Experiment Overview

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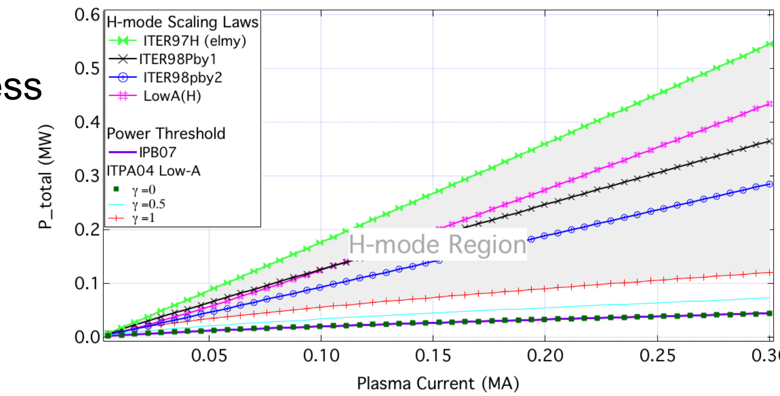
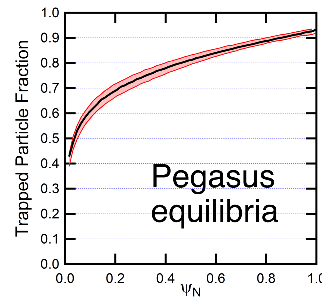
Operation at A ~ 1 Offers Ready Access to Advanced Tokamak Physics

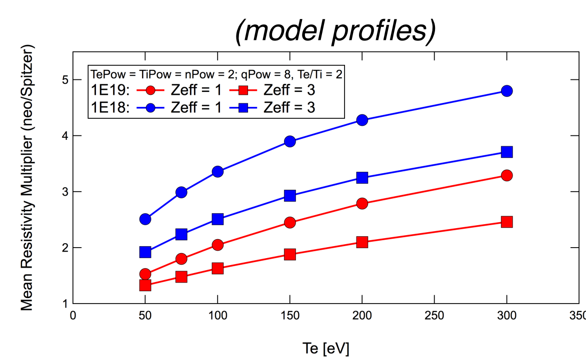
- Very low B_t at modest I_p = very low P_{th} for H-mode access
  - High edge shear = separatrix not necessarily needed
  - Easy access with ohmic heating only
  - ***BUT*** need hot edge => centerstack fueling



H-mode power threshold and ohmic confinement scalings for PEGASUS.

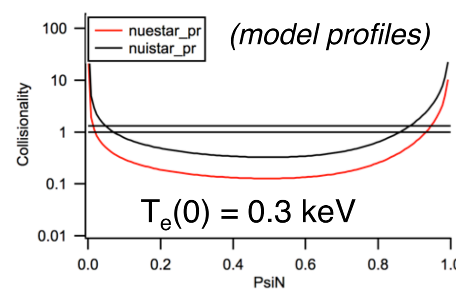
- Short connection lengths and very strong trapping = neoclassical effects at low T_e
  - High particle trapping fractions
  - Strongly non-Spitzer resistivity
  - Bootstrap current possible





- High j_{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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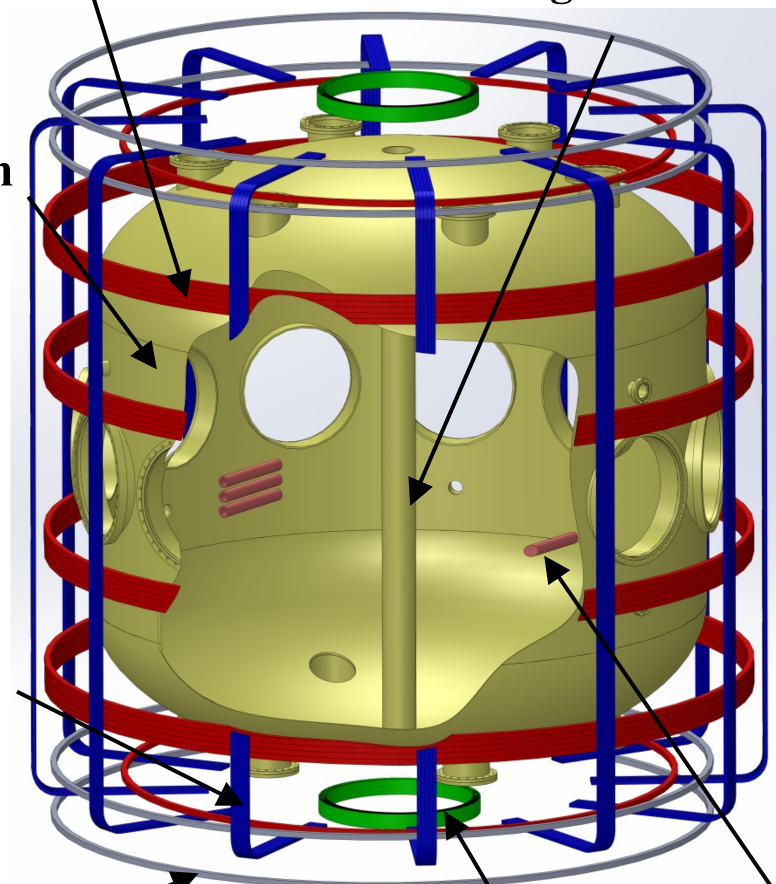
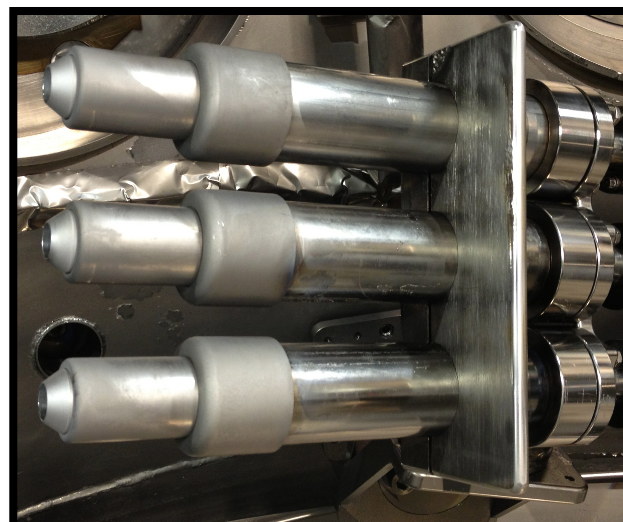
Pegasus is a Compact, Ultralow-A ST



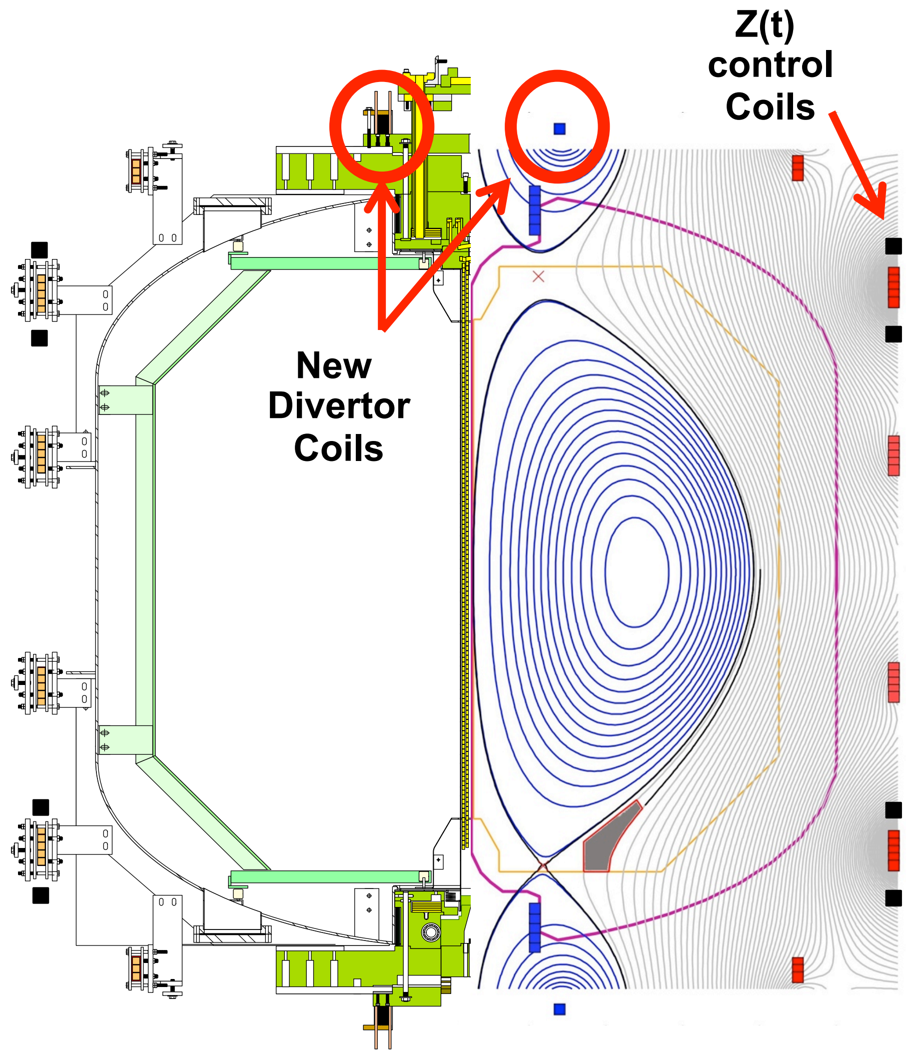
Experimental Parameters

Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	$\leq$ .23	$\leq$ 0.30
I_N (MA/m-T)	6 – 14	6 – 20
RB_t (T-m)	$\leq$ 0.06	$\leq$ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	$\leq$ 0.025	$\leq$ 0.05
β_t (%)	$\leq$ 25	> 40



