H-mode Edge Turbulence and Pedestal Measurements in PEGASUS Plasmas

D. M. Kriete

J. L. Barr, G. M. Bodner, M. W. Bongard, R. J. Fonck,

K. E. Thome, D. S. Thompson



University of Wisconsin-Madison

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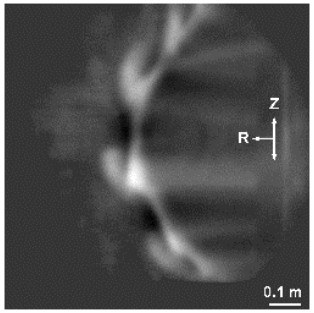


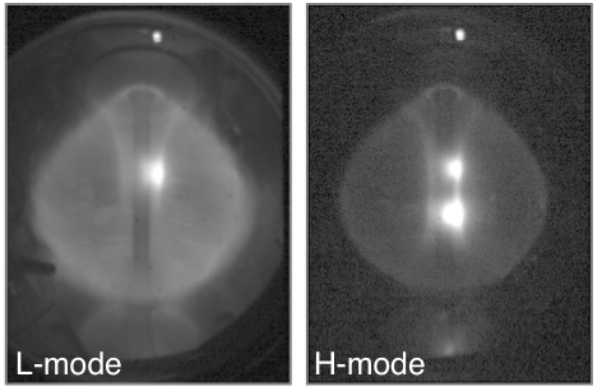
PEGASUS Toroidal Experiment

A ~ 1 Operations Provide Access to AT Physics

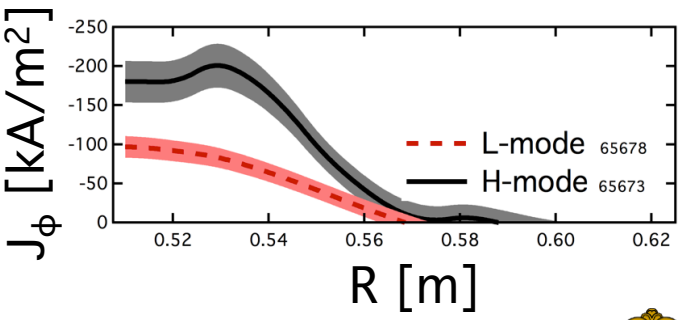
- $A \sim 1 \rightarrow$ high I_p at very low B_T
  - Excitation of peeling modes without J_{BS}[1,2]
  - Easy access to H-mode regime and ELMs
  - Neoclassical effects (resistivity enhancement)

PEGASUS





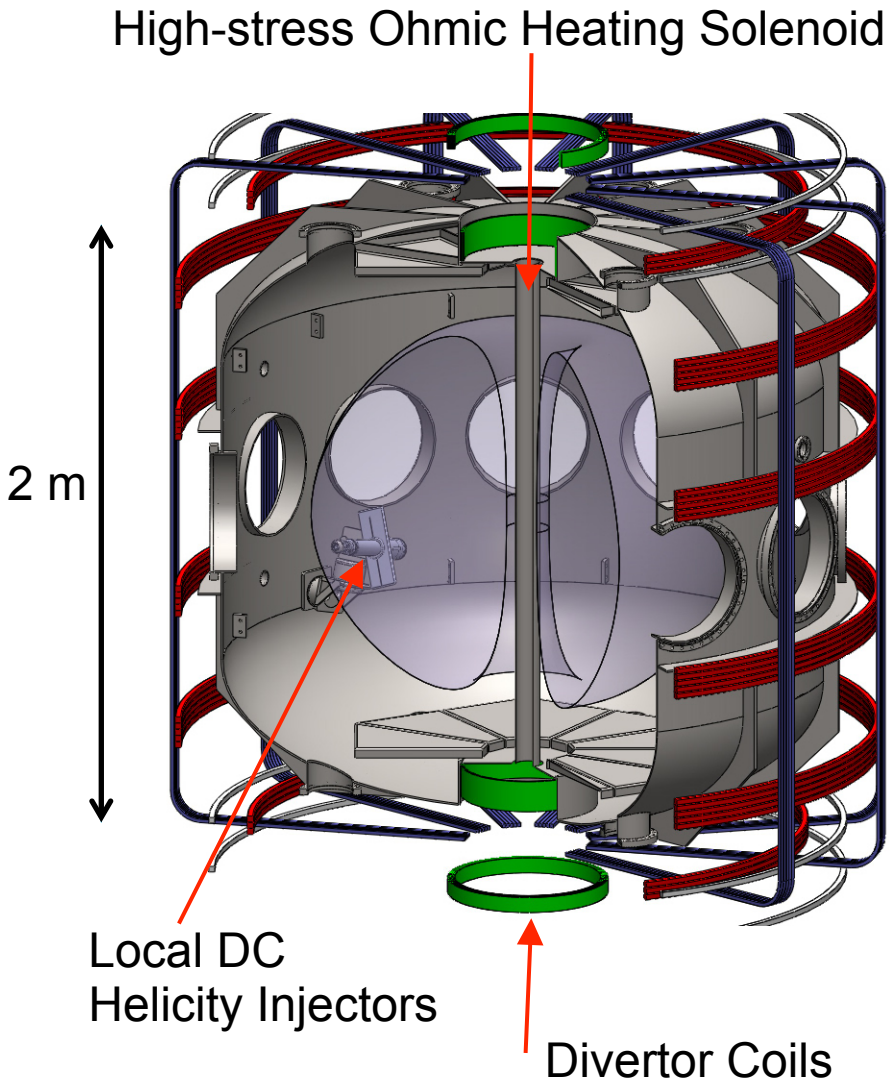
- Modest-sized plasma and relatively low T_e
  - Allows diagnostic access to pedestal
  - Pedestal $J_\phi(R, t)$, $p(R, t)$, and $v_\phi(R, t)$ via probes



[1] Bongard *et al.*, Phys. Rev. Lett **107**, 035003 (2011).
[2] Bongard *et al.*, Nucl. Fusion **54**, 114008 (2014).

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PEGASUS Provides H-mode Plasmas at Ultralow-*A*



Experimental Parameters

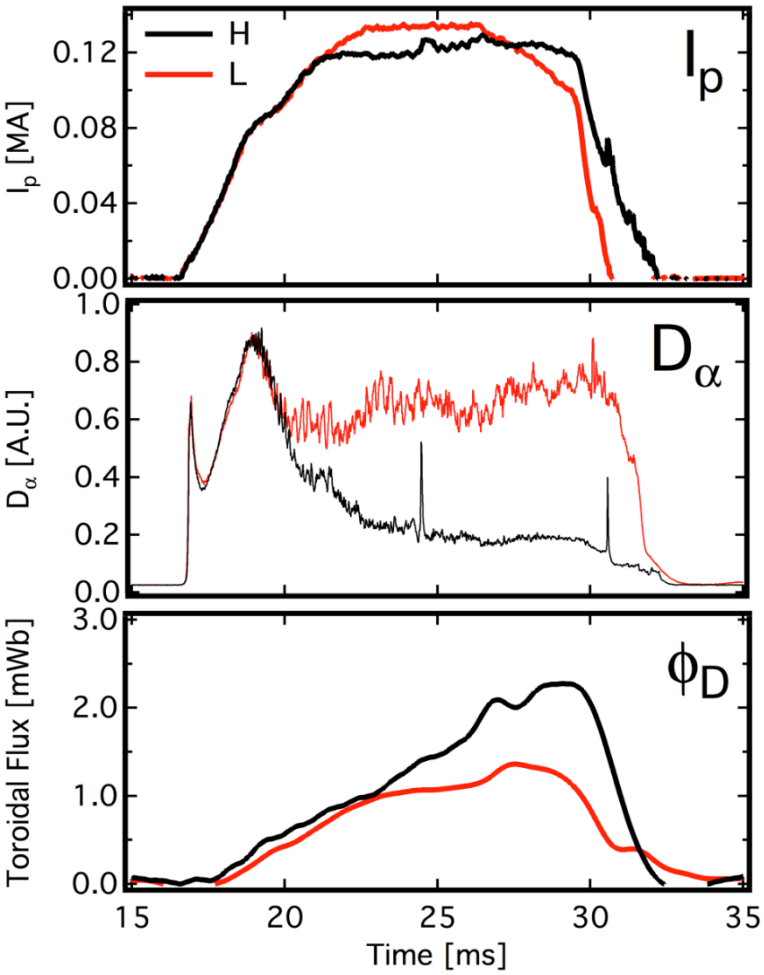
A	1.15 – 1.3
R (m)	0.2 – 0.45
I_p (MA)	$\leq$ 0.25
B_T (T)	< 0.2
$\Delta\tau_{shot}$ (s)	$\leq$ 0.025
Z_{eff}	~ 1
Recycling Coefficient	< 0.7

