Advanced Tokamak Physics Studies on an Intermediate-Scale Spherical Tokamak

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PEGASUS Toroidal Experiment



Outline

- Introduction to PEGASUS
- H-mode Characterization
- Power Threshold
- ELMs
- Conclusion

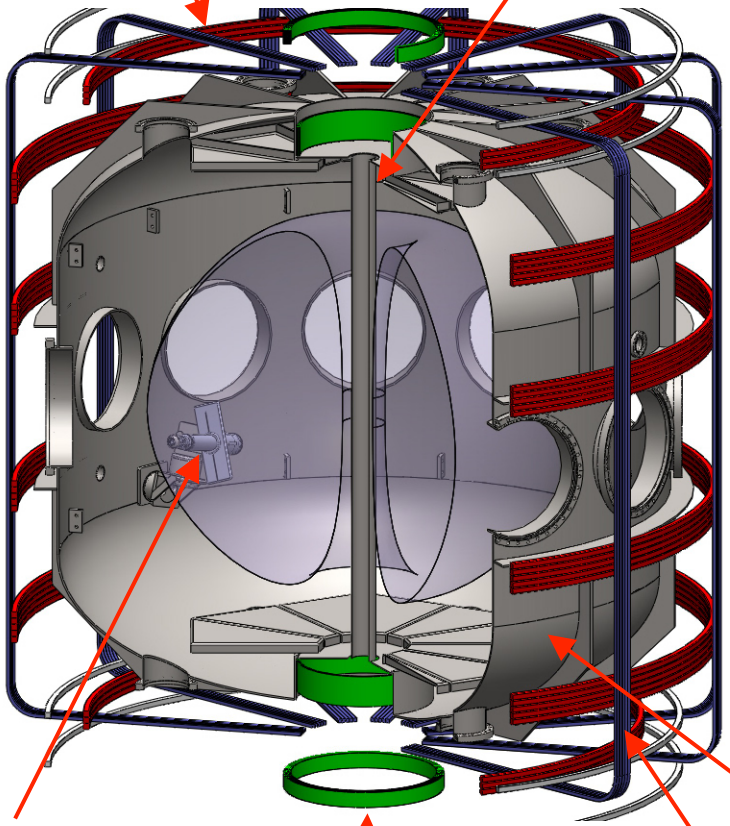


Operation at A~1 Offers Ready Access to Advanced Tokamak Physics

- *A*~1 implies high I_p at low B_T and extreme toroidicity
  - H-mode Access
  - High J_{edge}/B_T plus H-mode pedestal = ELMs
  - Short connection lengths, very strong trapping = neoclassical effects at low T_e
  - High-β studies at tokamak limits
- Strong shaping

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PEGASUS is a Compact, Ultralow-*A* ST



Experimental Parameters

Parameter	Achieved
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .25
κ	1.4 – 3.7
Δt_{shot} (s)	≤ 0.025
β_t (%)	≤ 25

Major research thrusts:

- Tokamak physics at small aspect ratio
- Non-inductive startup and growth

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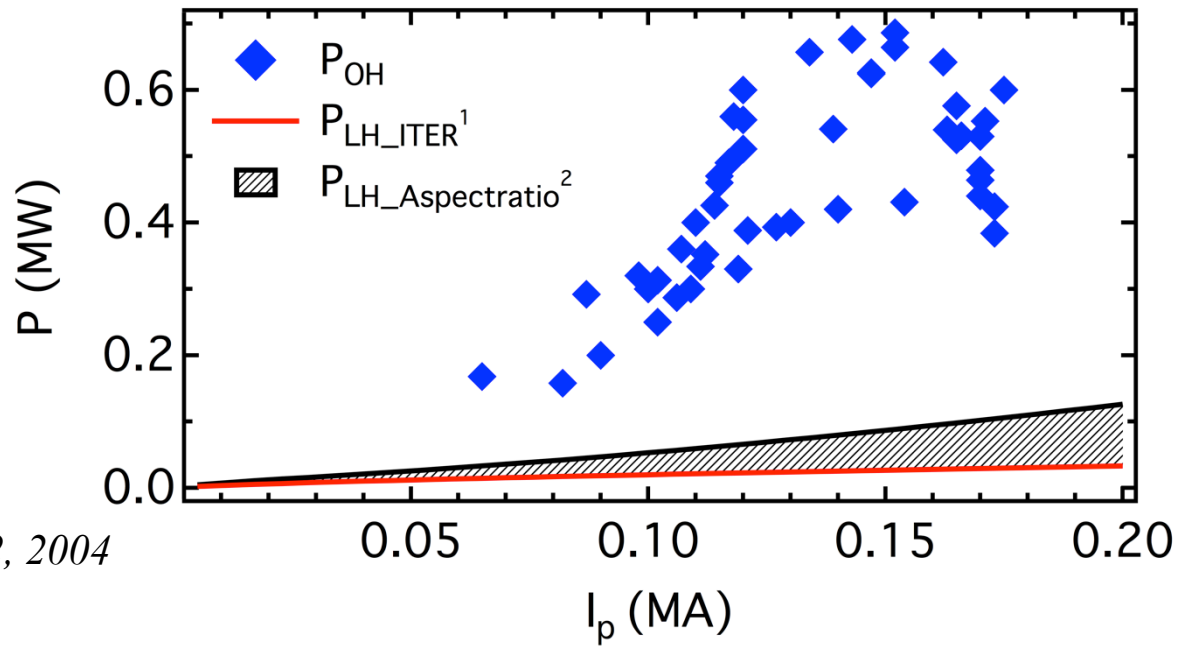
PEGASUS P_{OH} >> P_{LH} Predictions

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

- P_{LH} empirical 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



[1] *Nucl. Fus.*, **47**, S82, 2007.
[2] *Plasma Phys. Control. Fus.*, **46**, A232, 2004

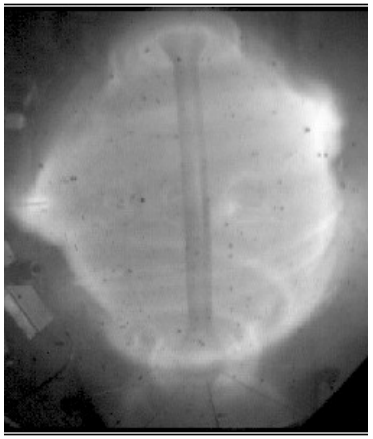
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Fueling Location, Particularly in STs, is Critical for Achieving H-mode

- H-mode achieved using high-field-side (HFS) fueling
  - Similar to MAST and NSTX[1]
  - Both limited and diverted
- Accessible with only P_{OH}