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 kV, 14 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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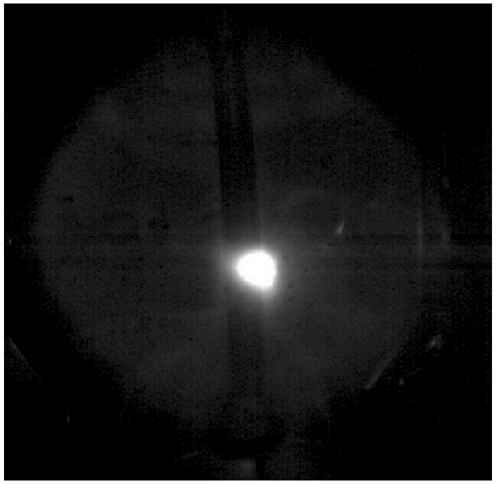
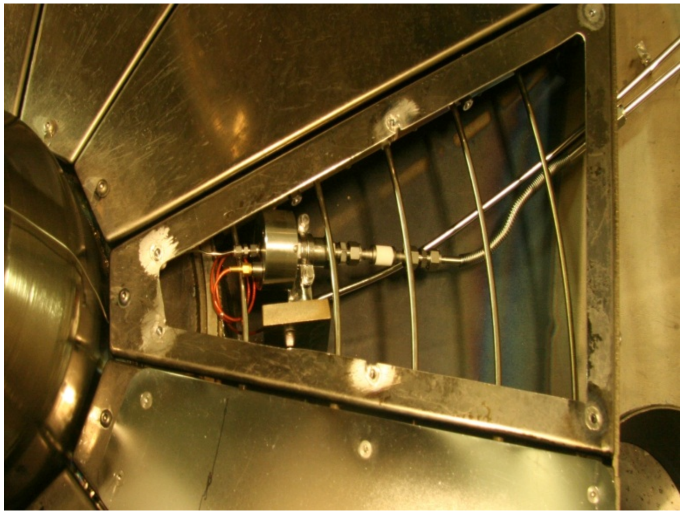
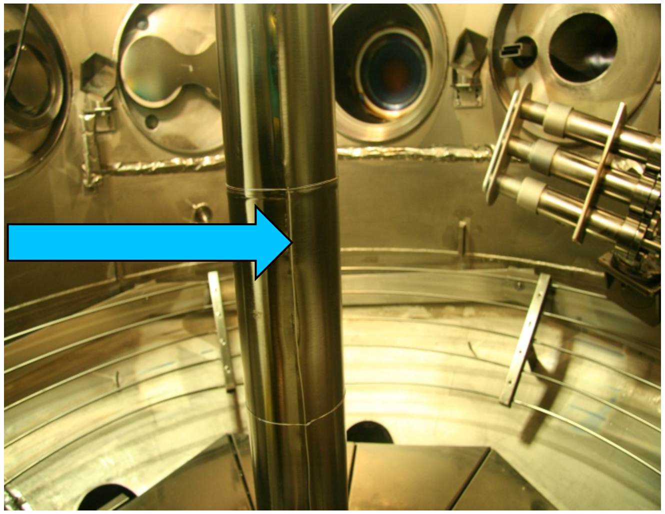
Implemented Internal High-field Side Gas Valve

- Characteristics
  - In-vacuum piezoelectric valve
  - z = - 30 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_{thres} depends strongly on n_e, B_{TF}, and ion ∇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_{thres} scaling
  - This equation has 21.4% RMSE and no ST data

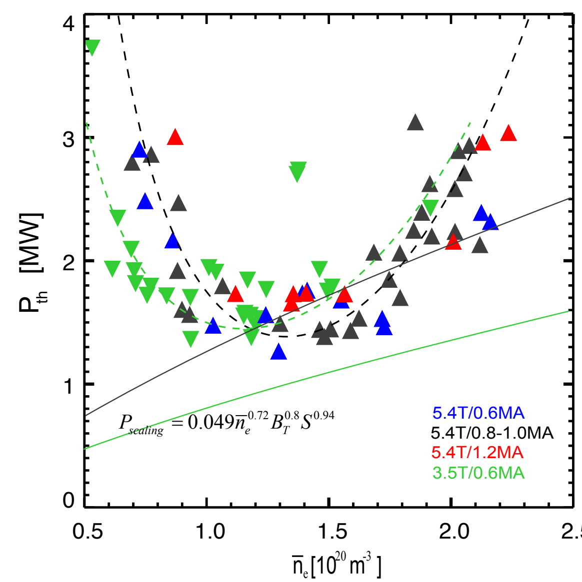
$$P_{PIPB} = 0.042 n_{20}^{0.73} B_{TF}^{0.74} S^{0.98}$$

$$S = 4\pi^2 a R \left(\frac{1+\kappa^2}{2}\right)^2$$

- 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_{th} has nonlinear dependence on N_e



Y. Ma, et al, "Scaling of H-mode threshold power and L–H edge conditions with favourable ion grad- Bdrift in Alcator C-Mod," Nuclear Fusion, vol. 52, no. 2, p. 023010, 2012.

Different empirical scaling explicitly incorporates aspect ratio

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

$$\left|B\right|_{out} = (B_{tout}^2 + B_{pout}^2)^{0.5},\ \ B_{tout} = B_{TF}\frac{A}{A+1},\ \ B_{pout} = \frac{\mu_0 I_p}{2\pi a}(1+\varepsilon),$$

$$F(A) = \frac{0.1A}{1-\left(\frac{2}{1+A}\right)^{0.5}} \qquad and \ \ \gamma = 0.5 \pm 0.5$$

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

I. H. mode Power Threshold Database and T. p. b. Takizuda, "Roles of aspect ratio, absolute B and effective Z of the H-mode power threshold in tokamaks of the ITPA database," Plasma Physics and Controlled Fusion, vol. 46, no. 5A, pp. A227–A233, 2004.

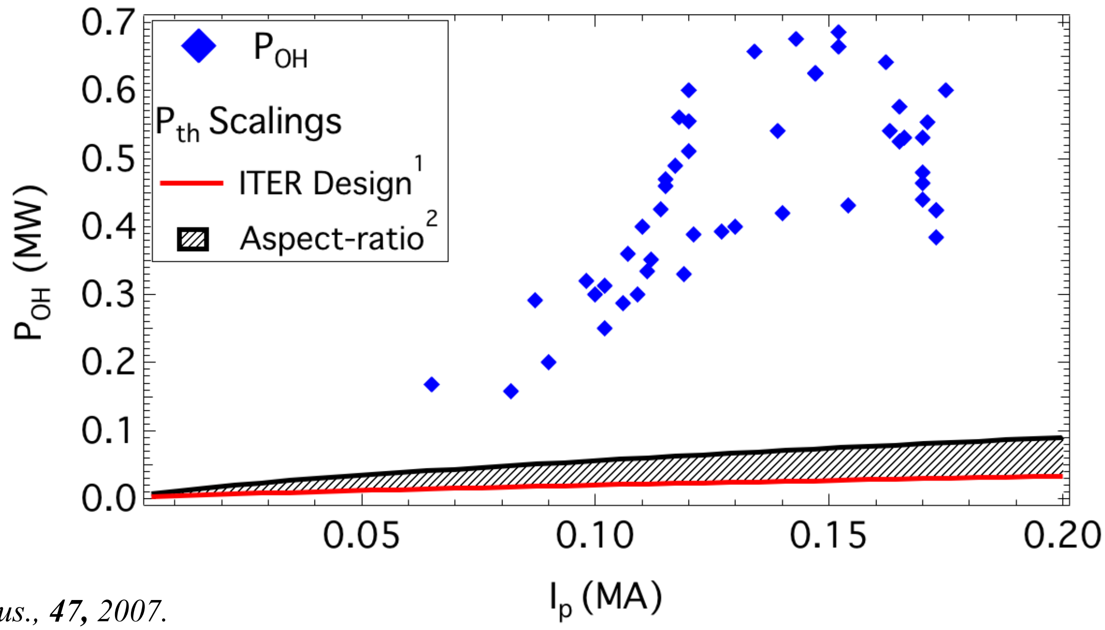
PEGASUS P_{OH} Exceeds P_{th} Predictions

