Experiment Overview
Operation at $A \sim 1$ Offers Ready Access to Advanced Tokamak Physics

- Very low $B_t$ at modest $I_p = $ very low $P_{th}$ for H-mode access
  - High edge shear = separatrix not necessarily needed
  - Easy access with ohmic heating only
  - **BUT** need hot edge $\Rightarrow$ centerstack fueling

- Short connection lengths and very strong trapping = neoclassical effects at low $T_e$
  - High particle trapping fractions
  - Strongly non-Spitzer resistivity
  - Bootstrap current possible

- High $j_{\text{edge}}/B_t$ plus H-mode pedestal = Peeling mode and peeling-ballooning modes accessible

- With short pulse and low $<T_e>$, easy diagnostic accessibility
  - e.g., probes in pedestal region

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Pegasus is a Compact, Ultralow-A ST

**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.15 – 1.3</td>
<td>1.12 – 1.3</td>
</tr>
<tr>
<td>R(m)</td>
<td>0.2 – 0.45</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤ .23</td>
<td>≤ 0.30</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6 – 14</td>
<td>6 – 20</td>
</tr>
<tr>
<td>R_B (T-m)</td>
<td>≤ 0.06</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>κ</td>
<td>1.4 – 3.7</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>τ_shot (s)</td>
<td>≤ 0.025</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>β_t (%)</td>
<td>≤ 25</td>
<td>&gt; 40</td>
</tr>
</tbody>
</table>

Local Helicity Injectors

New Divertor Coils

Vacuum Vessel

Equilibrium Field Coils

High-stress Ohmic heating solenoid

Toroidal Field Coils

Ohmic Trim Coils

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Device Upgrades Support Expanded Helicity Injection, Edge Physics Studies

- **Helicity Injection Systems**
  - Injector material, design optimization: *reduced PMI*
  - Active fueling control
  - Multi-aperture injector array for high-$I_p$ startup

- **Power Supplies, Heating, Fueling**
  - New helicity injection power: $2.2 \text{ kV}, 14 \text{ kA supply}$
  - Centerstack fueling: *LHI fueling and H-mode access*

- **Expanded PF Coil Set and Control**
  - New PF coils, power systems: *vertical control*

- **Diagnostic Deployment and Improvements**
  - Multipoint Thomson Scattering
  - High-speed $T_i(R,t)$: *Anomalous reconnection heating*

- **New divertor coils → separatrix operation**
  - Exploit H-mode operating regime
  - Flux expansion to optimize LHI startup

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Characteristics

- In-vacuum piezoelectric valve
- $z = -30 \text{ cm}$
- Throughput 300-3000 Torr*L/s
- Stabilized with heat shielding
L→ H Power Threshold as A → 1
Power threshold required to enter H-mode

- Sufficient power must be applied to trigger a transition from L-mode to H-mode
  - Power can be provided by NBI, ECH, ICH, LH, OH
  - Also achieved by biasing the plasma using an external electrode or by biasing a limiter
  - $P_{\text{thres}}$ depends strongly on $n_e$, $B_{TF}$, and ion $\nabla B$ drift direction

- Nature of transition is still under investigation due to lack of first-principles model with predictive capability
  - E.g. predator-prey, flow shear
L-H Power threshold scaling from experiment data

- Recommended scaling from Progress on ITER Physics Basis (2007), high-A $P_{\text{thres}}$ scaling
  - This equation has 21.4% RMSE and no ST data
    \[
    P_{\text{PIP}} = 0.042 n_{20}^{0.73} B_{TF}^{0.74} S^{0.98}
    \]
    \[
    S = 4\pi^2 aR\left(\frac{1+\kappa^2}{2}\right)^2
    \]

- Earlier high-A scaling (ITPA, 2004)
  - MAST ($A \approx 1.45$) requires 1.6 x more power,
    NSTX ($A \approx 1.32$) requires 3.7 x more power
    \[
    P_{04} = 0.06 n_{20}^{0.7} B_{TF}^{0.7} S^{0.9}
    \]