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Standard Signatures in OH H-mode

- Quiescent edge
- Reduced D_α
- Large and small ELMs
- Bifurcation in $\phi_D(t)$
- Core impurity T_i increases
- Increased core T_e indicated
  - CV only observed in H-mode (E_{ion}=392 eV)
  - Thomson $T_{eH}(0) > T_{eL}(0)$
- Increased core rotation



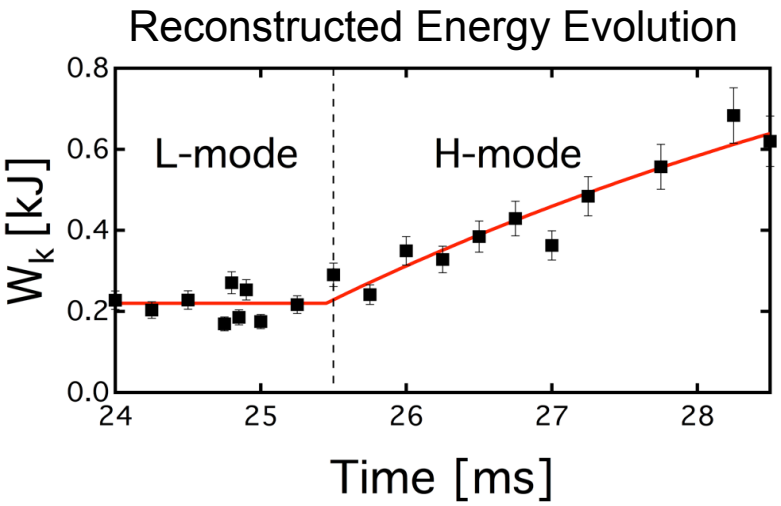
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Energy Confinement Improves in H-mode

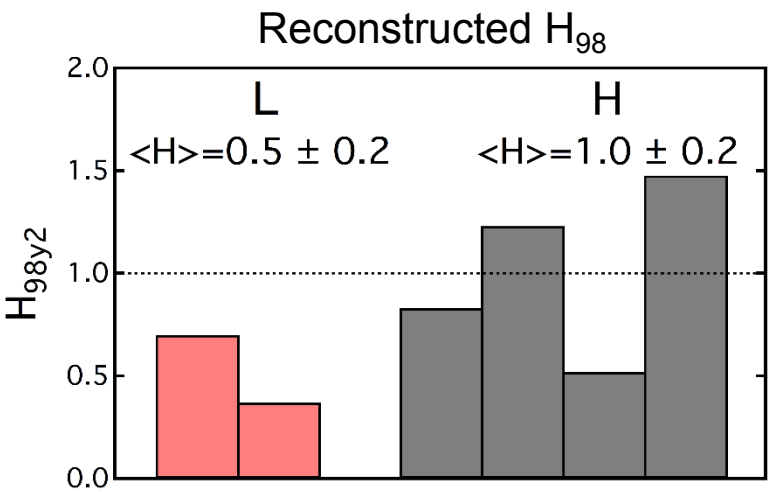
- Equilibrium reconstructions yield τ_e

$$\tau_e = \frac{W_k}{P_{in} - dW/dt - P_{RAD}}$$

  - Challenges: short pulse, MHD, $I_{wall}(t)$
  - Significant dW/dt



- W_k (τ_e) increases after L-H transition
  - H_{98} increases from 0.5 to 1.0[1]



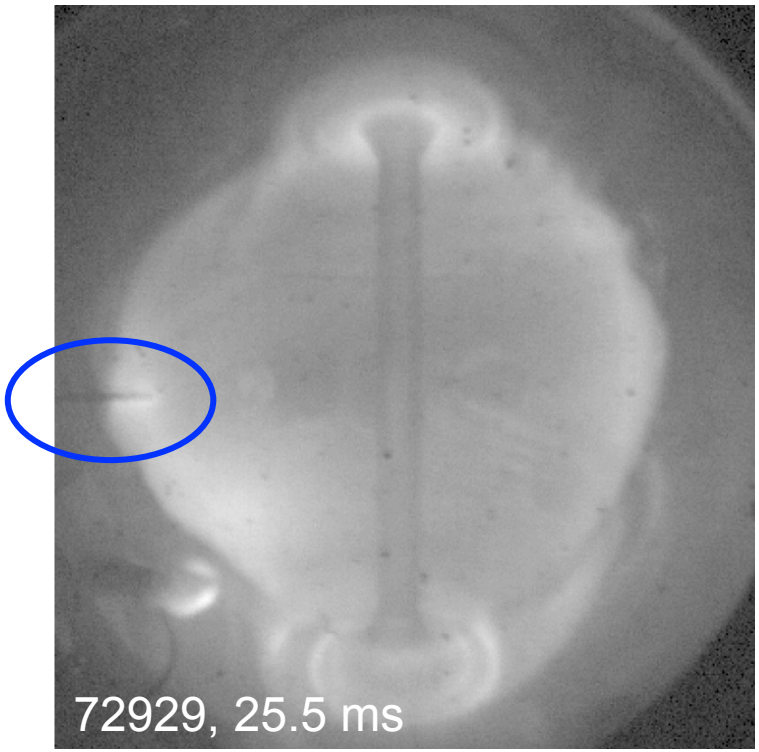
[1] See Thome, GP12.00115

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Unique Pedestal Access with Probes

- $A \sim 1$: very low $B_T \rightarrow$ low T_e
  - Probes compatible with edge
  - High spatiotemporal resolution
- Hall probe array obtains $J_{edge}(R,t)$[1]
  - $B_z(R,t)$ directly measured
  - Ampère's law provides $J_\phi(R,t)$[2]
- Triple Langmuir probe for $p_{edge}(t)$
  - Radially scannable
  - $n_e(t)$, $T_e(t)$, and $\Phi(t)$ measured