Limited

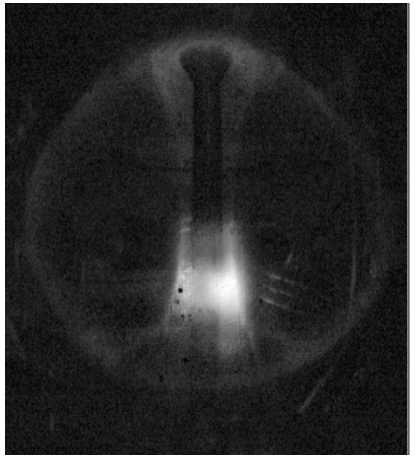
LFS Fueled



HFS Fueled



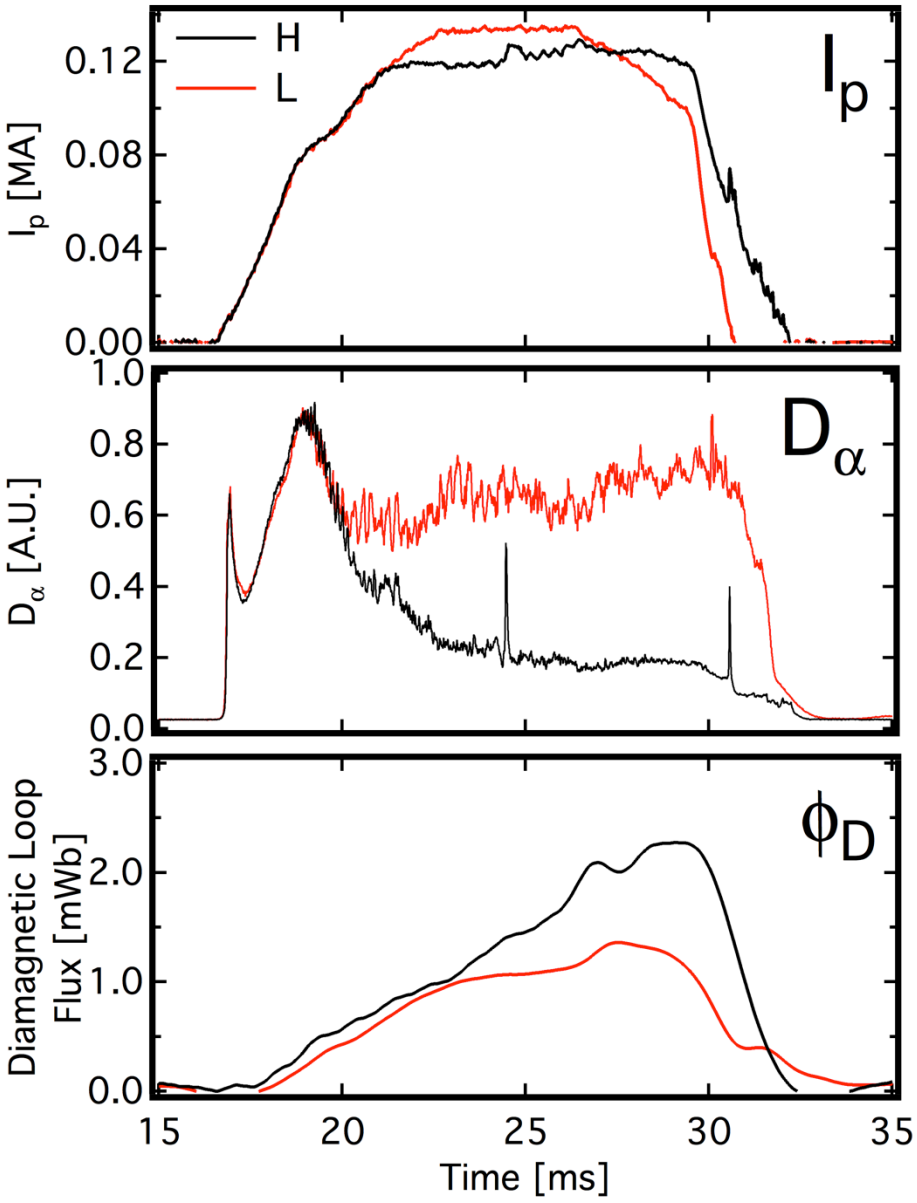
Diverted



[1] *Plasma Phys. Control. Fus.*, ***46***, *2004.*

Ohmic H-mode Plasmas have Standard Signatures

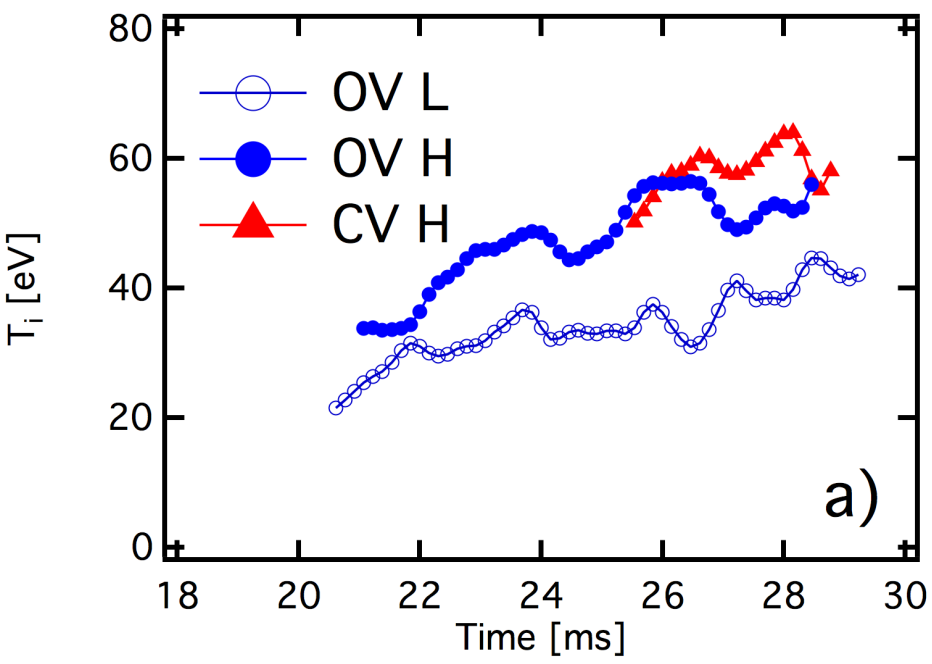
- Quiescent edge
- Reduced D_α
- D_α gradient increases by 3
- Large and small ELMs
- Bifurcation in ϕ_D
  - Transport equilibrium not attained
- Increased core T_e, T_i inferred

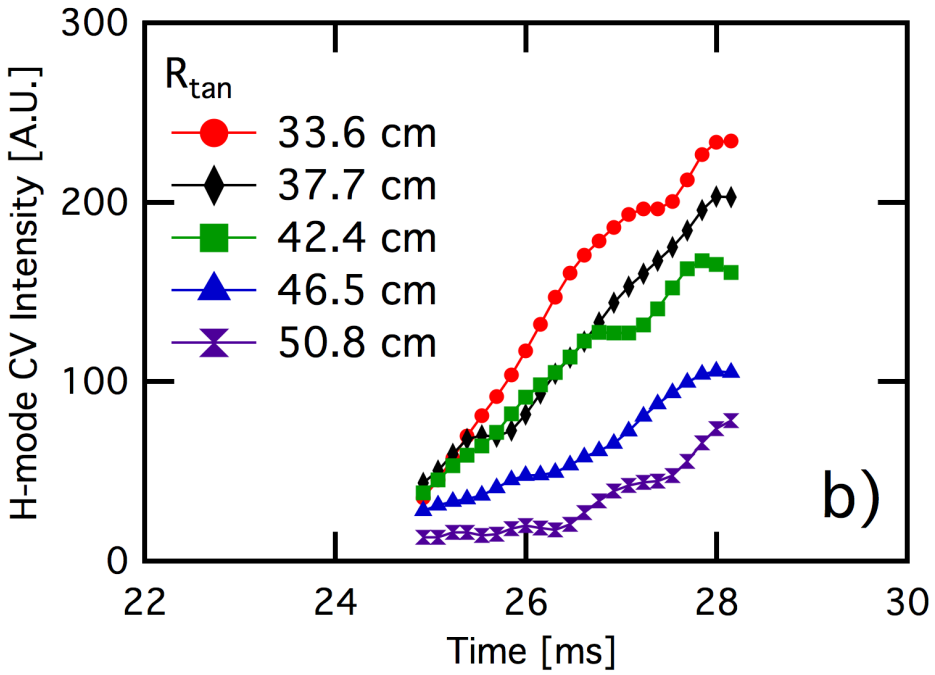


Core T_i and T_e Heating Indicated During H-mode

- Preliminary Thomson scattering measurements suggest some increase in $T_e(0)$ in H-mode
  - Need full $T_e(R,t)$ profiles to resolve spatial and time variations

- Impurity $T_i(0)$ doubles from 30 eV to 60 eV
  - CV only seen in core H-mode plasmas, implying higher and centrally peaked T_e
  - Transport equilibrium not attained