- More complicated: $P_{\text{th}}$ has nonlinear dependence on $N_e$

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Different empirical scaling explicitly incorporates aspect ratio

\[ P_{\text{thr\_low-A}} = 0.072 n_{20}^{0.7} |B|_{\text{out}}^{0.7} S^{0.9} \left( \frac{Z_{\text{eff}}}{2} \right)^{0.7} F(A)^\gamma \]

\[ |B|_{\text{out}} = (B_{\text{in}}^2 + B_{\text{out}}^2)^{0.5}, \quad B_{\text{in}} = B_{TF} \frac{A}{A+1}, \quad B_{\text{out}} = \frac{\mu_0 I_p}{2\pi a} (1 + \varepsilon), \]

\[ F(A) = \frac{0.1A}{1 - \left( \frac{2}{1+A} \right)^{0.5}} \quad \text{and} \quad \gamma = 0.5 \pm 0.5 \]

- But this equation essentially has a 100% error bar on A, demonstrating more low-A data could be valuable


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L-H power threshold scalings: \( P_{th} \sim n_e B_T^{0.7} S \)
- At very low-A and hence low \( B_T \), \( P_{th} \) is very low
- Scalings\(^1\,\,2\) suggest PEGASUS \( P_{th} < 0.1 \) MW
- \( P_{OH} = 0.2–0.7 \) MW

Modest \( t_{\text{shot}} \) and \( <T_e> \) allow probes in pedestal

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</thead>
<tbody>
<tr>
<td>( B_T (T) )</td>
<td>0.08–0.16</td>
</tr>
<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>( \leq 0.21 )</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>1.4–3.7</td>
</tr>
<tr>
<td>( t_{\text{shot}} (s) )</td>
<td>( \leq 0.025 )</td>
</tr>
<tr>
<td>( T_e (eV) )</td>
<td>100–200</td>
</tr>
</tbody>
</table>

\(^1\) Accepted ITER design threshold \( P_{th} \): K. Ikeda, ” Nucl. Fus., 47, 2007.
\(^2\) \( P_{th} \) with low-A data: I. H. mode Power Threshold, Plasma Phys. Control. Fus., 46, 2004

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H-mode in Ohmic Plasmas
Ohmic H-mode Plasmas have Standard Signatures

- H-mode signatures observed:
  - Quiescent edge
  - Increased core $T_e, T_i$ inferred
  - Reduced $D_\alpha$
  - Large and small ELMs suggested
  - Bifurcation in $\phi_D$
  - Core $v_\phi$ reverses

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Fueling Location, Particularly in STs, is Critical for Achieving H-mode

- LFS and HFS fueling

- H-mode achieved using HFS fueling
  - Similar to MAST and NSTX\(^1\)
  - Both limited and diverted

Impurity Spectroscopy Suggests $T_i$ and $T_e$ Increase in H-mode Core Region

- Chord-integrated $T_i(t)$ increases in H-phase
- Appearance of CV in H-phase only indicates increased $T_e(0,t)$

- CV not present in L-mode discharges
  - CV I.P. = 392 eV
  - OV I.P. = 113 eV

- CV intensity is centrally peaked

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Increased $I_i$ Indicated by Rise in Paramagnetism at L-H Transition

- Rise in diamagnetic flux loop signal indicates rise in paramagnetism at $A \sim 1$
  - Not a rise in total stored energy
  - Magnetic reconstructions confirm increased $I_i$ in H-phase
    - $H: I_i \sim 0.45; \ L: I_i \sim 0.35$

- At constant $I_p$, $V_{loop}$, this suggests localized core plasma heating
  - Supported by indication of $T_e(0)$ increase

Model Equilibrium

\[ J_{tor}(R) \text{ vs } I_i \]

\[ \Phi_D \text{ vs time (ms)} \]
$P_{th}$ and $J_{\text{edge}}(R)$ Pedestal
\( P_{th} \) Measured using \( V_{\text{loop}} \) Scans

- Infer \( t_{\text{LH}} \) from bifurcation in \( \phi_D \)
  - Vary \( P_{OH} = I_p \cdot V_{\text{loop}} \)
  - Constant \( I_{\text{EF}}, \) shape, fueling

- \( P_{th} \approx 0.25\text{–}0.30 \text{ MW} \)
  - Scalings predict \( < 0.1 \text{ MW} \)
PEGASUS Hall Probe Deployed to Measure J

- 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

\( J_\phi(R,t) \) 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* 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 \( J(R) \)

• Internal $B_z$ measurement from Hall probe array yield local $J_\phi(R,t)^1$

• Current gradient scale length significantly reduced in H-mode
  - $L \rightarrow H$: 6 → 2 cm
  - $\rho_i \approx 1.8$ cm

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$^1$ M. Bongard, Rev. Sci. Instrum. 81, 10E105 (2010).