- L-H power threshold scalings: $P_{th} \sim n_e^{0.7} B_T^{0.7} S$
  - 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_{shot} and $<T_e>$ allow probes in pedestal

Experimental Parameters

Parameter	Achieved
B_T (T)	0.08–0.16
A	1.15–1.3
R (m)	0.2–0.45
I_p (MA)	≤ 0.21
κ	1.4–3.7
t_{shot} (s)	≤ 0.025
T_e (eV)	100–200

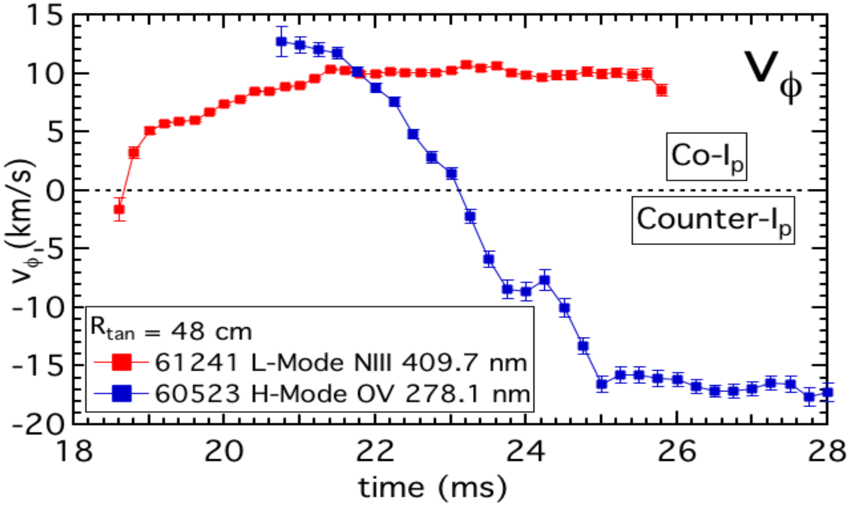


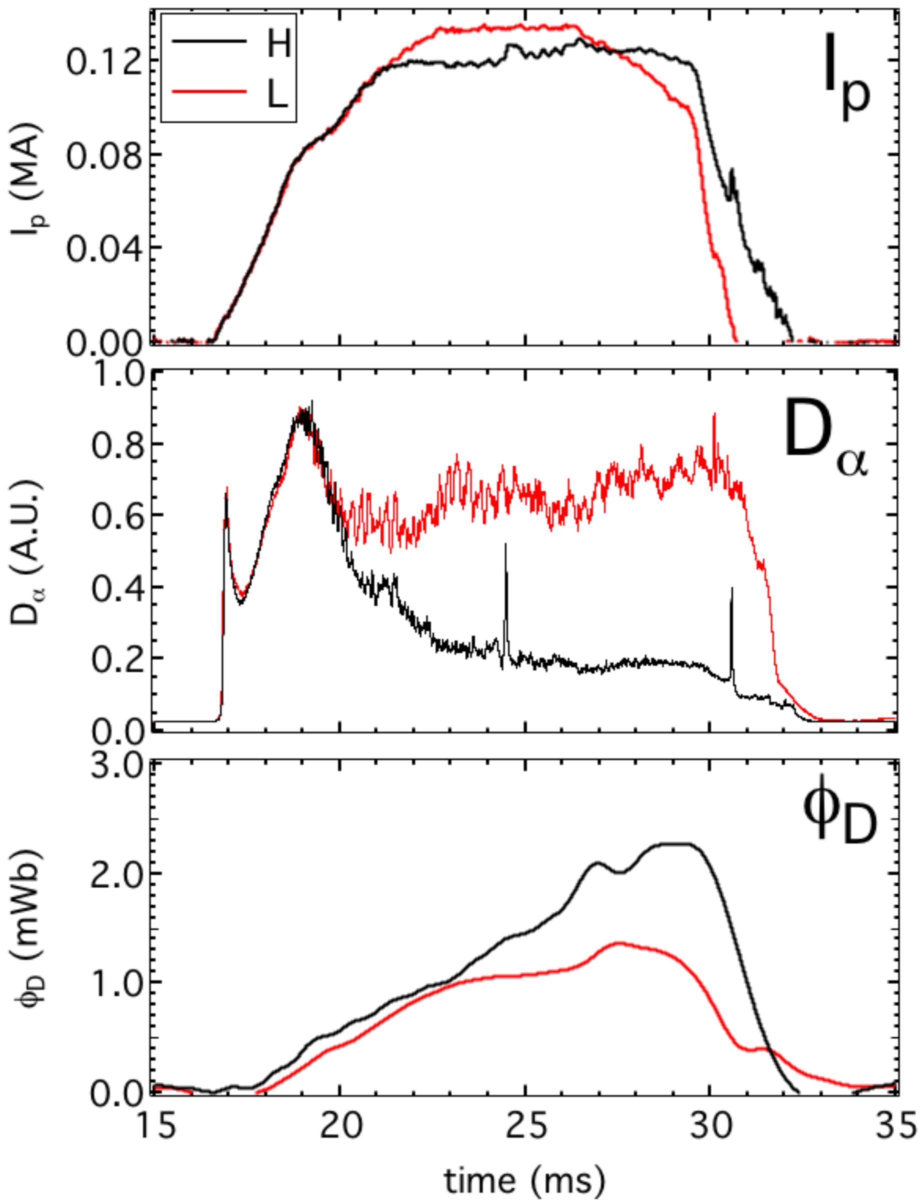
[1] *Accepted ITER design threshold P_{th}: K. Ikeda," Nucl. Fus.,* ***47,*** *2007.*
[2] *P_{th} with low-A data: I. H. mode Power Threshold, Plasma Phys. Control. Fus.,* ***46****, 2004*

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_α
  - Large and small ELMs suggested
  - Bifurcation in ϕ_D
  - Core v_ϕ reverses



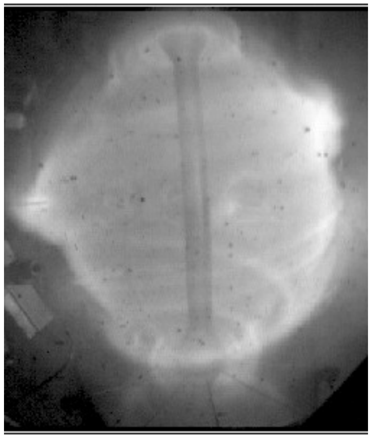


Fueling Location, Particularly in STs, is Critical for Achieving H-mode

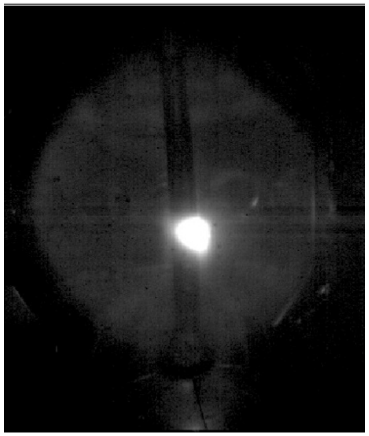
- LFS and HFS fueling
- H-mode achieved using HFS fueling
  - Similar to MAST and NSTX[1]
  - Both limited and diverted

Limited

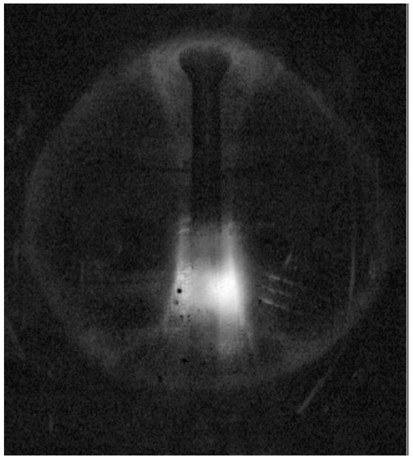
LFS Fueled (L)