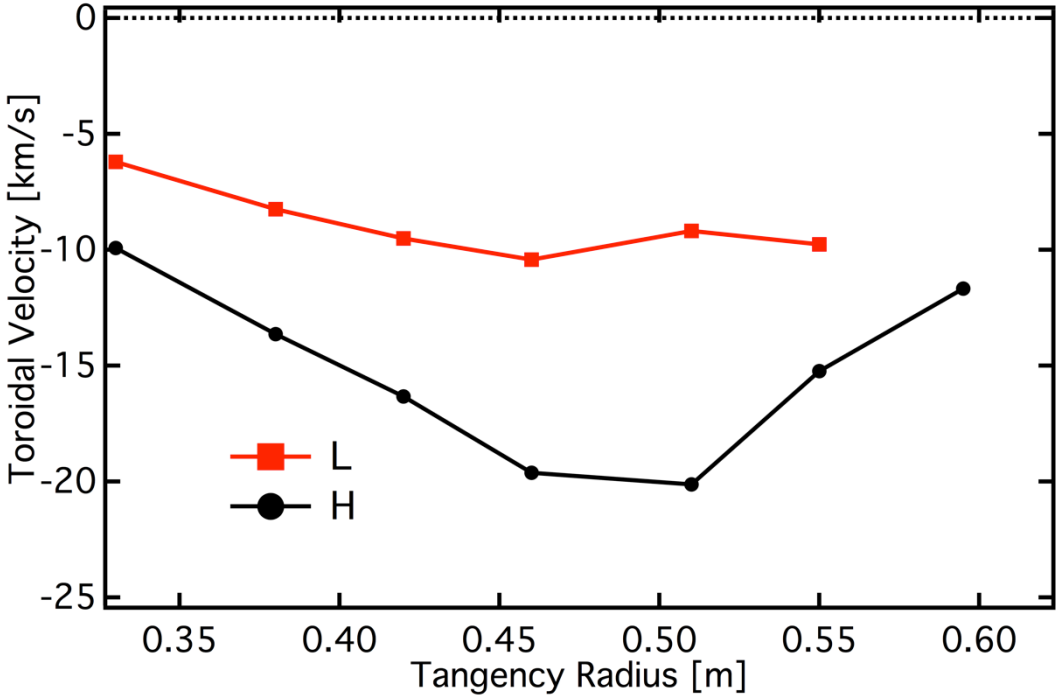




Edge Shear Increases in H-mode

- Chordally-integrated velocity profiles show increased shear in the outer region in H-mode

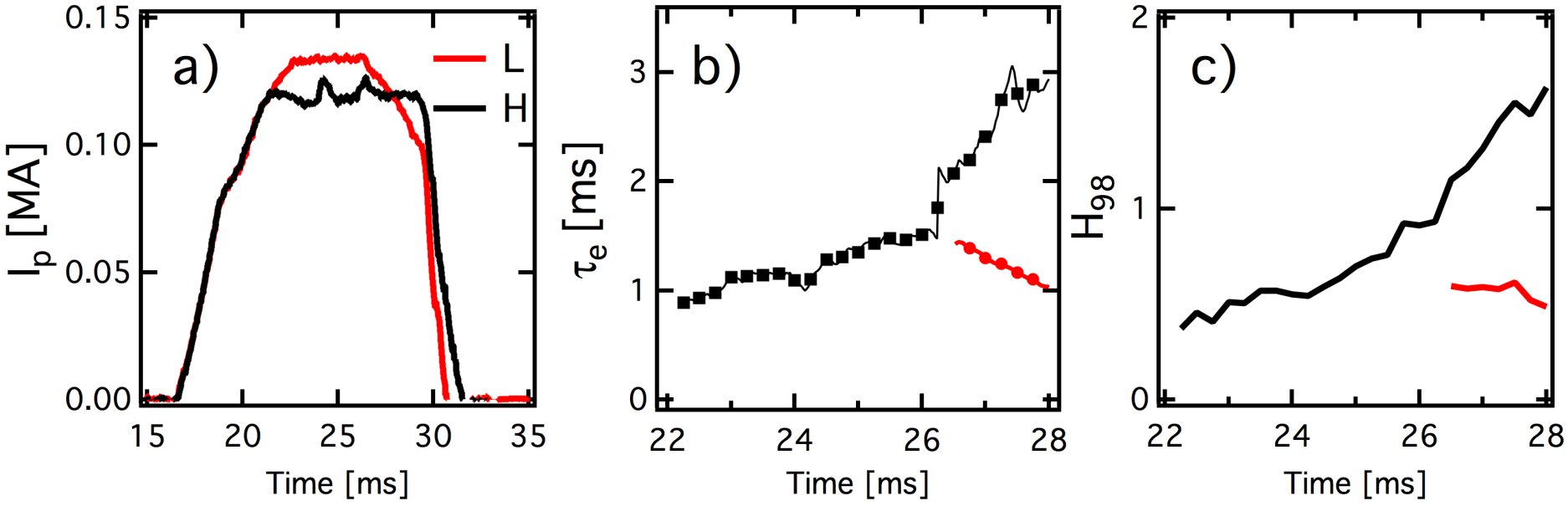
- Indirect evidence of E_r well



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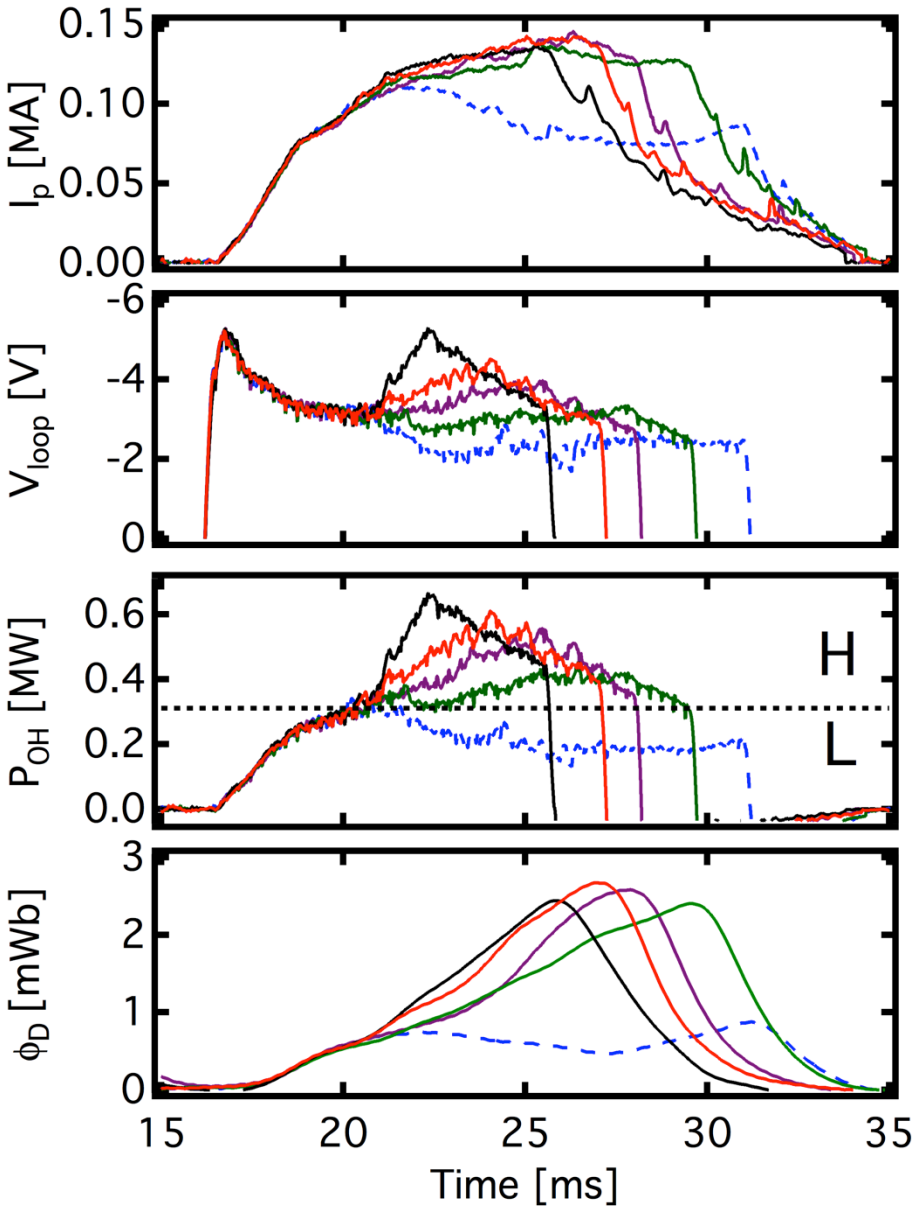
Energy Confinement Improves in H-mode