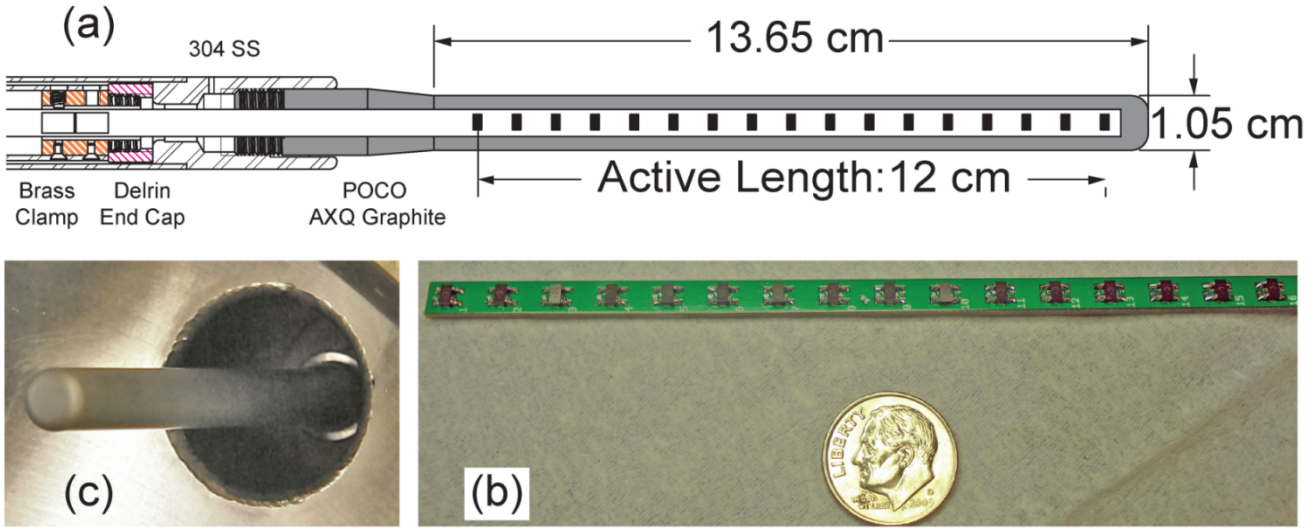
PEGASUS Plasma with Probe Inserted



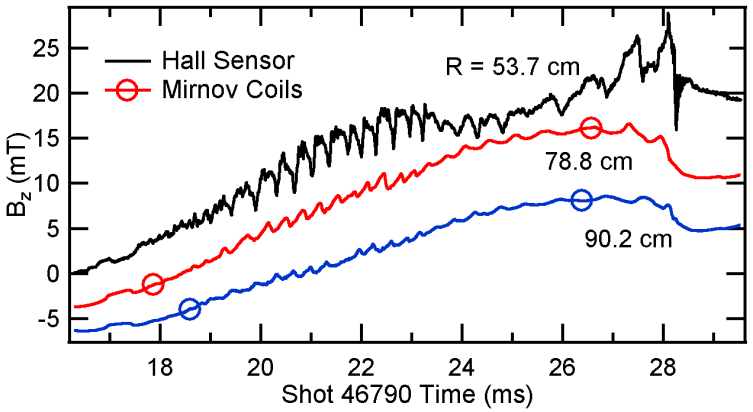
[1] Bongard *et al.*, Phys. Rev. Lett **107**, 035003 (2011)
[2] Petty, *et al.*, Nucl. Fusion **42**, 1124 (2002)

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Hall Probe Measures $J_{edge}(R,t)$



- Precision $B_z(R, t)$ measurements
  - 16 solid-state InSb Hall sensors
  - 7.5 mm radial resolution
  - 85 kHz -3 dB bandwidth
- Carbon Armored
  - Compatible with L, H-mode to date

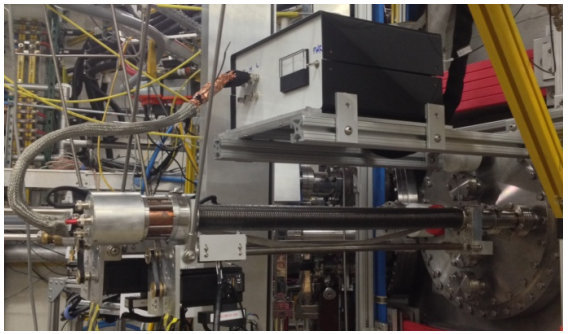


Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)

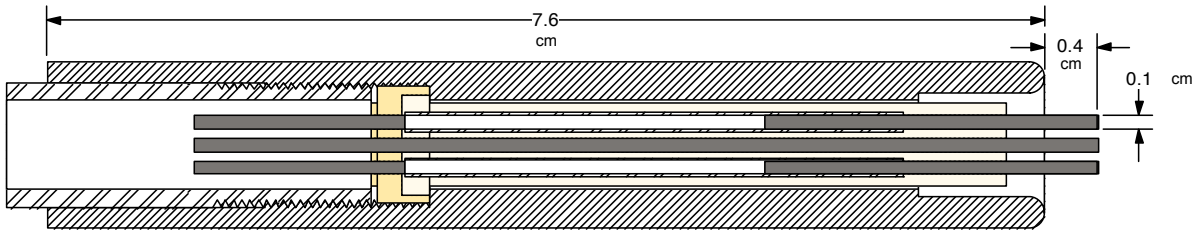
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Triple Langmuir Probe Measures $p_e(t)$

- W probe tips with 3mm separation
  - Biased to 150 V
- Graphite armored
  - 43 cm from tip for LHI compatibility
- Stepper motor radial position control
- 200 kHz bandwidth
- Electronics shielded from switching noise







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n_e and T_e Inferred from Triple Probe Transcendental Equation

- Bias voltage $V_B = V_H - V_L$ set experimentally
- Transcendental equation relates probe voltages to T_e

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

- If $eV_B \gg k_B T_e \longrightarrow T_e\,[eV] = \dfrac{V_H - \Phi_f}{\ln 2}$
  - Common approximation
  - Full transcendental solution used since $T_{e,ped} \sim V_B$

- Density is calculated from the ion saturation current

$$I^i_{sat} = A_p n_e e \left(\frac{k_B T_e}{m_i}\right)^{1/2} \exp(-1/2)$$

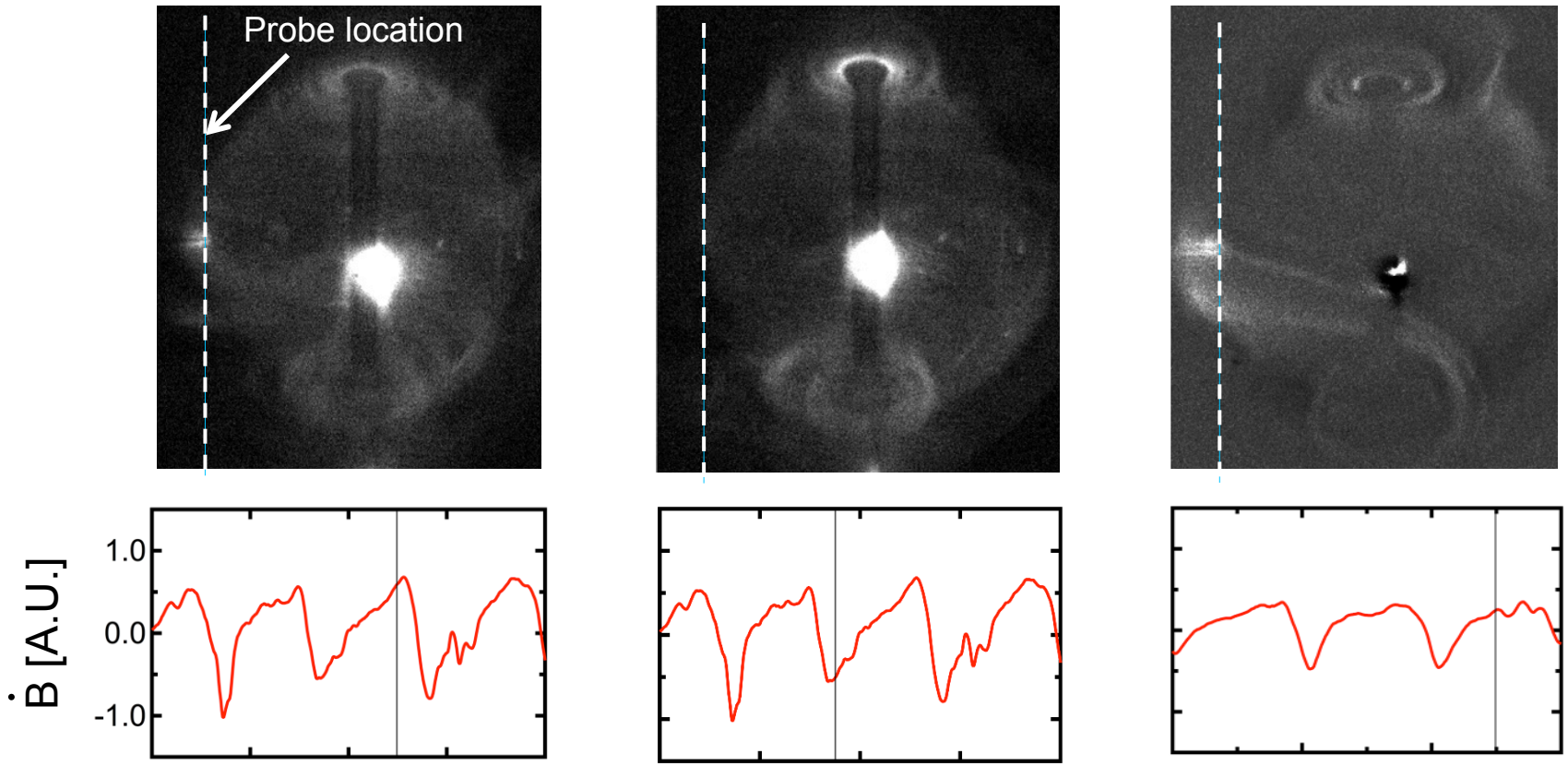
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Turbulence Studies Must Account for Plasma Motion