HFS Fueled (H)



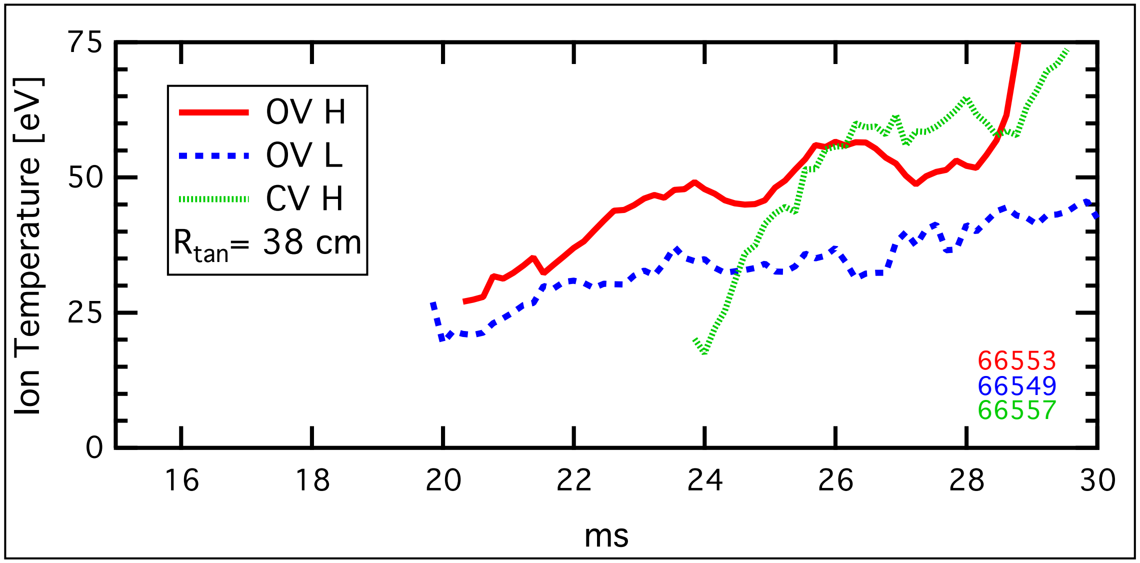
Diverted (H)



[1] *A. R. Field et al, Plasma Phys. Control. Fus.*, ***46***, *2004.*

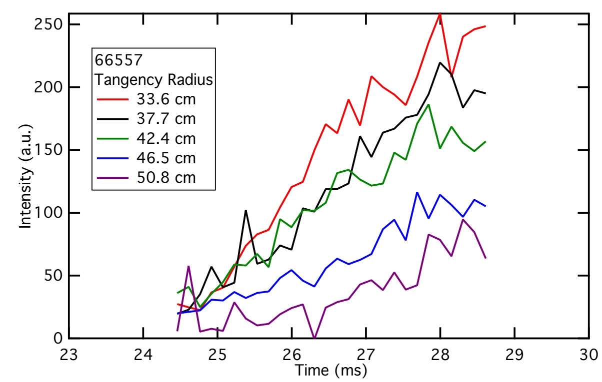
Impurity Spectroscopy Suggests T_i and T_e Increase in H-mode Core Region

- 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



RJF, 2013 APS/DPP, Denver

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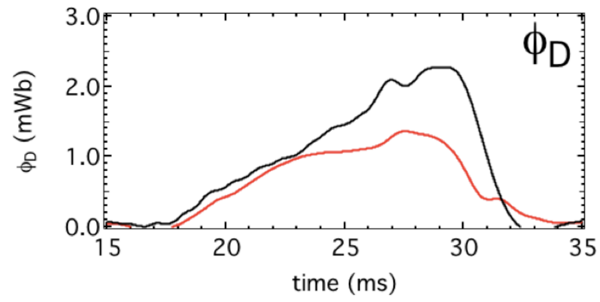
Increased l_i Indicated by Rise in Paramagnetism at L-H Transition

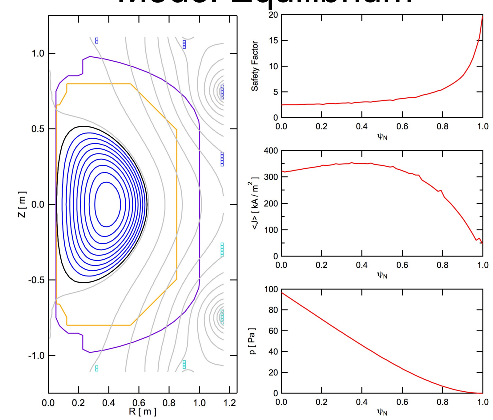
- Rise in diamagnetic flux loop signal indicates rise in *paramagnetism* at A ~ 1
  - Not a rise in total stored energy
  - Magnetic reconstructions confirm increased l_i in H-phase
    - H: l_i ~ 0.45;   L: l_i ~ 0.35

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

H-mode indicated by rise in paramagnetism



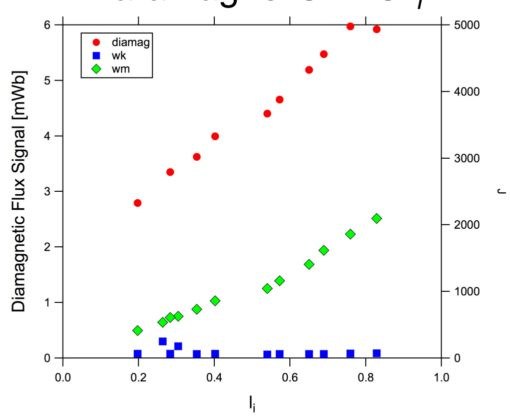
Model Equilibrium



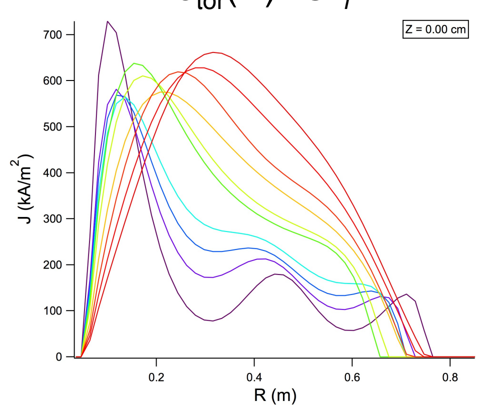
Equilibrium Parameters
Shot 12345, 0.000 ms

I_p	150 kA	R_0	0.354 m
β_t	0.0035	a	0.299 m
ℓ_i	0.54	A	1.18
β_p	0.019	κ	1.7
W	1101 J	δ	0.43
B_{T0}	0.177 T	q_{95}	11.6

Paramagnetism vs l_i



J_{tor}(R) vs l_i



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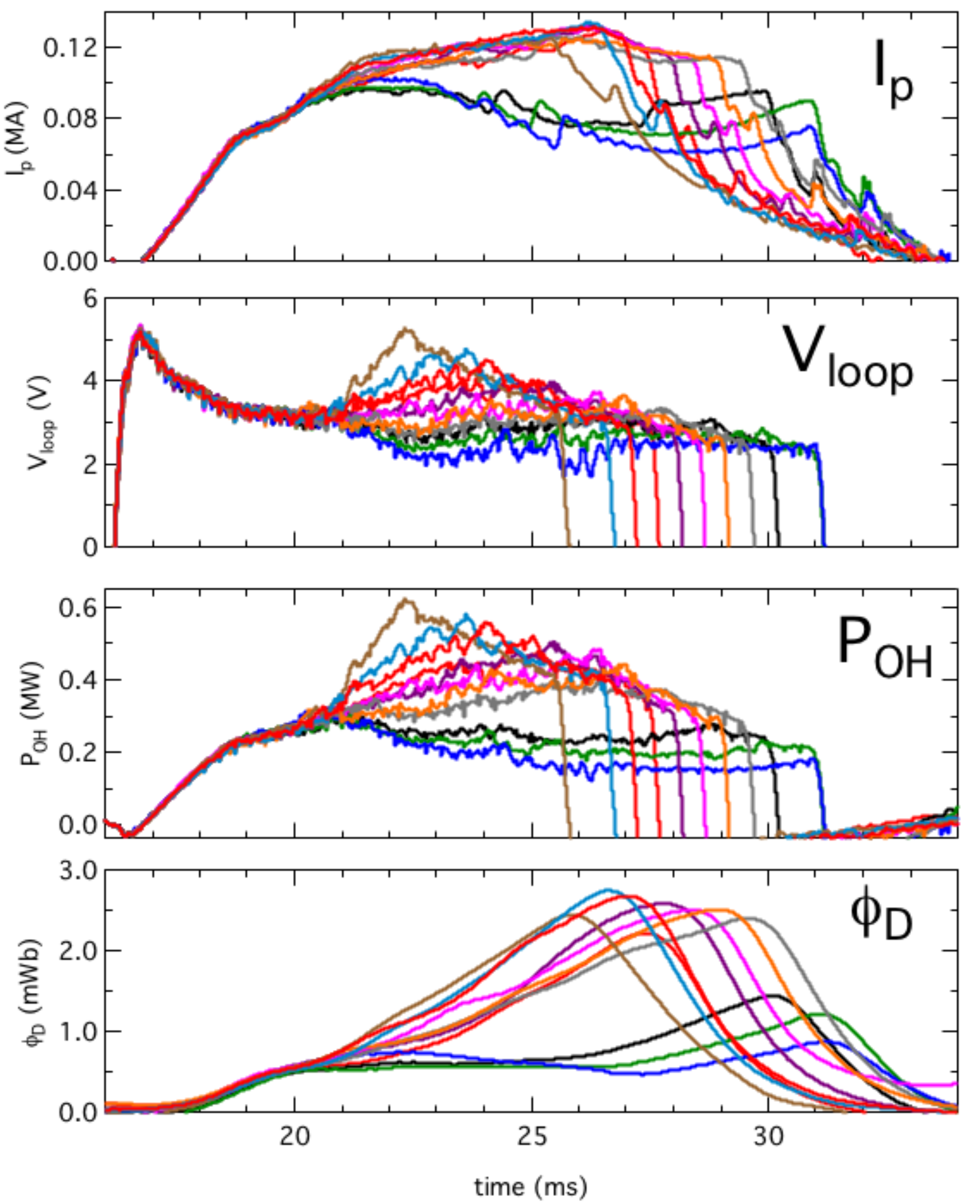
P_{th} and $J_{edge}(R)$ Pedestal