- τ_e from time-evolving magnetic reconstruction
- 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

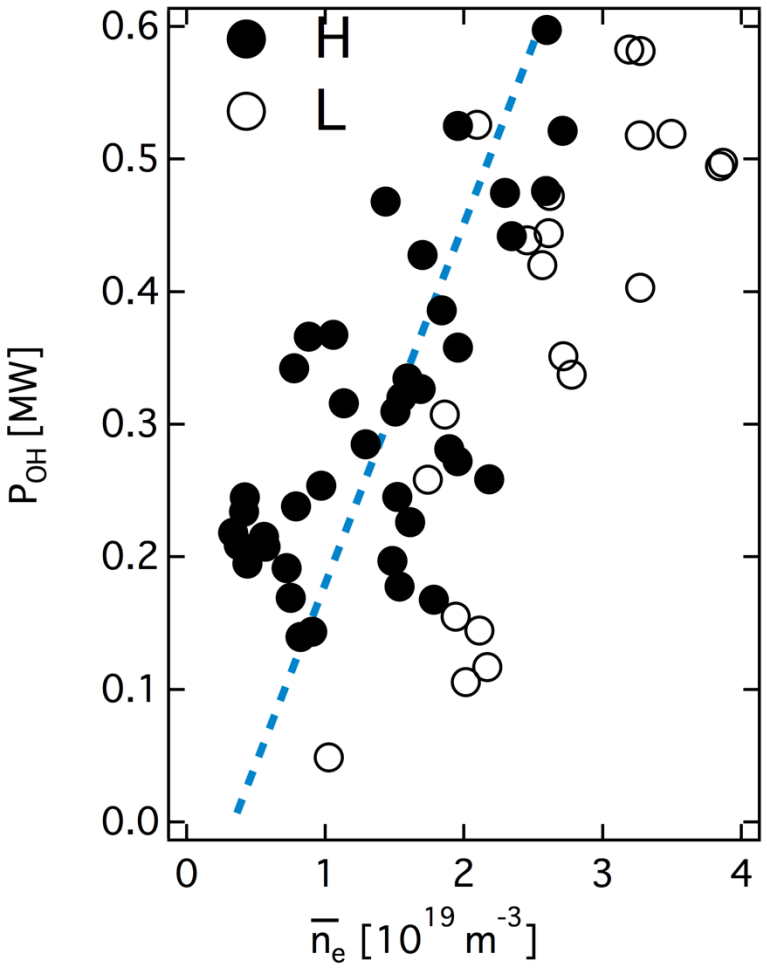


P_{LH} Measured via V_{loop} Scans

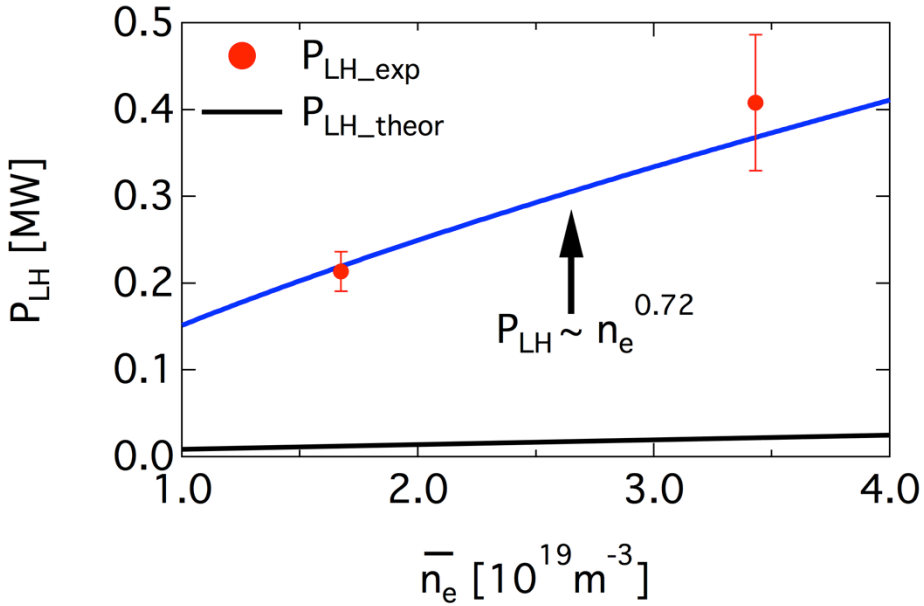
- Infer t_{LH} from bifurcation in ϕ_D
  - Vary $P_{OH} = I_p V_{loop}$
  - Constant I_{EF}, shape, fueling
- P_{OH} ~ 0.25–0.30 MW
  - High-*A* Scalings predict << 0.1 MW
- $P_{LH_exp} = P_{OH}$ - dW/dt
  - dW/dt by magnetic equilibrium reconstruction
  - ~30% correction



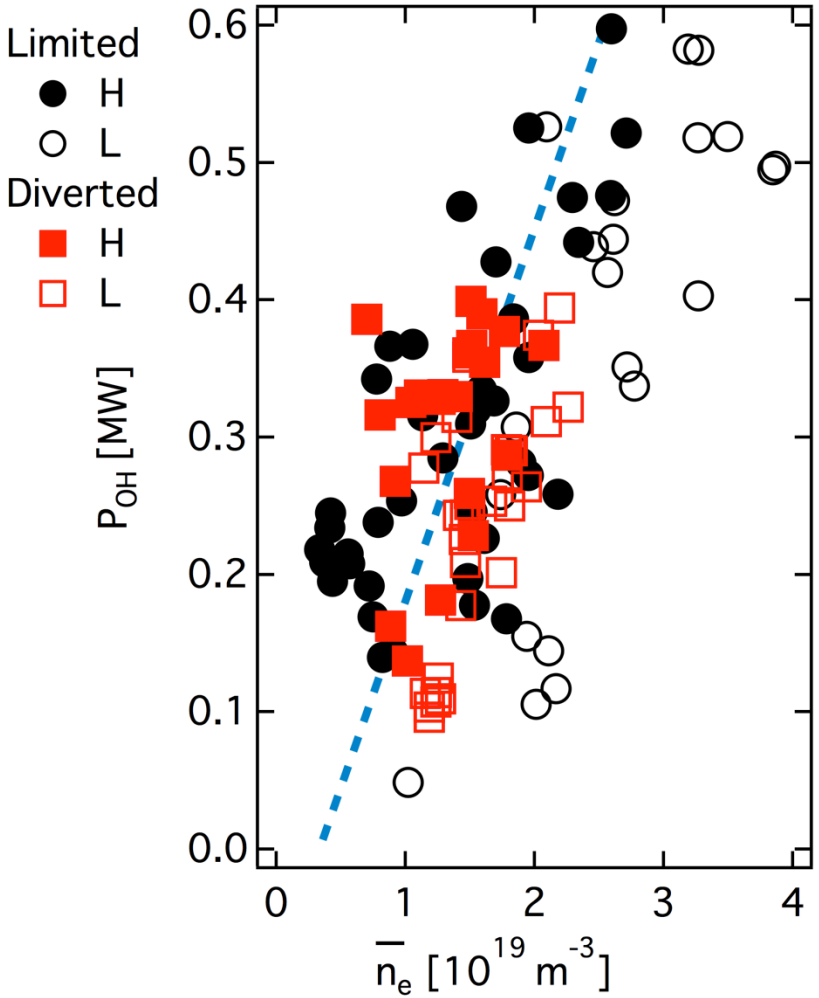
Limited P_{LH} Follows Standard n_e Dependence



- P_{OH} = 0.1-0.6 MW
  - Density dependence
    - No observed $n_e$min
  - Much greater than scaling predictions