Edge expanded: probe immersed

Edge contracted: probe in SOL

ELM strikes probe

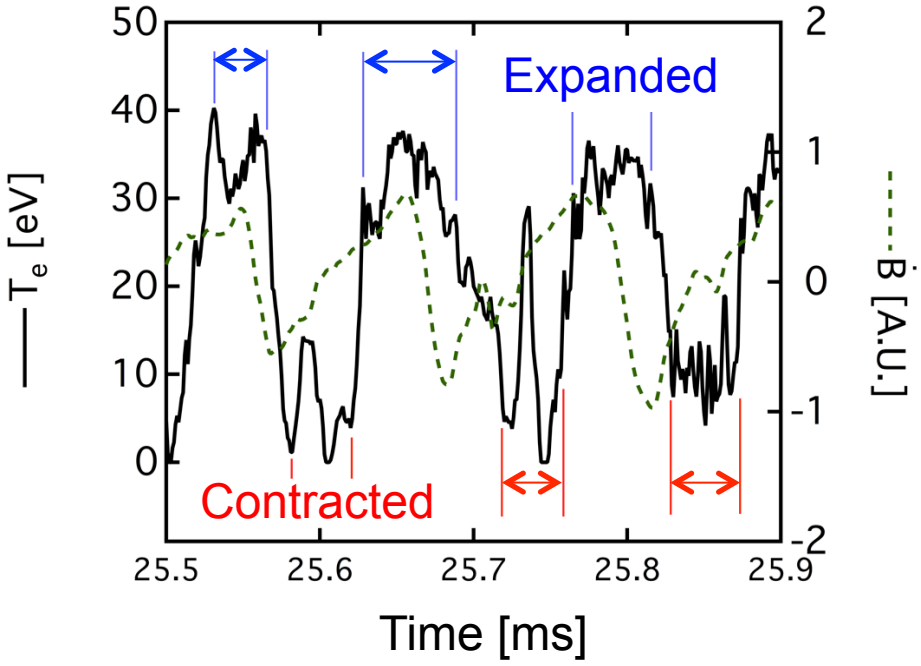


- Plasma edge moves about fixed probe location

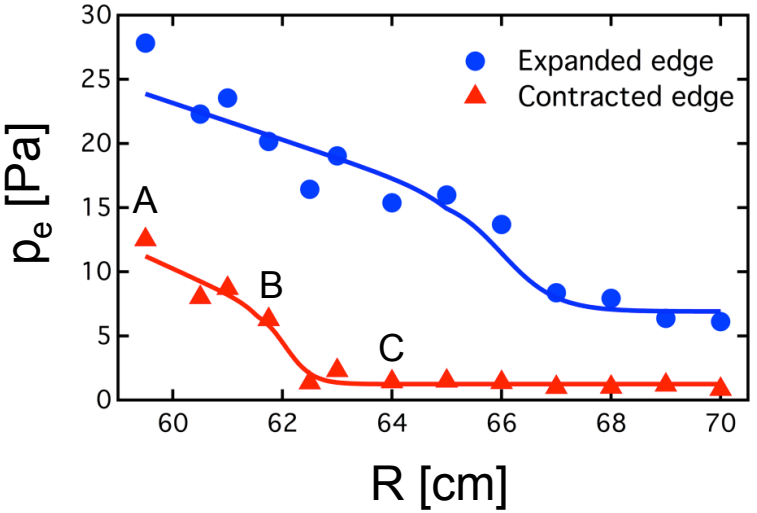
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Pedestal Moves Periodically with MHD

- n_e, T_e sampled at fixed phase
  - 1.8 ms time window
  - Expanded edge
  - Contracted edge

