, $\beta_T$

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• **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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$J_\phi(R,t)$ Calculable Directly from Ampère’s Law

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

- Simplest test follows from $B_R(Z)$ or $B_Z(R)$ measurements
- Petty$^1$ 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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• Straightforward J estimation
  – Obtain Hall Probe $B_z(R,t)$
  – Compute $dB_z/dR$ using interpolated smoothing spline\(^1\)
  – 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

\(^1\)Reinsch, Numerische Mathematik 10, 177 (1967)

Current Pedestal Measured with High Time and Space Resolution

- Short pulse, low T\textsubscript{e} allow detailed J\textsubscript{edge} and p\textsubscript{edge} profiles
  - J\textsubscript{\phi}(R,t) from Hall Probe B\textsubscript{z} measurements\textsuperscript{1,2}
  - p(R,t) will be obtained with Langmuir probes

- Clear current pedestal observed
  - H scale length \sim 2 cm
  - L scale length \sim 4 cm

• STs magnetic structure opposite of ATs
  – Large (“Type I”): intermediate-n
    • Infrequent, violent, $P_{OH} \gg P_{LH}$
  – Small (“Type III”): low-n
    • common, less perturbing, $P_{OH} \sim P_{LH}$

• Precursors grow on MHD times (10’s μs)
  – Simultaneously unstable modes
  – Dominant $n = 8$ grows continuously
  – Non-dominant components fluctuate prior to crash
Large ELM $J_{\text{edge}}(R,t)$ Dynamics Measured Throughout Single ELM Cycle

- Complex $J_{\text{edge}}(R,t)$ evolution
  1) Modest but steep pedestal
  2) Rapid buildup until crash
  3) Collapse with wider pedestal gradient
  4) Current-hole filament ejection
  5) Recovery: lower than pre-ELM pedestal

- $J_{\text{edge}}(R,t)$ evolution similar to that seen in JOREK MHD$^1$ simulations
  - Potential for unique simultaneous measurements of $J_{\text{edge}}(R,t)$ and $p_{\text{edge}}(R,t)$

Closer Inspection of $J_{\text{edge}}$ Reveals Complex Dynamic Behavior

- Current profile evolution through ELM cycle shows complex multimodal behavior

- Opportunities for detailed comparisons to nonlinear MHD simulations
  - E.g. NIMROD, JOREK, BOUT
Triple Langmuir Probe Design and Implementation

- Three 1mm W probe tips with 3 mm spacing
- Tips epoxied to PEEK spacer
- BN guide faces plasma
- Graphite shield covers leading 43 cm
- Circuit upgrade: initial bias set to 150 V, capable of 300V
- Arcus DMX-ETH 23 stepper motor for remote operation
Switching Power Supplies Require Proper Shielding Techniques

- **PEGASUS** diagnostics require careful shielding and isolation techniques
  - Triaxial shielding
  - Local differential line drivers
  - Optical triggering

- High bandwidth requires local signal processing / power supplies
  - 200V EMCO ULP05 DC-DC converter provides high voltage probe bias
  - Anti-aliasing board as well as optical triggering components are powered using a series of 9V batteries
Triple Probe Theory

- Bias voltage is manually set: \( V_B = V_H - V_L \)

\[
\frac{1 - \exp[e(\Phi_f - V_H)/k_B T_e]}{1 - \exp(-eV_B/k_B T_e)} = \frac{1}{2}
\]

- If \( eV_B \gg k_B T_e \)

\[
T_e[eV] = \frac{V_H - \Phi_f}{\ln 2}
\]

- Density is calculated from the ion saturation current

\[
I_{sat}^i = A_p n_e e \left( \frac{k_B T_e}{m_i} \right)^{1/2} \exp(-1/2)
\]

- With a small correction for impurities

\[
n_e = \frac{I_{sat}^i}{A_p e} \left( \frac{m_p}{k_B T_e} \right)^{1/2} \tilde{Z}^* \exp(1/2)
\]

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• Langmuir probe was inserted into a repeatable target discharge with $I_p \sim 140$ kA.

• Langmuir Probe was radially scanned from SOL (~70 cm) to top of the pedestal (~58 cm).

• Insertion of the Langmuir Probe was limited by flaring at the probe tips.
Smoothing Techniques used to Filter Raw LP Signals

- Initial measurements have high frequency signal variation.
  - Due to edge turbulence and effects of MHD/edge deflection

- A 10 kHz Gaussian smoothing eliminated high frequency characteristics, while maintaining the measurement integrity.
$p_e(R,t)$ Shows a Strong Correlation to MHD Fluctuations

- A phase relationship exists between the $p_e$ signal and the MHD activity.

- The drop in Mirnov signal represents a plasma edge growth, while the rise represents a plasma edge shrinkage.

- This MHD activity creates fluctuations in the $p_e (R,t)$ profile and distorts the pedestal measurements.
Analysis Suggests Evidence of Pedestal Structure in the Pressure Profile

- $p_e$ profiles at maximum $I_p$ ($t = 26-27\text{ms}$)
- Average of the total $p_e$ signal
- Average of the $p_{e,\text{baseline}}$ signal
  - Mitigate effects of MHD-induced movement

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• Probe measurements represent a feasible strategy to support edge pedestal investigations.

• Magnetic Hall Probe provides a detailed evolution of $J_{\text{edge}}$

• Eliminated ubiquitous switching noise in LP signals.

• Initial Langmuir Probe scans suggest a pressure pedestal in the edge region of H-Mode discharges.

• Future Work:
  – Employ LHI startup to provide MHD-quiescent Ohmic H-mode
  – Deploy a multiple triple probe array to complement the Hall Probe array
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http://pegasus.ep.wisc.edu/Technical_Reports

or via email gbudner@wisc.edu

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