Diverted P_{OH} ≈ Limited P_{OH}

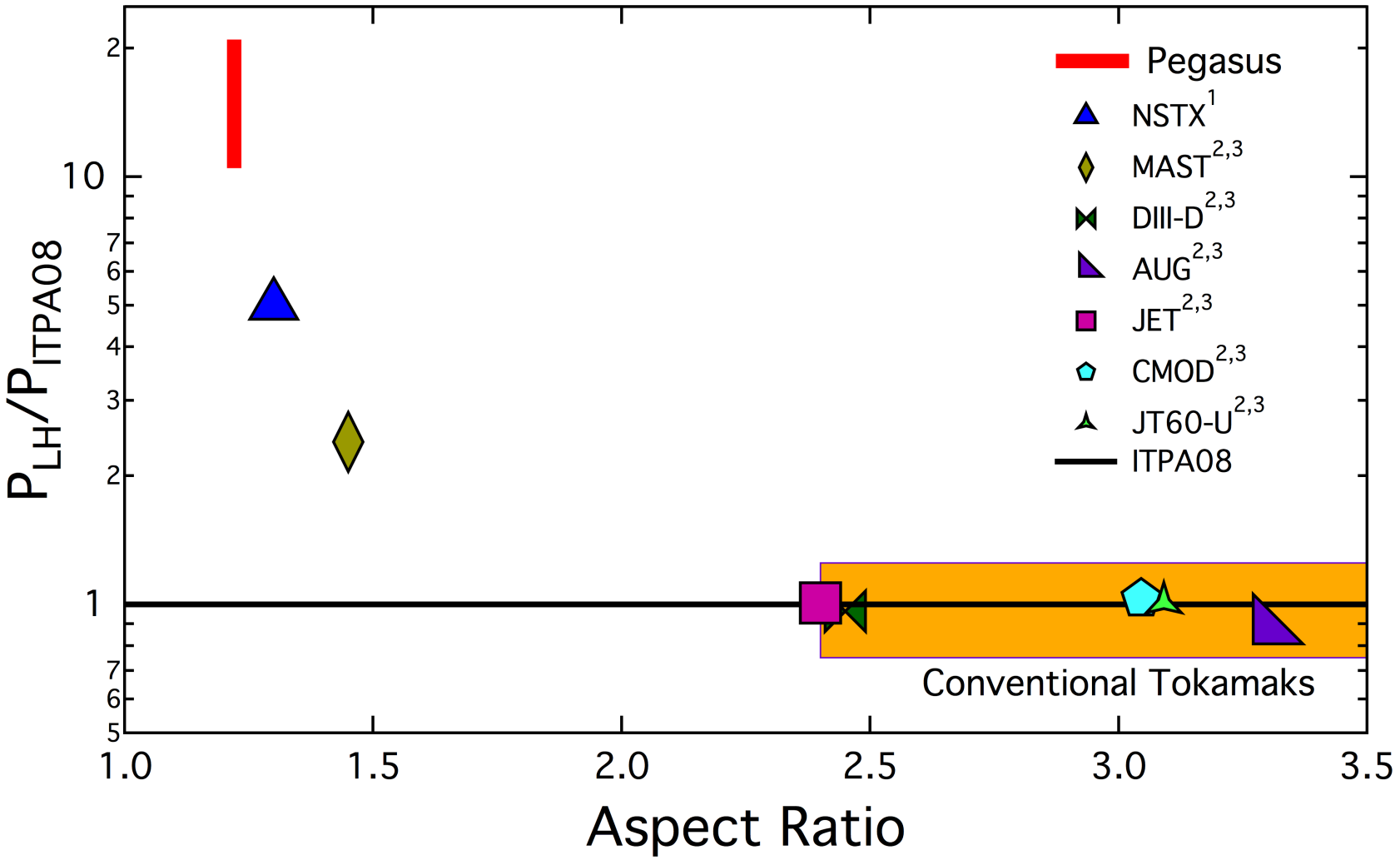


- P_{OH} measured in USN diverted (favorable ∇B drift direction)
  - Density dependence
    - No observed $n_e$min
  - Much greater than scaling predictions

- No difference in diverted P_{OH} from limited P_{OH}
  - Possibly due to little difference in edge magnetic shear at low *A* between limited and diverted plasmas?

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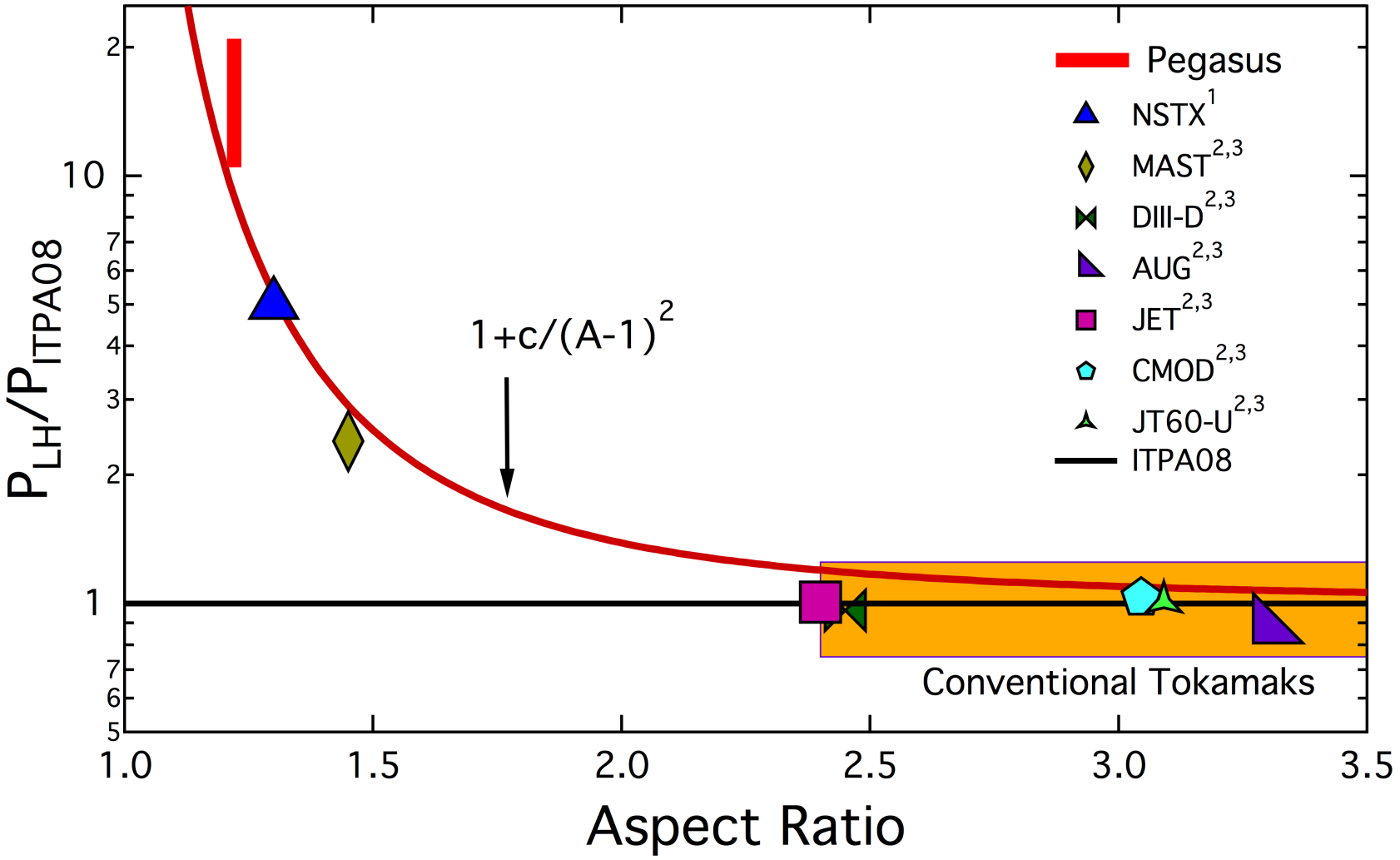
Power Threshold Increases with Aspect Ratio



[1] *Nucl. Fusion.*, ***50****, 064010,* 2010 .
[2] Journal of Physics: Conference Series, **123**, 012033, 2008.
[3] *Tokamaks*, 4th ed. 2011, 630.