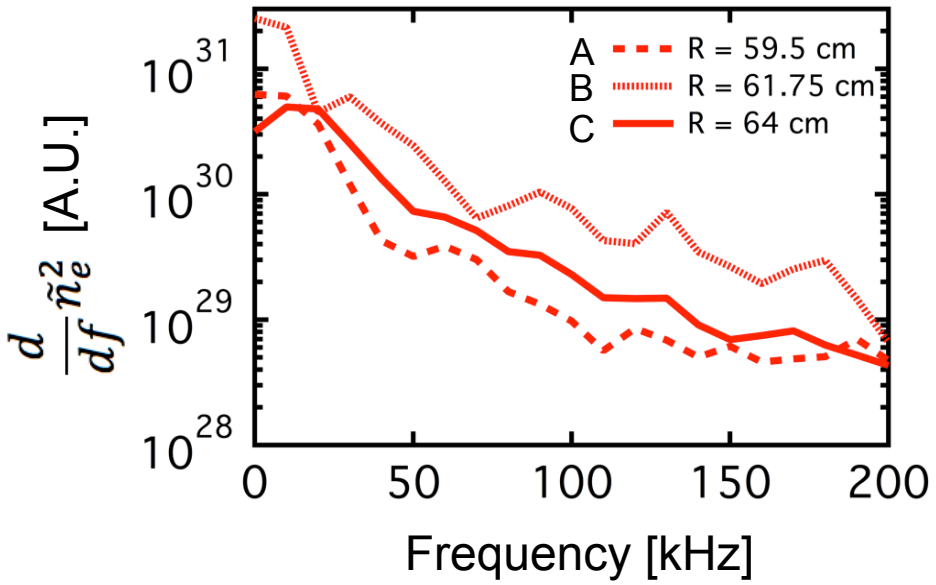


- Translation of p_e profile
  - 4 cm displacement



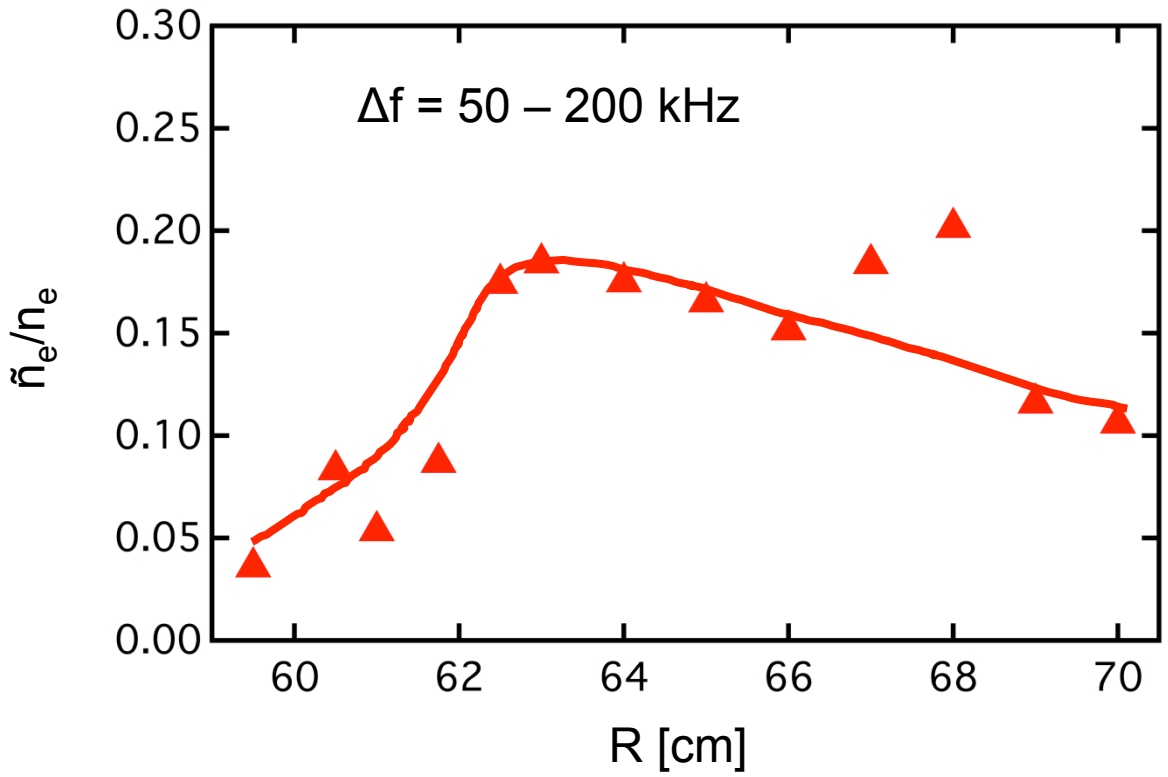
Fluctuation Spectra Obtained After MHD Correction

- Correction permits radial comparison of fluctuation spectra
- High frequency spectral content used to isolate MHD
  - $f_{MHD} < 50$ kHz
  - $f > 50$ kHz, turbulence data used
- Turbulent fluctuations reduced inside pedestal



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$\tilde{n}_e/n_e$ Decreased Inside H-mode Pedestal



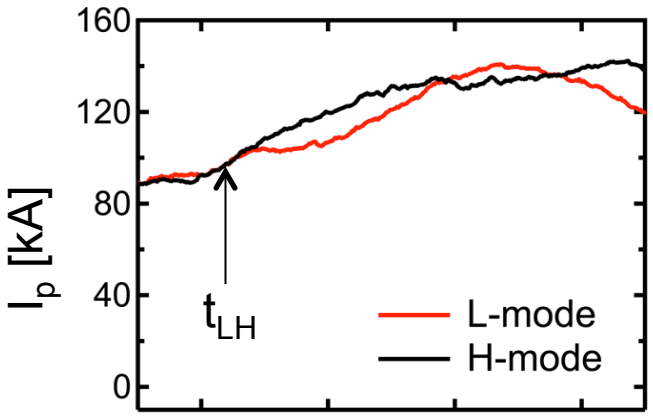
- $\tilde{n}_e/n_e$ drops rapidly inside LCFS
  - Behavior characteristic of tokamak edges[1]

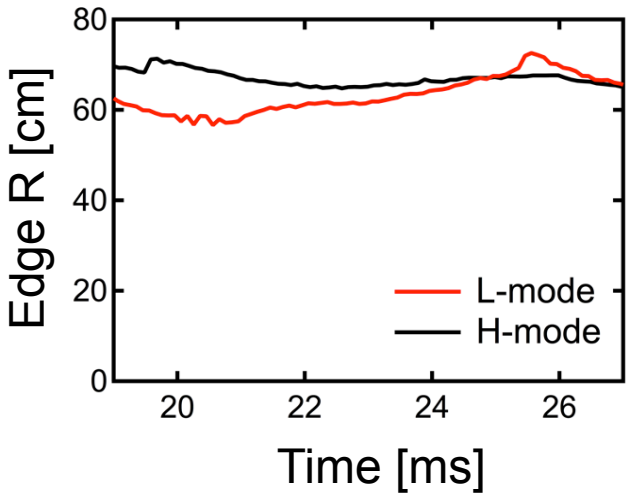
[1] Wootton *et al.*, Phys. Fluids B **2**, 12 (1990)

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Langmuir Probe Radially Scanned to Determine Pressure Profiles

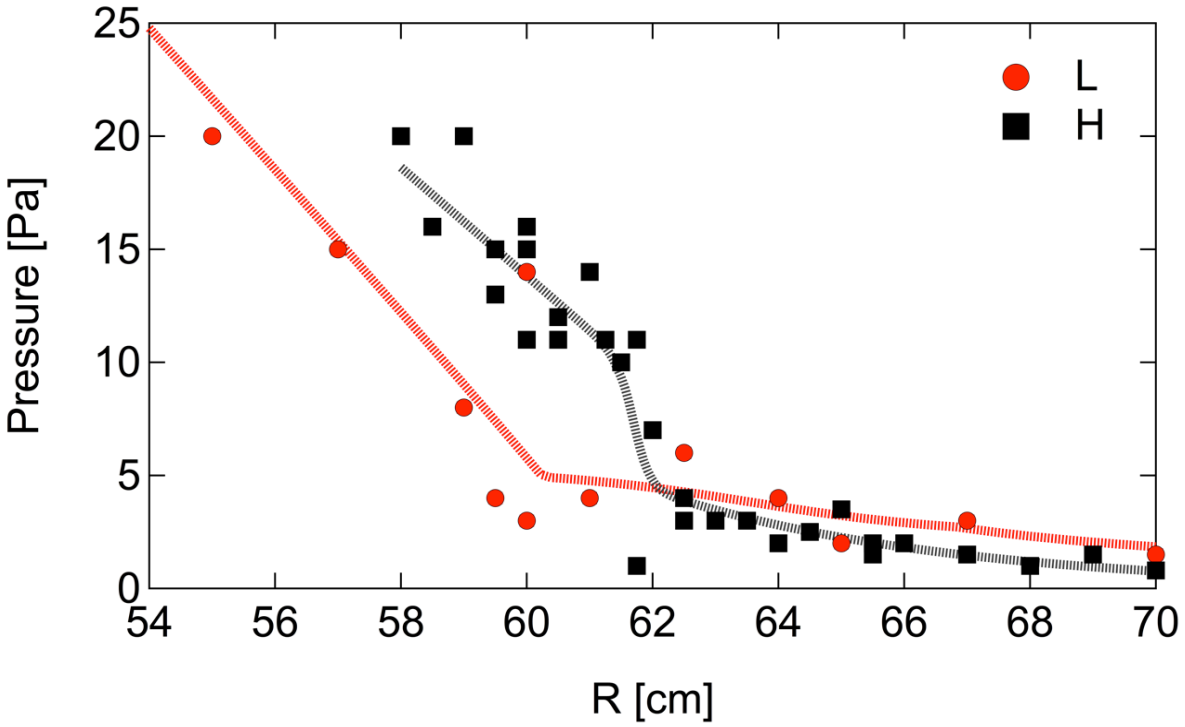
- Multi-shot profile: SOL – pedestal top
  - $R_{probe} = 48–70$ cm; $R_{edge} \sim 62$ cm
- Reproducible target plasmas
  - L, H-mode targets
  - >20 shots for each target
- Increased H-mode T_e limits insertion past pedestal top
  - By contrast, no limit observed in L-mode