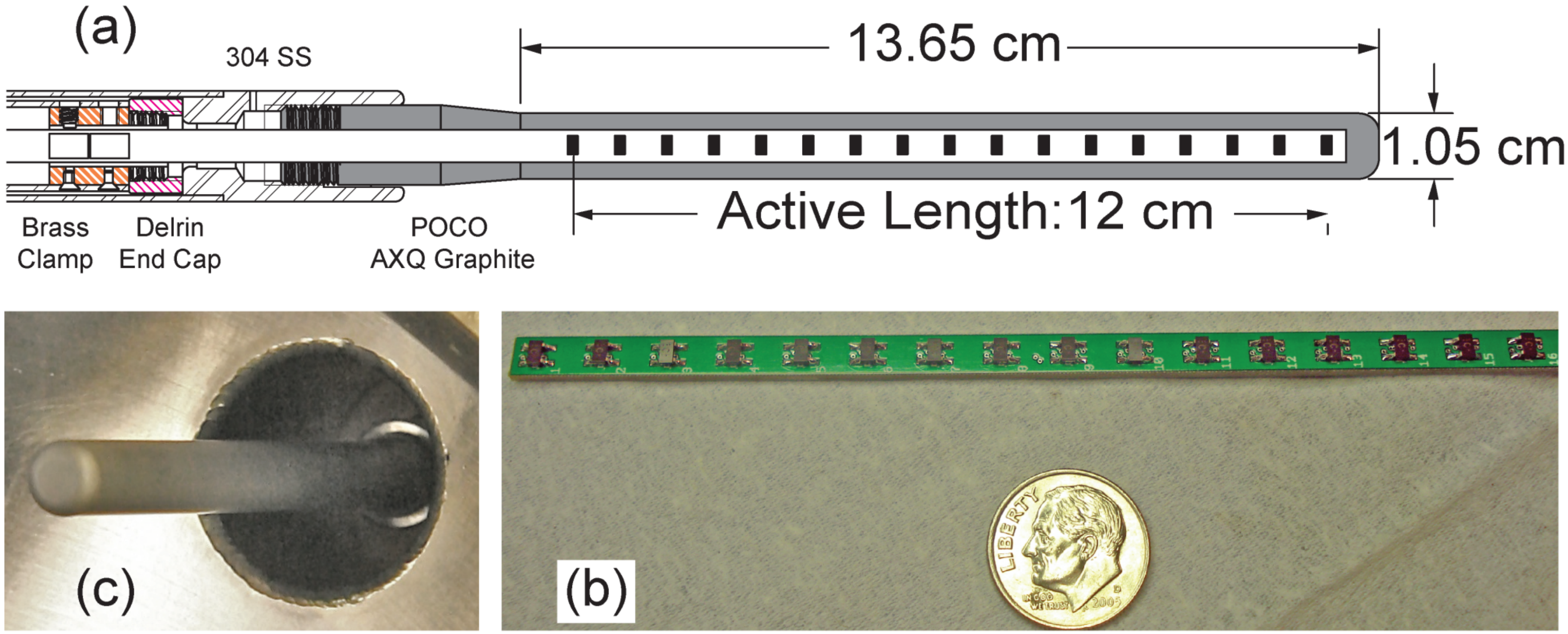
P_{th} Measured using V_{loop} Scans

- Infer t_{LH} from bifurcation in ϕ_D
  - Vary $P_{OH} = I_p V_{loop}$
  - Constant I_{EF}, shape, fueling



- P_{th} ~ 0.25–0.30 MW
  - Scalings predict < 0.1 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

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

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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* solves for an off-midplane $B_Z(R)$ measurement set and an elliptical plasma cross-section:

$$\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R - R_0)} \left(1 - \frac{Z^2 R_0}{\kappa^2 R (R - R_0)^2}\right) - \frac{dB_Z}{dR} \left(1 + \frac{Z^2}{\kappa^4 (R - R_0)^2}\right)$$

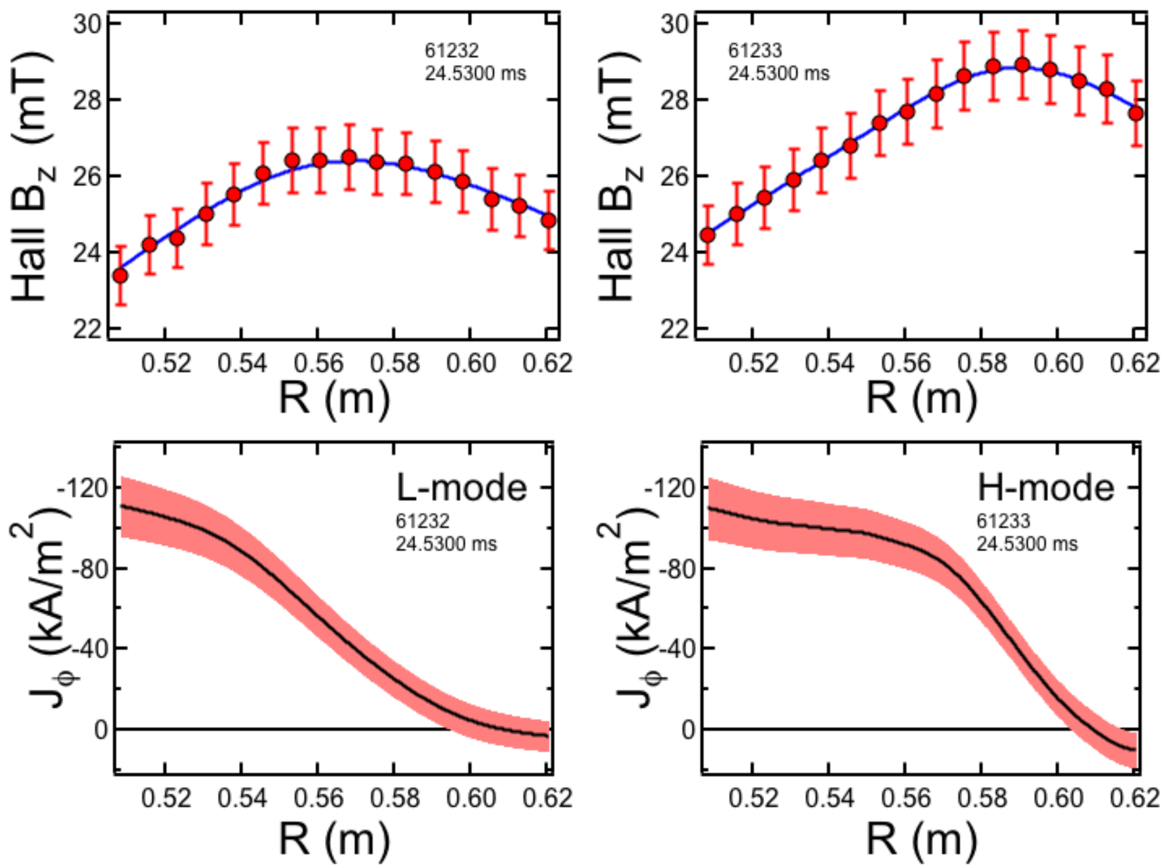
- Does not make assumptions on shape of J(R)