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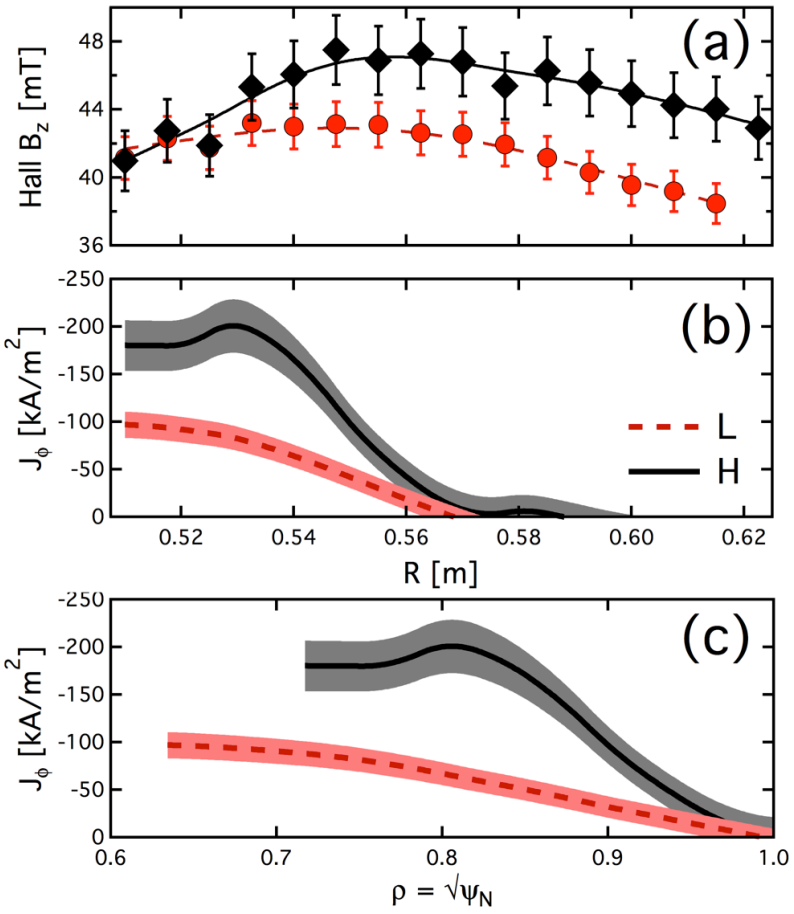
P_{LH} anomaly with A similar to q_{edge}, β_T, etc



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Current Pedestal Measured using Hall Probe Array

- Short pulse, low T_e allow detailed J_{edge} and p_{edge} profiles
- $J_\phi(R,t)$ from Hall Probe B_z measurements
  - Clear current pedestal observed
- p(R,t) will be obtained with Langmuir probes
- These measurements can be used to validate models
  - E.g. EPED

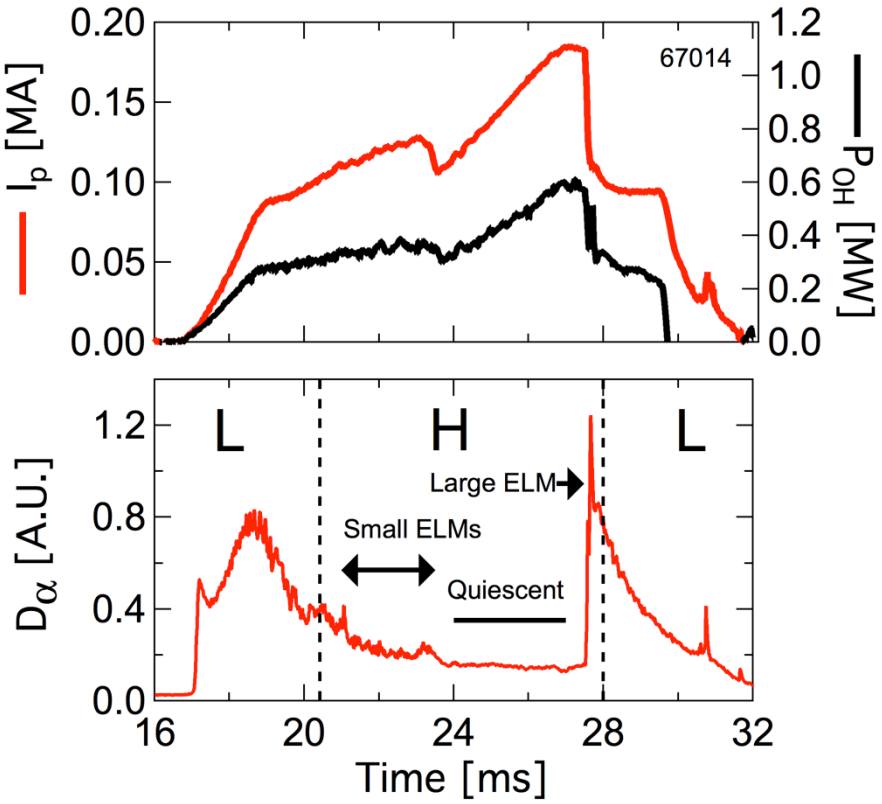


[1] *Bongard, Rev. Sci. Instrum.* ***81****, 10E105, 2010. &* Bongard, PRL, **107** , 035003, 2011.

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Large and Small ELMs Reminiscent of Type I and III ELMs are Seen

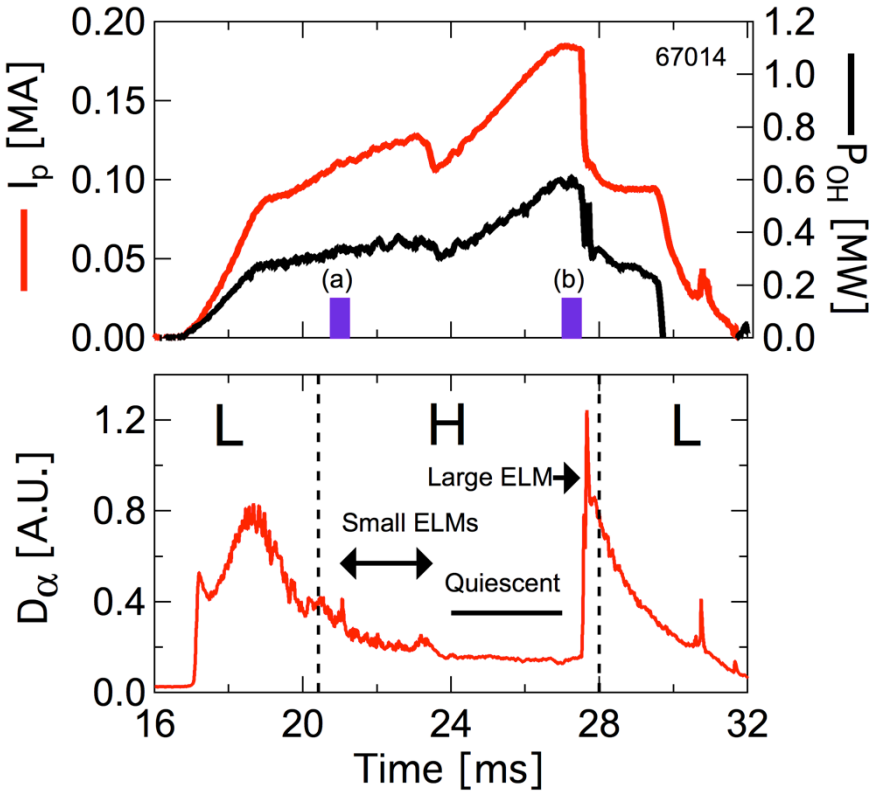
- Filament structures observed
  - Temporally coincident with D_α bursts
- Small ELMs more ubiquitous and less perturbing
  - Occur at lower P_{OH}
- Large ELMs infrequent and violent
  - Can cause H-L back-transition
  - Occur at high P_{OH}