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General Observations
Large and Small ELMs Suggestive of Type I and III ELMs are Seen

- Filament structures observed
  - Large ELMs infrequent and violent
    - Can cause H-L back-transition
    - Occur at high $P_{OH}$
  - Small ELMs more ubiquitous and less perturbing
    - Occur at lower $P_{OH}$

- $n$ measured with close-fitting coil array through ELM crash
  - PEGASUS results similar to NSTX
    - Large (“Type I”): intermediate-$n$
    - Small (“Type III”): low-$n$
  - STs appear to have structure opposite that of ATs

Coherent filaments associated with ELMs

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Divertor Coils Activated to Access Standard Separatrix-Limited H-modes

- Initial results: no clear difference between diverted and non-diverted
- But, short pulse length complicates $\tau_E$ measurement

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High-$I_p$, long-pulse H-mode plasmas desirable for Pegasus goals

- Confinement and edge stability studies
- Attaining high $\beta_i$ regime

Need additional current drive

- LHI-initiated discharge readily couples to ohmically-driven H-mode

But, difficult to raise $I_p$ in ohmic phase with available V-sec

- May be influenced by: residual MHD activity; increasing $l_i(t)$

High $I_p$, long-pulse operation awaits new integrated LHI assembly, power systems upgrades, and new OH solenoid

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Non-solenoidal startup and H-mode facilitates access to high-\(\beta_t\) regime as \(A \rightarrow 1\)

- Pegasus designed to explore tokamak stability limits at \(A \sim 1\)

- Requires access to relevant space
  - High \(I_p/I_{\text{tf}}\)
  - Good OH confinement

- Research thrusts should enable access to this unique stability regime
  - LHI: High \(I_p/I_{\text{tf}}\)
  - H-mode: Good OH confinement

\[\begin{align*}
\text{RJF, 2013 APS/DPP, Denver}
\end{align*}\]
Summary: A ~ 1 Operation Enables Studies of H-mode Phenomena

- Low toroidal field at A ~ 1 facilitates access to H-mode
  - $P_{th} \sim 5x$ greater than $P_{th}$ scalings’ predictions
  - Edge current pedestal observed

- Large, small ELMs observed and $J_{edge}(R,t)$ dynamics measured
  - Clear difference in toroidal mode numbers between large and small ELMs
  - $J_{edge}(R, t)$ shows current-hole perturbation during ELMs

- Proposed upgrades will extend studies to wider parameter space
  - New OH solenoid: 5-6x V-sec increase (courtesy PPPL)
    - Increased pulse length, transport equilibrium; more relaxed $J(R)$
  - $2x B_{tf}$ increase: vary $P_{th}$; edge stability boundaries
  - Core and edge plasma diagnostics
    - Multipoint Thomson scattering
    - Edge electrostatic and magnetic probes
    - Core ion spectroscopy

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Direct $J_{\phi}(R)$ Profiles Obtained in PEGASUS

- Straightforward J estimation
  - Obtain Hall Probe $B_z(R,t)$
  - Compute $dB_z/dR$ using interpolated smoothing spline*
  - 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

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*: Reinsch, Numerische Mathematik 10, 177 (1967)
Type I and Type III ELMs seen in H-mode

- Tentatively identified via magnetic signatures
  - Type I expected to have intermediate n modes
  - Type III expected to have low n modes

- Typically only one Type I ELM occurs in a discharge

- Many Type III ELMs occur in a single discharge

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Edge Current Pedestal Observed in H-Mode

- Internal B measurements from Hall array* yield local $J_\phi(R,t)$**
  - Map to $\psi_N$ only approximate

- Current gradient scale length significantly reduced in H-mode
  $L \rightarrow H: 6 \rightarrow 2$ cm

**: C.C. Petty et al., Nucl. Fusion 42, 1124 (2002)