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

Current Pedestal Measured using Hall Probe Array

- Internal B_z measurement from Hall probe array yie local $J_\phi(R,t)$[1]

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



[1] *M. Bongard, Rev. Sci. Instrum.* ***81****, 10E105 (2010).*

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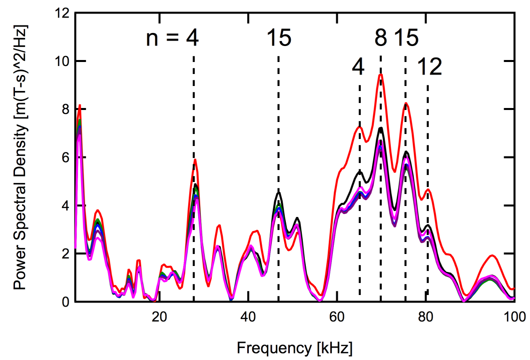
General Observations

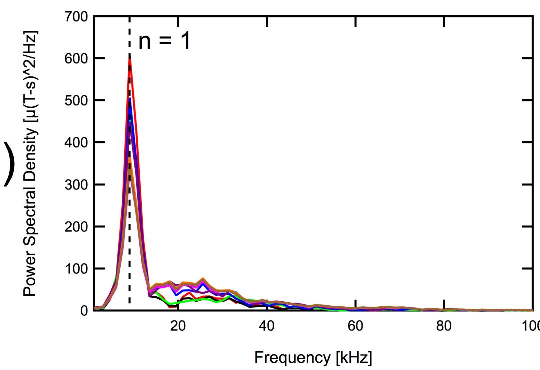
Large and Small ELMs Suggestive of Type I and III ELMs are Seen

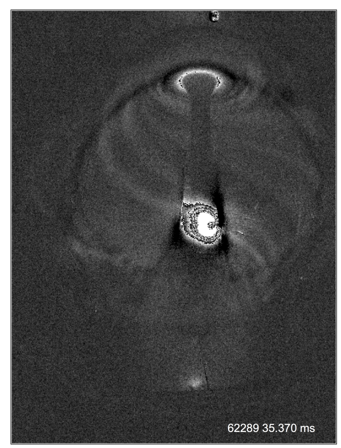
- Filament structures observed
  - Large ELMs infrequent and violent
    - Can cause H-L back-transition
    - Occur at high P_{OH}
  - Small ELMs more ubiquitous and less perturbing
    - Occur at lower P_{OH}
- n measured with close-fitting coil array through ELM crash
  - PEGASUS results similar to NSTX
    - Large ("Type I"): intermediate-n
    - Small ("Type III"): low-n
  - STs appear to have structure opposite that of ATs



Large (Type I)

Small (Type III)





Coherent filaments associated with ELMs

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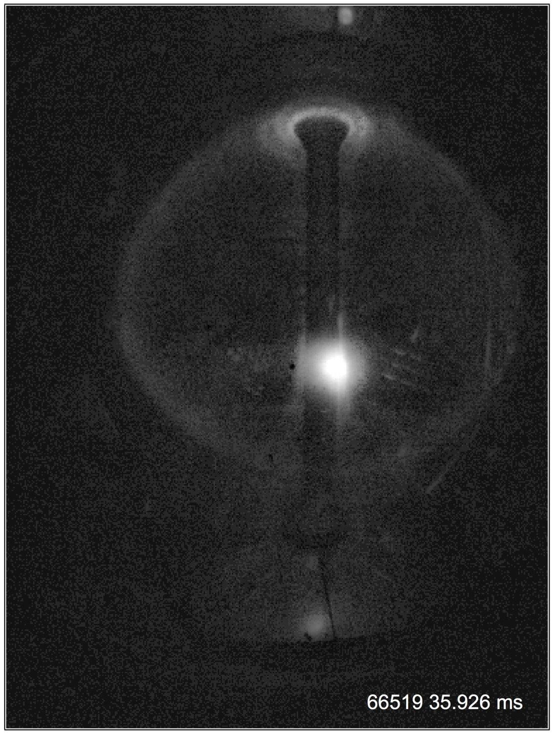
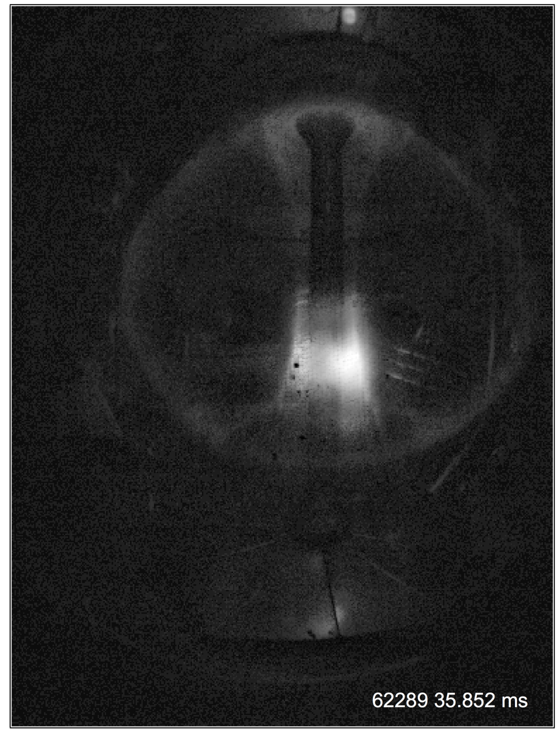
Divertor Coils Activated to Access Standard Separatrix-Limited H-modes

Non-diverted:
Centerstack Limited



Diverted:
Separatrix Limited



- Initial results: no clear difference between diverted and non-diverted
- *But*, short pulse length complicates τ_E measurement

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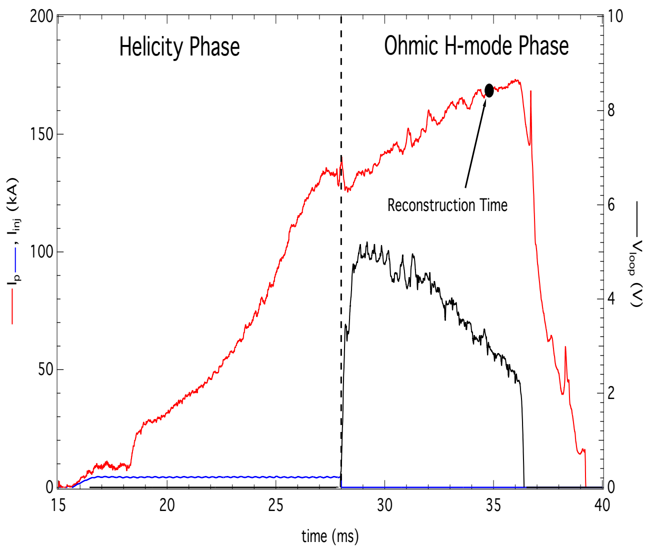
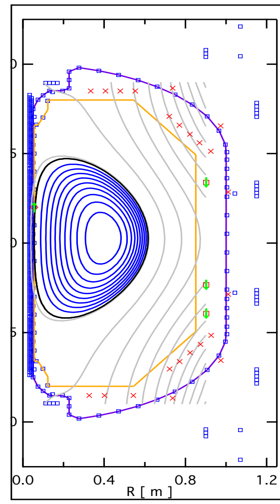
LHI Startup Compatible with Consequent High-Quality OH H-mode

- High-Ip, long-pulse H-mode plasmas desirable for Pegasus goals
  - Confinement and edge stability studies
  - Attaining high β_t regime
- Need additional current drive
  - LHI-initiated discharge readily couples to ohmically-driven H-mode





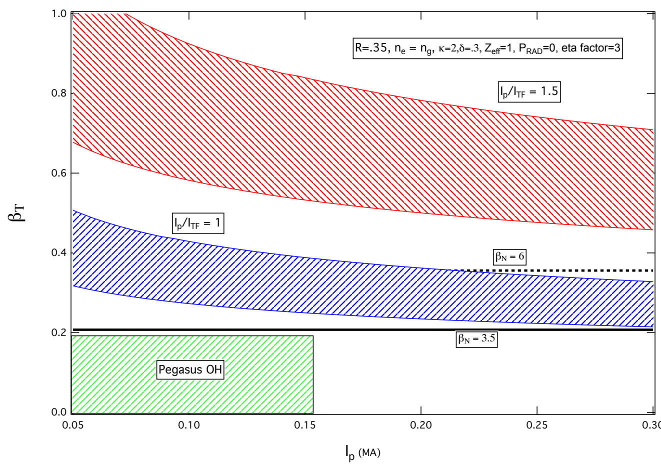
Equilibrium Parameters
Shot 66221, 34.80 ms