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H-mode Pressure Pedestal Observed



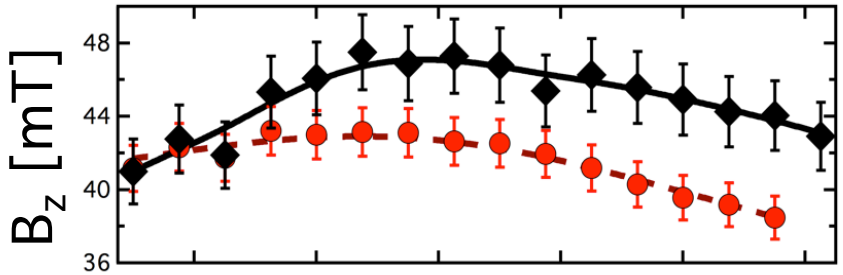
- $\langle p_e \rangle$ inferred from p_e minima
- H-mode best fits modified hyperbolic tangent[1]
- L-mode best fits bilinear trend

[1] Groebner *et al.*, Plasma Phys. Control. Fusion **40**, 673 (1998)

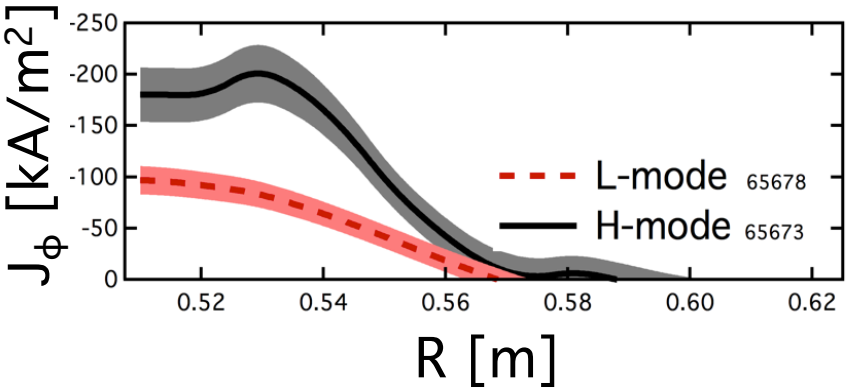
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H-mode Current Pedestal Observed

- Current profile measured in similar L and H shots
  - Measured in between ELMs



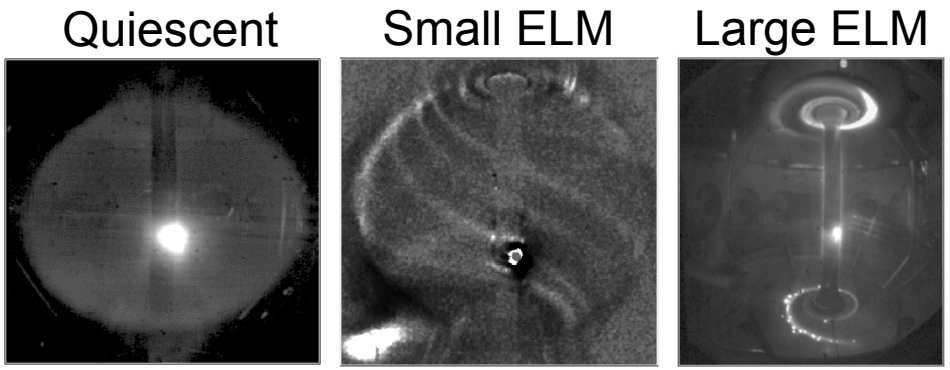
- Current scale length contracts
  - H scale length ~ 2 cm
  - L scale length ~ 4 cm

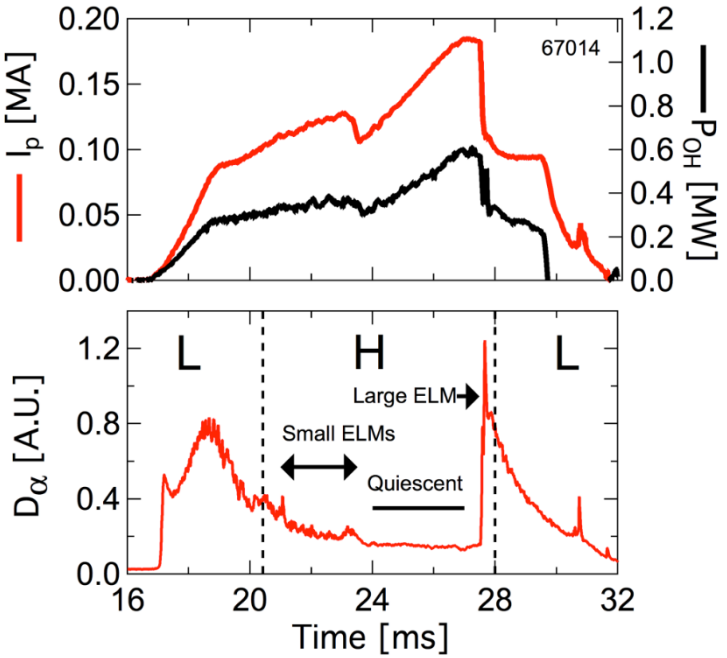


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A ~ 1 Enables Nonlinear ELM Studies

- Filament structures observed
  - Coincident with D_α bursts
- Small ("Type III") ELMs ubiquitous, less perturbing
  - $P_{OH} \sim P_{LH}$
- Large ("Type I") ELMs infrequent, violent
  - $P_{OH} >> P_{LH}$
  - Can cause H-L back-transition