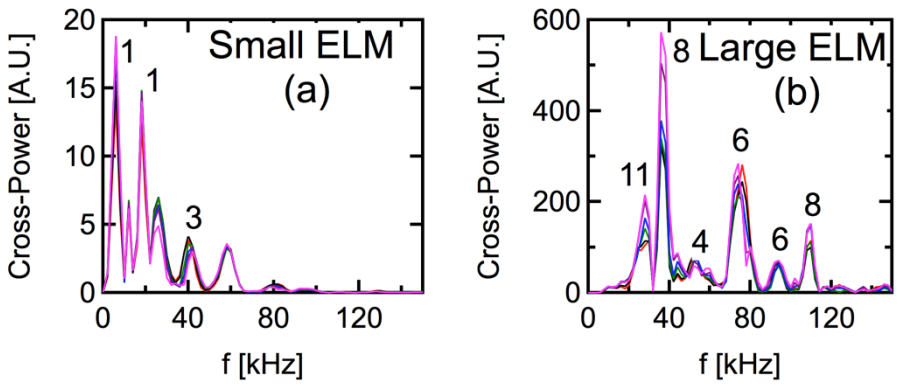


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ELM Magnetic Structure at low *A* Opposite of that at high *A*

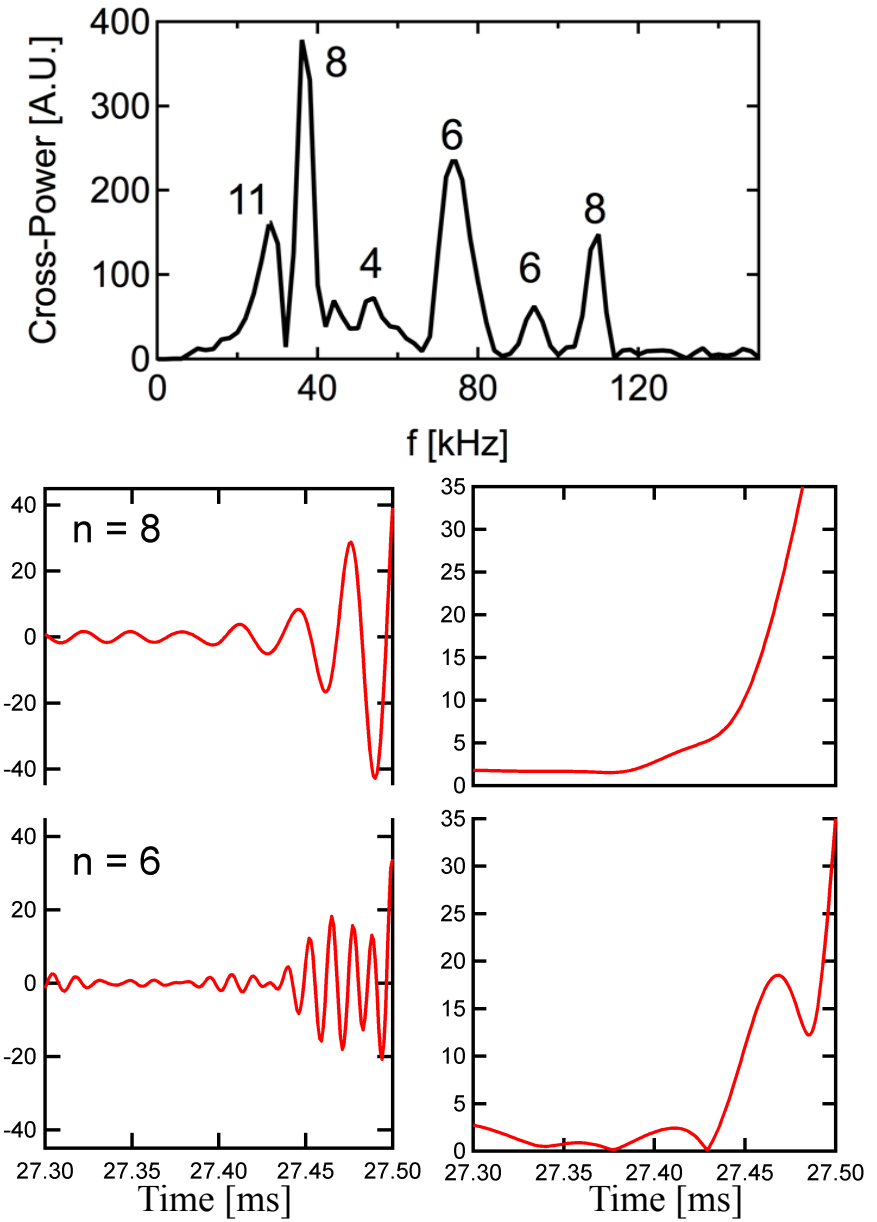
- PEGASUS & NSTX structure opposite that of ATs
  - Possibly due to increased peeling drive at low *A* (J_{edge}/B)
- Small ("Type III"): low-n
  - Peeling mode driven
- Large ("Type I"): intermediate-n
  - Peeling-ballooning mode driven





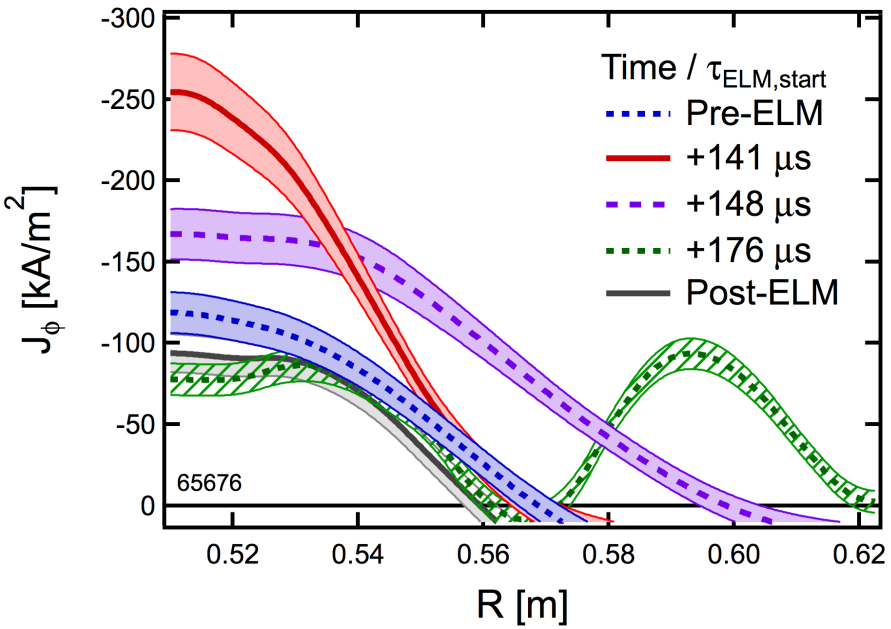
ELM Precursor Components Grow on MHD Timescales

- Magnetic signature of ELMs have multiple n components
  - Simultaneously unstable modes
- Bandpass-filtered Mirnov components: different growth rates present
  - Timescale: < 10's μs
  - Dominant n = 8 grows continuously
  - n = 6 component fluctuates prior to crash

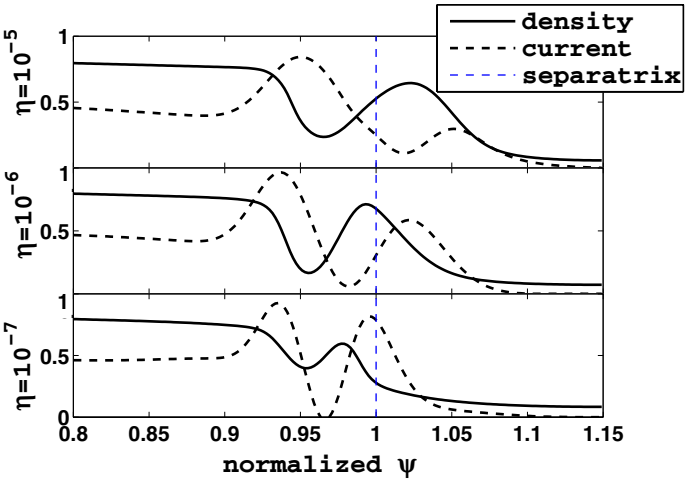


Large ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Cycle

- Large ELM $J_{edge}(R,t)$ shows complex evolution
  1) **Modest but steep J_{edge} pedestal**
  2) **Rapid buildup of J_{edge} until crash**
  3) **Collapse with wider pedestal grad (similar to L-mode)**
  4) **Current-hole filament ejection**
  5) **Recovery: slightly lower than pre-pedestal**