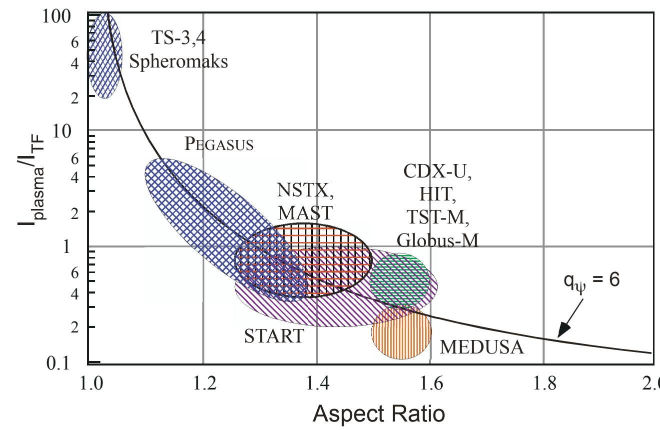
I_p	169 kA	R_0	0.336 m
β_t	0.081	a	0.281 m
ℓ_i	0.42	A	1.20
β_p	0.31	κ	1.6
W	2101 J	δ	0.44
B_{T0}	0.179 T	q_{95}	9.92

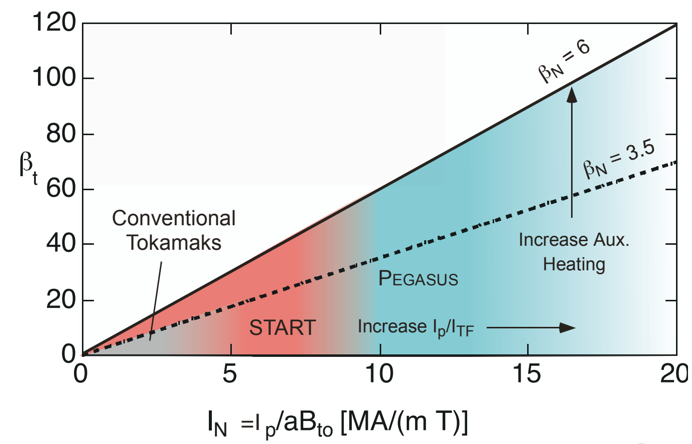
- But, difficult to raise I_p in ohmic phase with available V-sec
  - May be influenced by: residual MHD activity; increasing $l_i(t)$
- High I_p, long-pulse operation awaits new integrated LHI assembly, power systems upgrades, and new OH solenoid

Non-solenoidal startup and H-mode Facilitates Access to high-β_t Regime as A→1

- Pegasus designed to explore tokamak stability limits at A ~ 1
- Requires access to relevant space
  - High I_p/I_{tf}
  - Good OH confinement







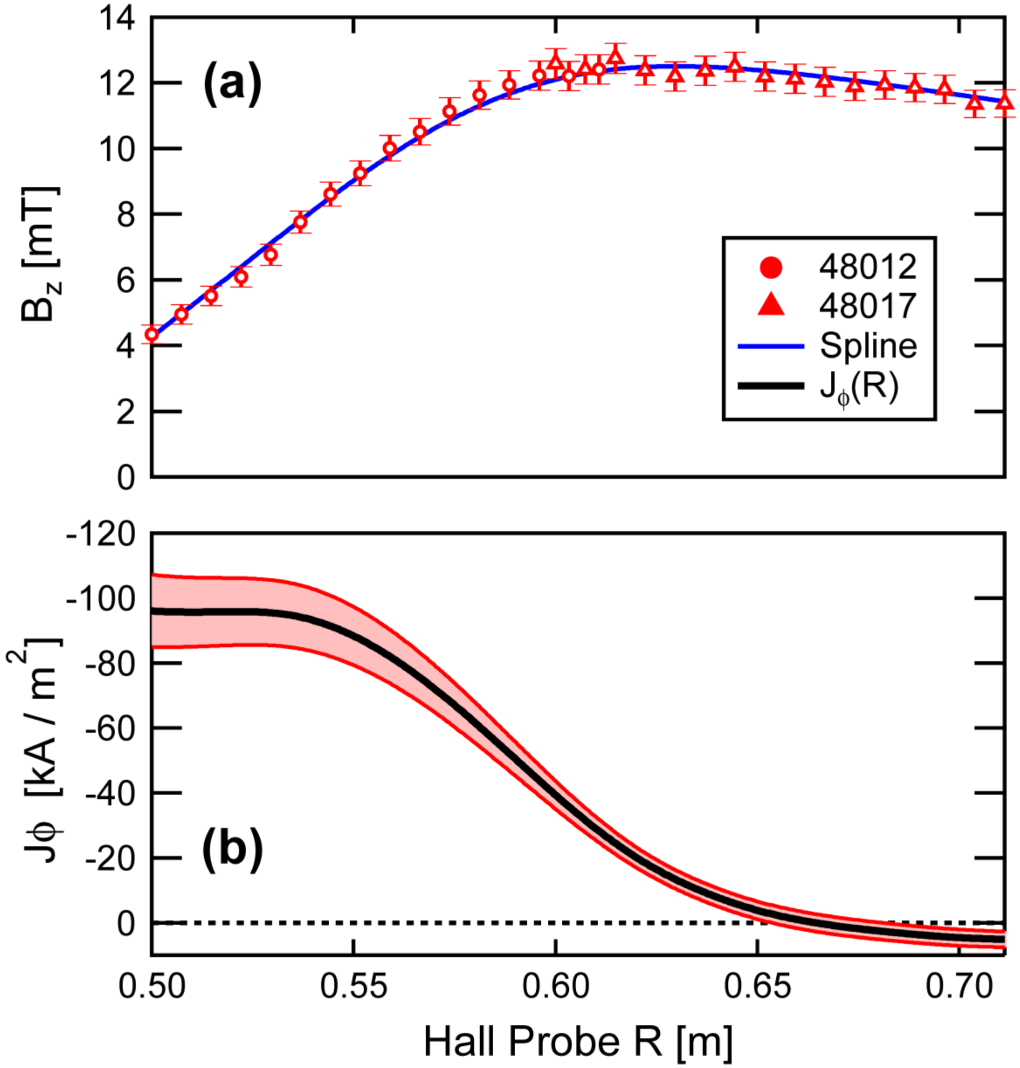
- Research thrusts should enable access to this unique stability regime
  - LHI: High I_p/I_{tf}
  - H-mode: Good OH confinement

Summary: A ~ 1 Operation Enables Studies of H-mode Phenomena

- Low toroidal field at A ~ 1 facilitates access to H-mode
  - P_{th} ~ 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

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

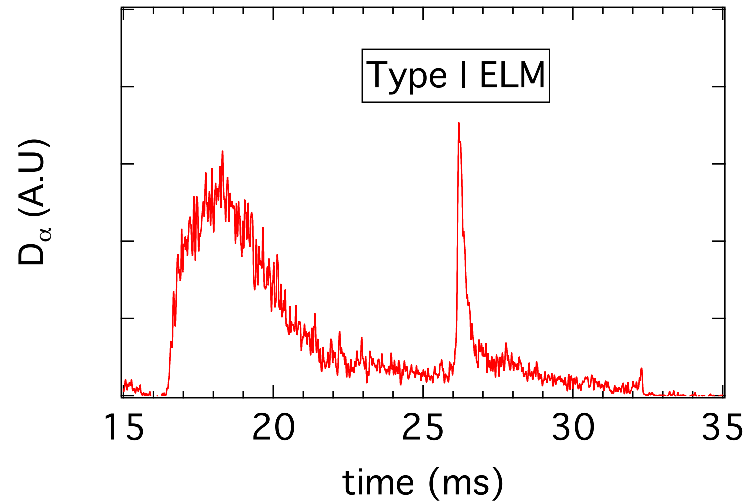


Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

*: Reinsch, Numerische Mathematik **10**, 177 (1967)

