H-mode and ELM Characteristics at Ultralow Aspect Ratio in the Pegasus Experiment

R.J. Fonck,
J.L. Barr, M.W. Bongard, D.M. Kriete, J. M. Perry, J.A. Reusch, and K.E. Thome (ORAU)

58th Annual APS-DPP Meeting
San Jose, CA
November 2, 2016
Pegasus ST at A~1 Facilitates AT Science Studies at Small Scale

- **Local Helicity Injection (LHI) for ST Startup**
  - Inject current streams in plasma edge

- **H-mode Physics at Ultralow-A**
  - H-mode and ELM characteristics

- **Access to high \( I_N > 10 \)**
  - Tokamak stability limits at A ~ 1

---

A

\( A \quad 1.15 \text{ – } 1.3 \)

R (m)

\( R \quad 0.2 \text{ – } 0.45 \)

\( I_p \text{ (MA)} \quad \leq 0.25 \)

\( B_T \text{ (T)} \quad < 0.2 \)

\( \Delta \tau_{\text{shot}} \text{ (s)} \quad \leq 0.025 \)
H-mode Readily Accessed at $A \sim 1$

**Limited L**

**Limited H**

*Fast visible imaging, $\Delta t \sim 30 \mu s$*

**Diverted H**

- Low $B_T$ at $A \sim 1$ -> low H-mode $P_{LH}$
  - $P_{OH} > > P_{IIPA08} \sim B_T^{0.80} n_e^{0.72} S^{0.94}$
  - Limited or Diverted topology

- **Standard H-mode features**
  - Quiescent edge
  - Reduced $H_\alpha$
  - Improved $\tau_E$
  - Some differences compared to high-$A$
H-mode: Pedestal Formation, Increased Confinement

- Short pulse, low $T_{e,\text{edge}}$

- **Simple probe access across pedestal**
  - $J_\phi$, $P$ pedestals in H-phase
    - $J_\phi(R,t)$: multichannel Hall probe
    - $p(R)$: triple Langmuir probe
  - Confinement increases 2x
    - Requires time-evolving reconstructions
    - L: $H_{98} \sim 0.5\pm0.2$
    - H: $H_{98} \sim 1.0\pm0.2$

---

Thome et al., Nucl. Fusion 57, 022018 (2017)
At Low A, $P_{LH} \gg P_{ITPA08}$

Multi-Machine $\frac{P_{LH}}{P_{ITPA08}}$ Comparison

1 Maingi et al., Nucl. Fusion 50, 064010 (2010)
\( P_{\text{LH}} \) Consistent with Global Scalings, but Low-A Differences

- Follows ITPA \( n_e \) scaling
  - FM\(^3\): \( \min n_e \sim 1 \times 10^{18} \text{ m}^{-3} \)

- Magnetic topology independence
  - Diverted, limited edge \( q(\psi) \) similar
  - FM\(^3\) model:
    \[
    (P_{\text{LH}}^{\text{LIM}}/P_{\text{LH}}^{\text{DIV}}) \sim (q_{\psi}^{\text{LIM}}/q_{\psi}^{\text{DIV}})^{-7/9} \sim 1
    \]

Normalized \( P_{\text{LH}} \) vs. Density

\[ P_{\text{OH}}/\left( B_T^{0.803} S_{0.941} \right) \text{ [MW/T.m\(^2\)]} \]

\( n_e [10^{20} \text{ m}^{-3}] \)

A \( \sim 1.2 \) Equilibria

\[ q, \psi_N, Z, R \text{ [m]} \]

Limited

Diverted

Fundamenski et al., Nucl. Fusion 52, 062003 (2012)
Local Helicity Injection Startup Compatible with Access to High-Quality Ohmic H-mode

- High-$I_p$, long-pulse H-mode plasmas desirable
  - Confinement, edge stability studies; attaining high $\beta_T$

- LHI creates tokamak plasmas via edge current drive
  - Taylor relaxation, helicity balance

- No fundamental obstacles to H-mode access from LHI physics

---

Battaglia et al., Nucl. Fusion 51, 073029 (2011)
Thome et al., Nucl. Fusion 57, 022018 (2017)
Validated, Predictive Theory Needed to Mitigate ELMs

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

- **Nonlinear extensions**
  - 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
ELMs create 3D filaments
- Coincident with $D_\alpha$ bursts

Small ("Type III"):
- Low-n, peeling-like
- Observed at $P_{OH} \sim P_{LH}$

Large ("Type I")
- Intermediate n
- Observed at $P_{OH} >> P_{LH}$
Nonlinear ELM Precursors Observable with Edge-Localized Mirnov Coil Array

- Simultaneously unstable $n$ during ELM
  - Detectable only within ~ cm of LCFS
  - Nonlinear energy exchange

- Modes grow on MHD timescales
  - $n = 8$ grows continuously
  - $n = 6$ fluctuates prior to crash

*Thome et al., Nucl. Fusion 57, 022018 (2017)*

Bandpass filtered dBz/dt (c), (e) and amplitudes (d), (f) of $n = 8$, $n = 6$ modes
ELM Magnetic Structure Varies with $A$

- Edge Mirnov array measures ELM toroidal mode spectrum
  - $n \leq 20$ resolved by multipoint cross-phase analyses