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

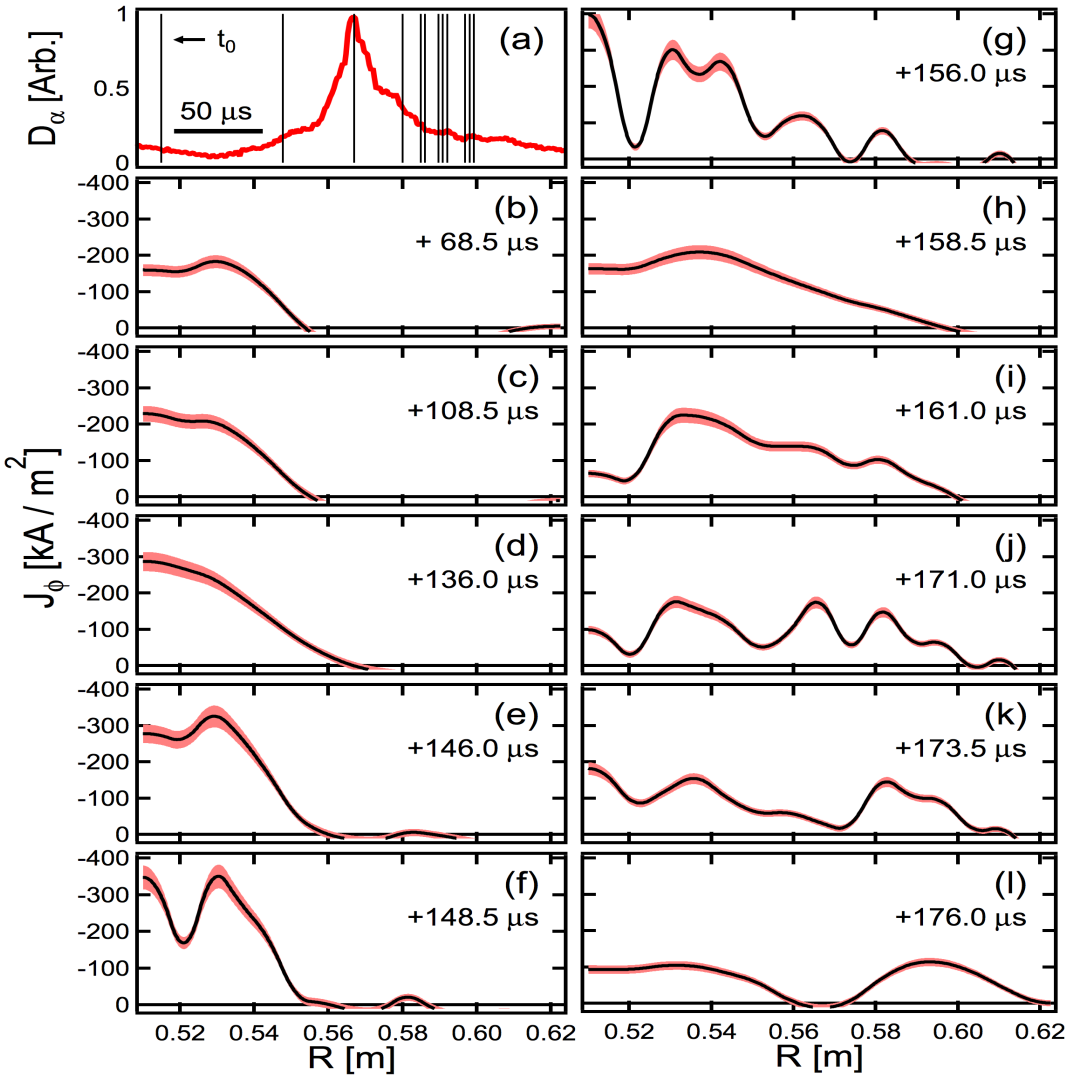


[1] *Plasma Physics Control. Fusion.*, **53**, 054014 2011.

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Closer Inspection of J_{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

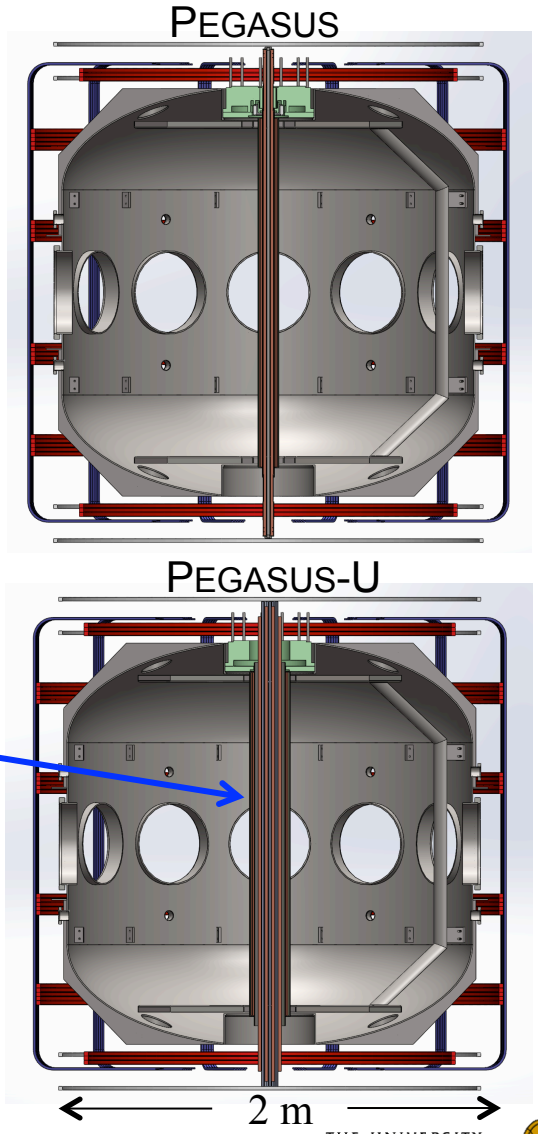


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PEGASUS-U Initiative: Advancing Non-Solenoidal Startup and AT Physics

- Mission
  - Physics and technology of LHI
  - Nonlinear ELM dynamics, H-mode physics
  - Tokamak stability limits: A~1 high β_T regime

- Facility enhancements
  - New centerstack assembly
    - B_T increases 5x
    - Δt_{pulse} ~ 100 msec
    - V-sec increases 6x (PPPL)
    - Improved separatrix operation
  - NSTX-U relevant LHI injector arrays
  - Diagnostics: multipoint TS; CHERS via DNB



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PEGASUS-U Provides Access to Nonlinear ELM Studies and H-mode Physics

- p(R,t), J(R,t), v_φ(R,t) through ELM cycles
  - Allow test of nonlinear ELM models
    - NIMROD, JOREK, BOUT
- ELM modification and mitigation
  - Vary J_{edge}(r), modify edge v_φ and shear via LHI
  - C-pellet injection for tests of models for ELM-pacing (w/ORNL)
- Integrated studies with BES on NSTX-U, DIII-D
  - Entry point for grad students to large facilities
- Neoclassical physics tests
  - J_{BS} model tests: Test Sauter model if sufficient edge pressure achieved

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Conclusions: A ~ 1 Operation Enables Studies of AT Physics

- H-mode achieved in plasma with simple diagnostic access
  - Standard characteristics: Pedestal; low D_α; increased τ_e; $H_{98} \geq 1$; etc.
- Features unique to low-*A* emerging
  - Strong P_{LH} threshold scaling with *A*
  - Little to no difference between limited and diverted H-modes
- Unique operating regime allows detailed studies of ELMs
  - Mode numbers at low-*A* opposite that of high-*A*
  - $J_{edge}(R,t)$ through ELM cycle shows some correspondence with simulations
- Overall, complements experiments on larger fusion facilities
  - Detailed measurements can elucidate more limited results on larger facilities