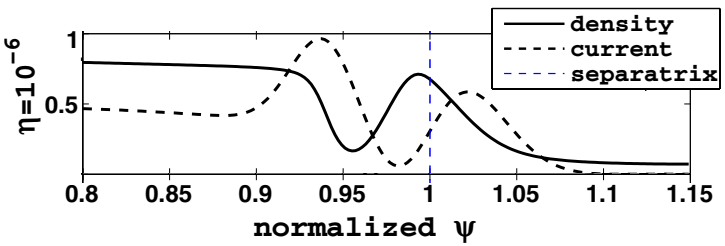




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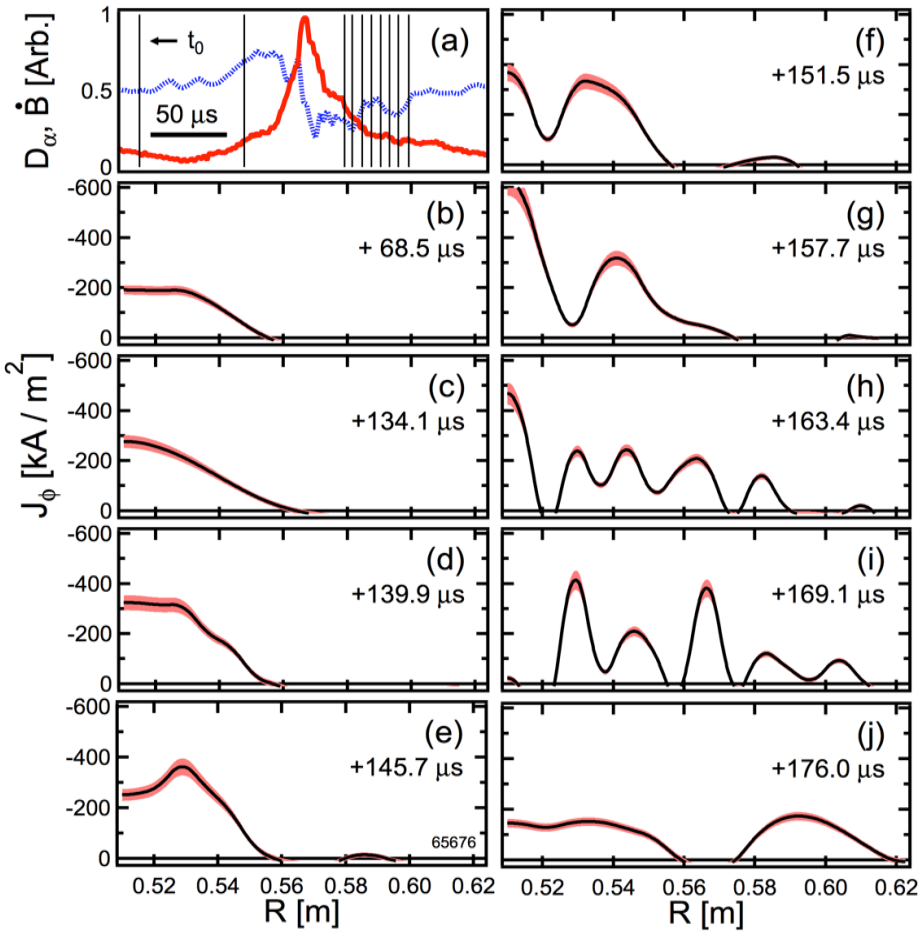
Complex Evolution of $J_{edge}(R,t)$ During ELMs

- Challenge: study nonlinear ELMs at τ_A
- Complex behavior with current-filament ejection
  - Time-averaged qualitatively similar to JOREK[1] results



[1] Pamela *et al.*, Plasma Phys. Control. Fusion **53**, 054014 (2011).

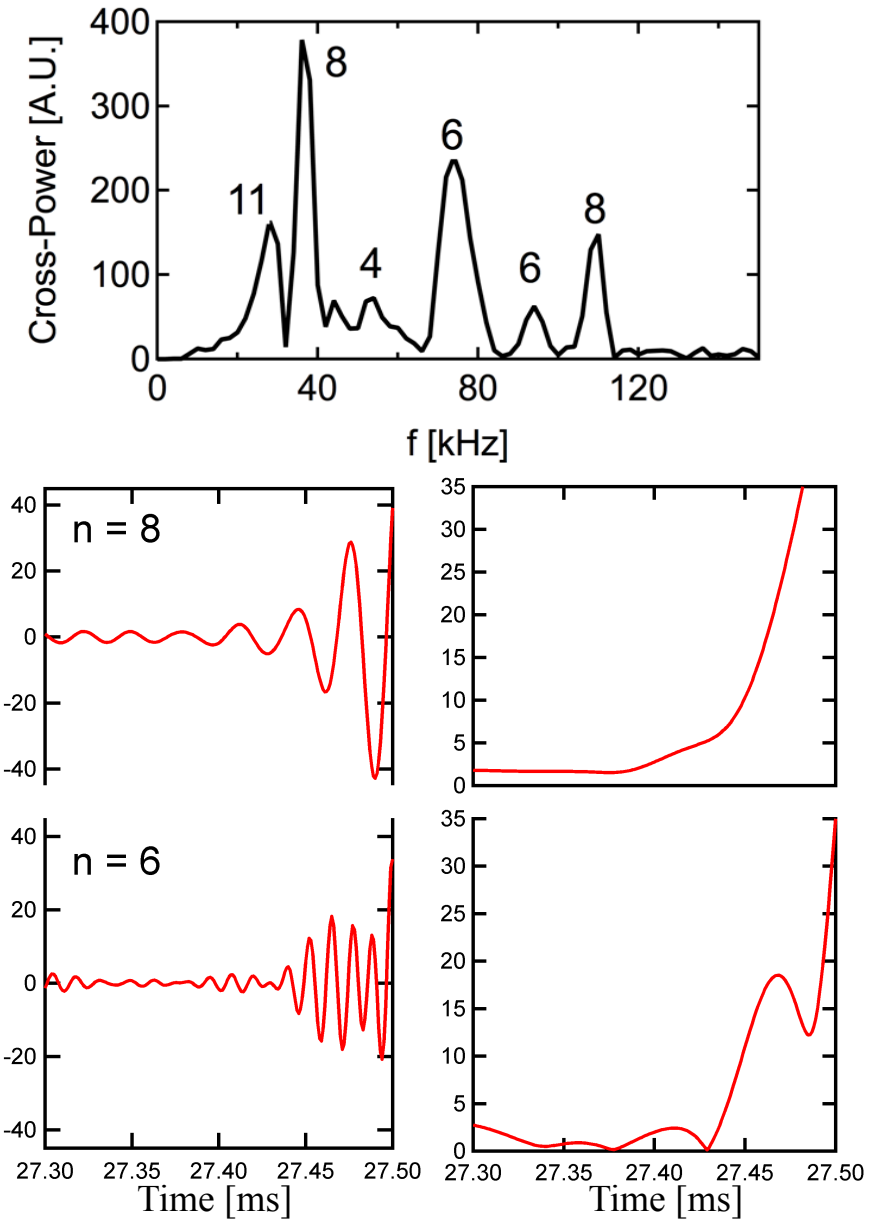
Type I ELM Evolution



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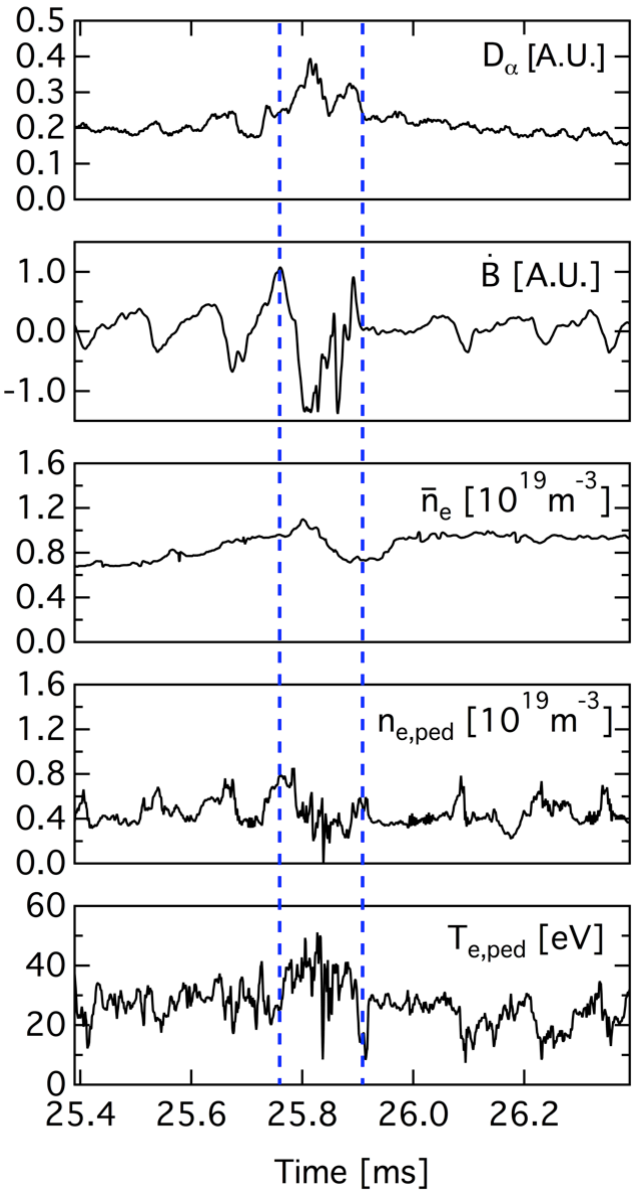
Nonlinear ELM Precursors Observed