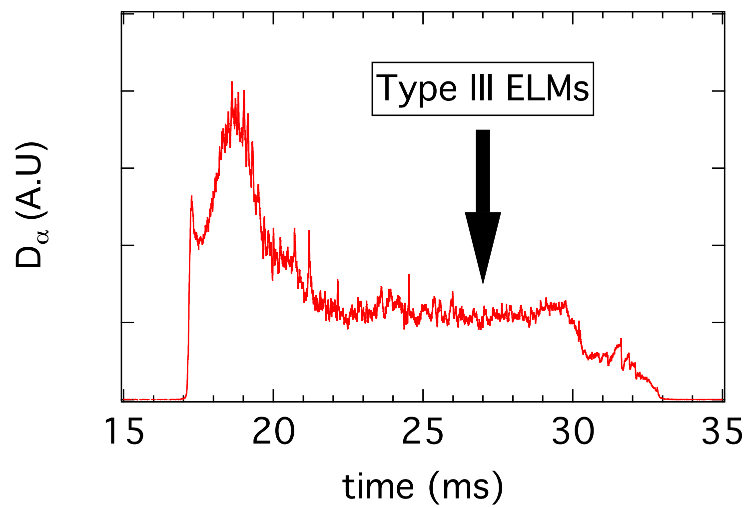
Type I and Type III ELMs seen in H-mode

- 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

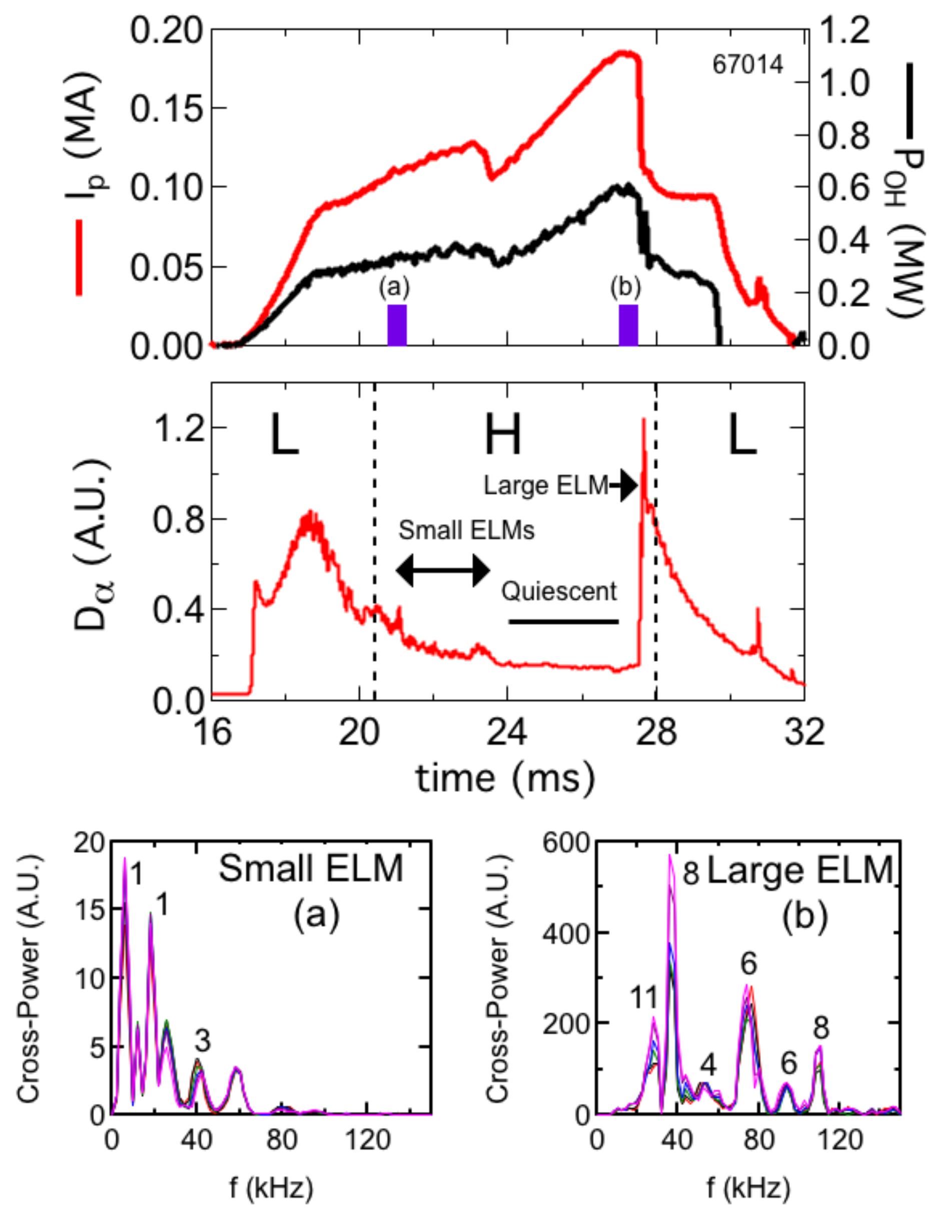
- Many Type III ELMs occur in a single discharge



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



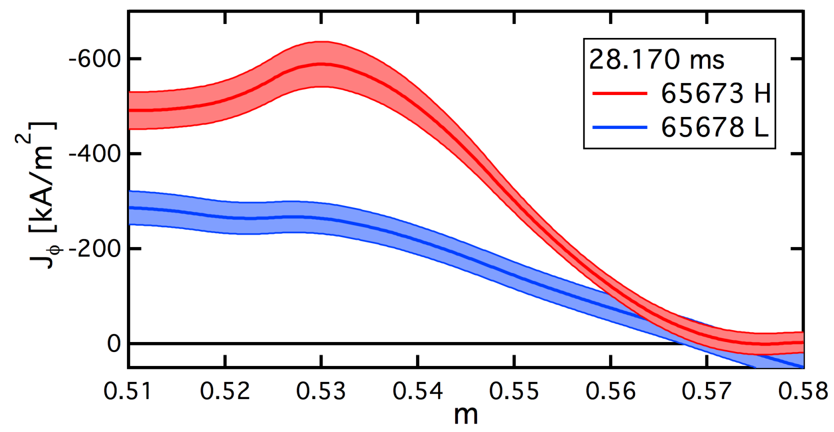
RJF, 2013 APS/DPP, Denver

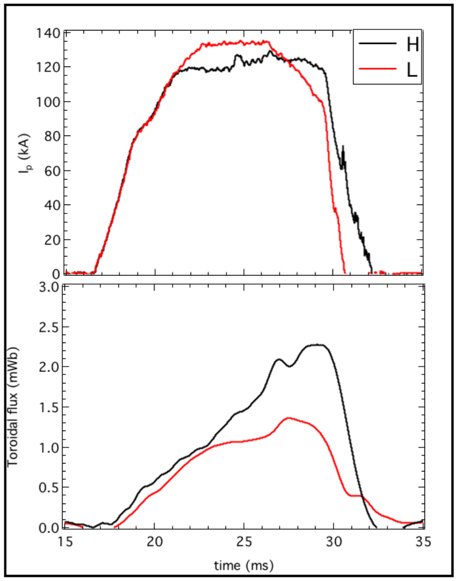
Edge Current Pedestal Observed in H-Mode

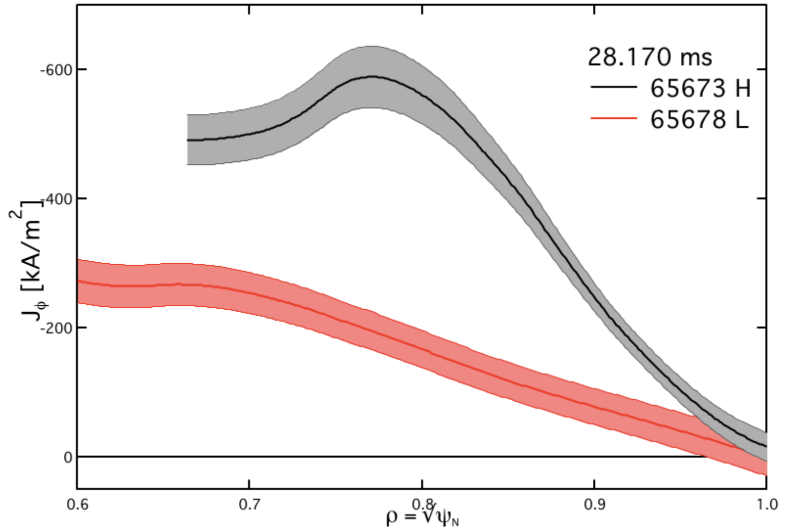
- Internal B measurements from Hall array* yield local $J_\phi(R,t)$**
  - Map to ψ_N only approximate

- Current gradient scale length significantly reduced in H-mode

  L → H: 6 → 2 cm







*: M.W. Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)
: C.C. Petty *et al.*, Nucl. Fusion **42, 1124 (2002)

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