- Type III: $A$ dependent
  - Low $A \leq 1.4$: $n \leq 1 – 4$
    - PEGASUS, NSTX
  - Conventional $A \sim 3$: $n > 8$

- Type I: $A$ independent
  - Intermediate-$n$
  - Low-$A$ devices have lower $n$

- Increased peeling drive at low-$A$
  - Higher $J_{\text{edge}}/B \rightarrow$ lower $n$

Maingi et al., Nucl. Fusion 45, 1066 (2005); Kass et al., Nucl. Fusion 38, 111 (1998)
PEGASUS Hall Probe Provides $J_{\text{edge}}(R, t)$ on Alfvénic Timescales

- Precision $B_z(R, t)$ measurements
  - 16 solid-state InSb Hall sensors
  - 7.5 mm radial resolution
  - 75 kHz large-signal bandwidth
  - 175 kHz small-signal bandwidth
- Carbon Armored
  - Compatible with L, H-mode to date

- $J_\phi$ obtained directly via Ampère’s Law
  - Assumes local tokamak equilibrium
  - No profile parameterization constraint

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

Petty et al., Nucl. Fusion 42, 1124 (2002)
J_{\text{edge}} \quad \text{Structure Reflected in } B_z \quad \text{Measurements}

**Type I Peak**

- \( J_\phi \) [kA/m²] vs. \( R \) [m]

**Type I Mid-Crash**

- \( J_\phi \) [kA/m²] vs. \( R \) [m]

**Filament Expulsion**

- \( J_\phi \) [kA/m²] vs. \( R \) [m]

---

RJF APS-DPP 2016 - 13
Feature observed during ELMs and peeling modes

- Validates mechanism hypothesized by EM blob transport theory
- Type III ELM: smaller perturbation, slower, no filament evident
- Type I: larger, faster, filament expulsion

Thome et al., Nucl. Fusion 57, 022018 (2017)
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

Nearest Imaging Times; Prior Frame Subtracted

(a) 24.440 ms

(b) 24.512 ms
**Type I ELM** $J_{\text{edge}}(R,t)$ **Dynamics Measured Throughout Single ELM Event**

- **Challenge**: nonlinear ELM dynamics at Alfvénic timescales

- Current profile evolution through ELM cycle shows complex multimodal behavior
  - Less spatial smoothing employed in Hall probe analysis

- Opportunities for detailed comparison to nonlinear MHD simulations
  - *e.g.* NIMROD, JOREK, BOUT++

---


• LHI system affects edge plasma
  – $I_{\text{inj}} \leq 5$ kA, $J_{\text{inj}} \sim 1$ kA/cm$^2$
  – Strong 3D edge current perturbation
    • Similar to LHCD on EAST\(^1\)
  – Edge biasing; modify rotation

• $J_{\text{edge}}$ injection in H-mode suggests ELM suppression
  – Low $I_{\text{inj}}$ = ELM suppression
  – High $I_{\text{inj}}$ = edge, discharge degradation

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

**H-mode Physics with Pedestal Diagnostic Access**
- Standard features: J, p pedestals; low $D_\alpha$, increased $\tau_e$
- Strong $P_{\text{LH}}$ threshold dependence on A
- Insensitivity to magnetic topology

**ELM Regimes Identified with Differing n Spectra**
- Large, Type I-like: intermediate $n$
- Small, Type III-like: low $n$
- Strong peeling drive @ low A
- Simultaneous spectrum of $n$ present during crash

**Nonlinear ELM Dynamics on Alfvénic Timescales**
- Nonlinear energy exchange in $n$ modes prior to crash
- Fast $J_{\text{edge}}(R, t)$: current-hole perturbation, filament expulsion

**Helical Edge Current Injection Affects Type III ELMs**
- Potential dual use of LHI injectors as ELM control actuator

**Proposed Upgrades:**
- Pedestal physics, nonlinear ELM physics and mitigation
- Local Helicity Injection in NSTX-U relevant conditions
• Nonlinear pedestal and ELM studies
  – Simultaneous measurements of $p(R,t)$, $J(R,t)$, $v_\phi(R,t)$
    • New edge diagnostics (probe arrays, DNB)
  – Tests of Sauter neoclassical bootstrap model

• ELM Modification and Mitigation
  – Novel 3D-Magnetic Perturbations coil array
    • LFS array: 12 toroidal $\times$ 7 poloidal
    • Helically-wound HFS coils
  – LHI current injectors in divertor, LFS regions
Title

2 Pegasus ST …

5 At Low A…

9 A-1 Regime Well-Suited for…

12 Pegasus Hall Probe Provides $J_{edge}(R,t)$ on Alfvénic Timescales

3 H-mode …

6 PLH consistent…

10 Nonlinear ELM…

13 $J_{edge}$ Structure Reflected in $B_2$ Measurements

4 H-Mode: Pedestal…

7 Local Helicity…

11 ELM Magnetic Structure…

14 Current-Hole $J_{edge}$ Perturbation Accompanies Edge Instability

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

8 Validated, Predictive…

16 Type I ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Event

17 3D Edge Current…

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

19 Back: Pegasus U Supports Focused Physics Mission

US Letter 8.5 x 11”