- Magnetic signature of ELMs have multiple n components
  - Simultaneously unstable modes
- Modes show different time evolutions
  - Isolated with bandpass filter
  - n = 8 grows continuously
  - n = 6 fluctuates prior to crash



Edge n_e, T_e Measured Throughout Large ELM

- Type I ELM
  - Fast n_e, T_e dynamics at R = 59.5 cm
- Edge T_e, n_e expelled during ELM
  - ~25% reduction in $T_{e,ped}$
  - ~20% reduction in $n_{e,ped}$
- Post-ELM, n_e recovers faster than T_e
- Motivates high spatial resolution array for comparison to nonlinear theory

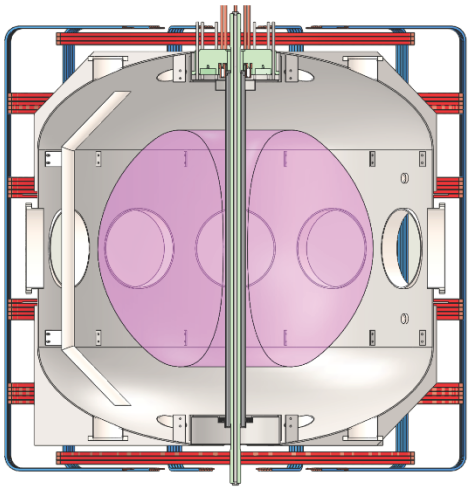


Future Work: Multiprobe Array, Stable Edge

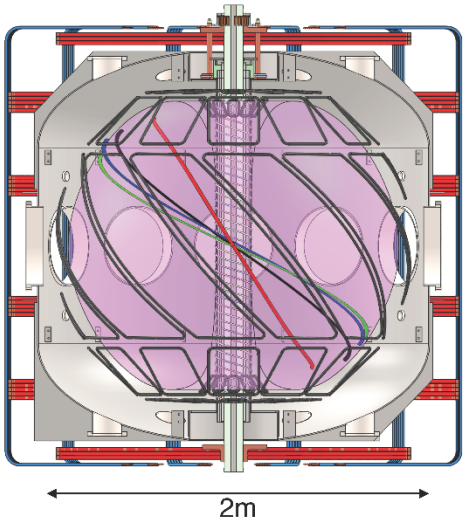
- Multiprobe array in design
  - Fast measurement of $n_e(R,t)$, $T_e(R,t)$, and $\Phi(R,t)$

- PEGASUS-U will couple diagnostics with stable, longer pulse scenario
  - LHI-OH Handoff
  - TF upgrade: >2x increase in B_T
  - New OH solenoid: 4x V-s

PEGASUS



PEGASUS-U



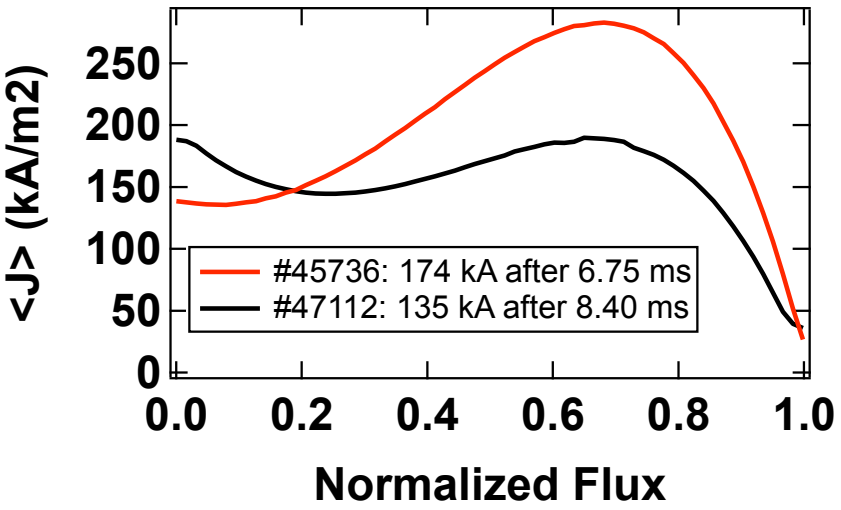
Multi-Langmuir Probe Design Underway

- 8 triple probes in a radial array
  - Gives $n_e(R,t)$, $T_e(R,t)$, and $\Phi(R,t)$
  - 2 MHz data acquisition
- Design to be informed by knowledge of correlation length
  - Will be determined by scanning two poloidally separated triple probes
- Enables study of nonlinear ELM and pedestal dynamics
  - Simultaneous $J_{edge}(R,t)$, $p_{edge}(R,t)$, and $v_\phi(R,t)$ through ELM cycles
- Allows characterization of turbulence spatial structure

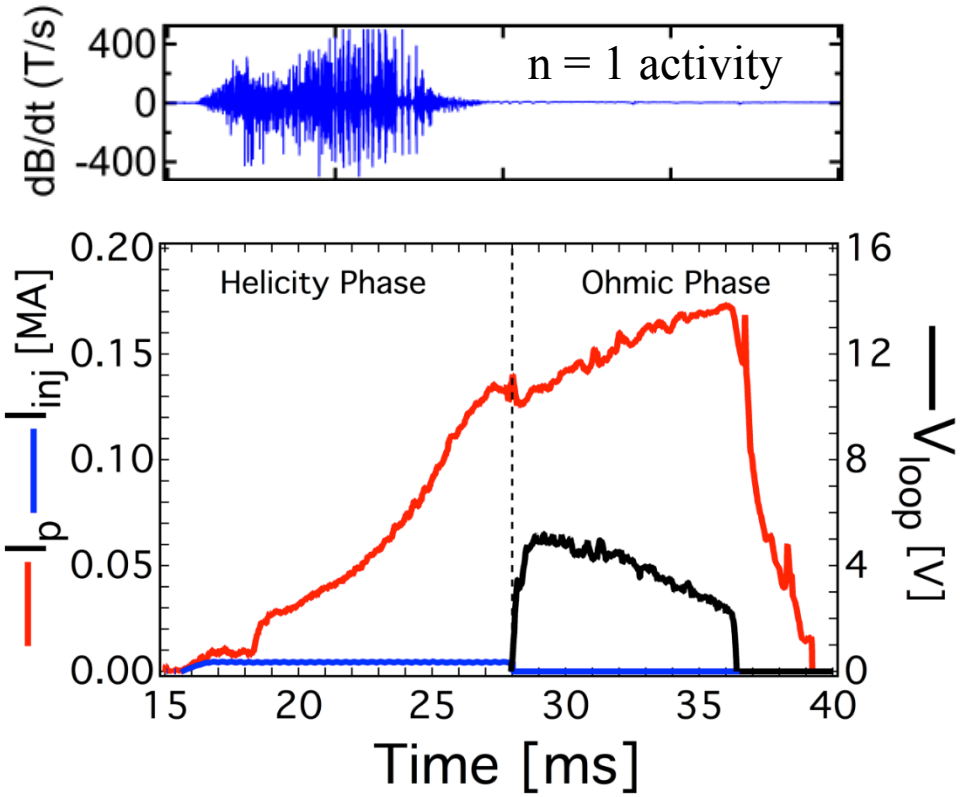
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LHI-OH Handoff Improves MHD Stability

- Handoff changes J profile
  - More core peaked in LHI-OH



- H-mode compatible with LHI startup
  - Low-n tearing stability improves



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Conclusions

- H-mode achieved in plasmas with probe pedestal access
- Current and pressure pedestals observed in H-mode
- Density fluctuations decrease inward of H-mode pedestal
- Probe measurements show nonlinear ELM dynamics
- Future Langmuir probe array to expand capability