Improved Density Control in the PEGASUS Toroidal Experiment using Internal Fueling

K. E. Thome, J. L. Barr, M. W. Bongard, M. G. Burke, J.A. Cole, R. J. Fonck, E. T. Hinson, A. J. Redd, G. R. Winz



University of Wisconsin-Madison

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PEGASUS Toroidal Experiment

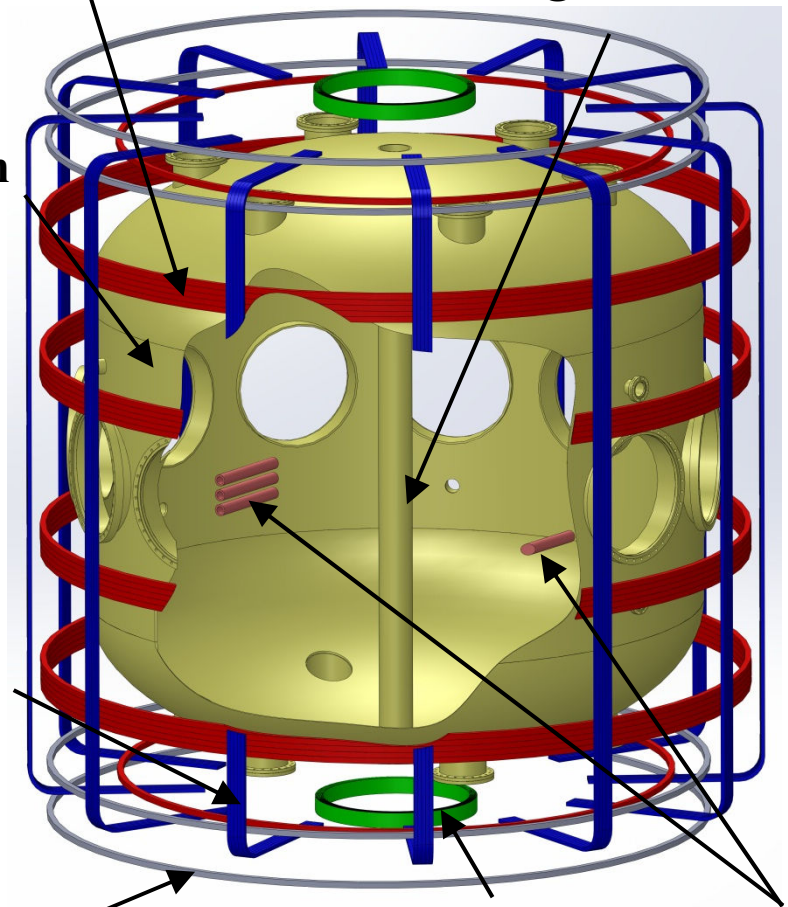
Motivation for Improved Density Control

- Recent experiments demonstrated that PEGASUS currently operates in an extremely low-recycling regime with $R < 0.8$ and $Z_{eff} \sim 1$
- Separating core plasma and local current source fueling is crucial to the success of helicity experiments
- Attaining high n_e/n_g operation is essential for stability experiments as $A \rightarrow 1$

Outline

- Introduction to PEGASUS
- Previous Results
- New Gas Valves
- Valve Results
- H-mode Results
- Future Work and Conclusions

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)	≤ .21	≤ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

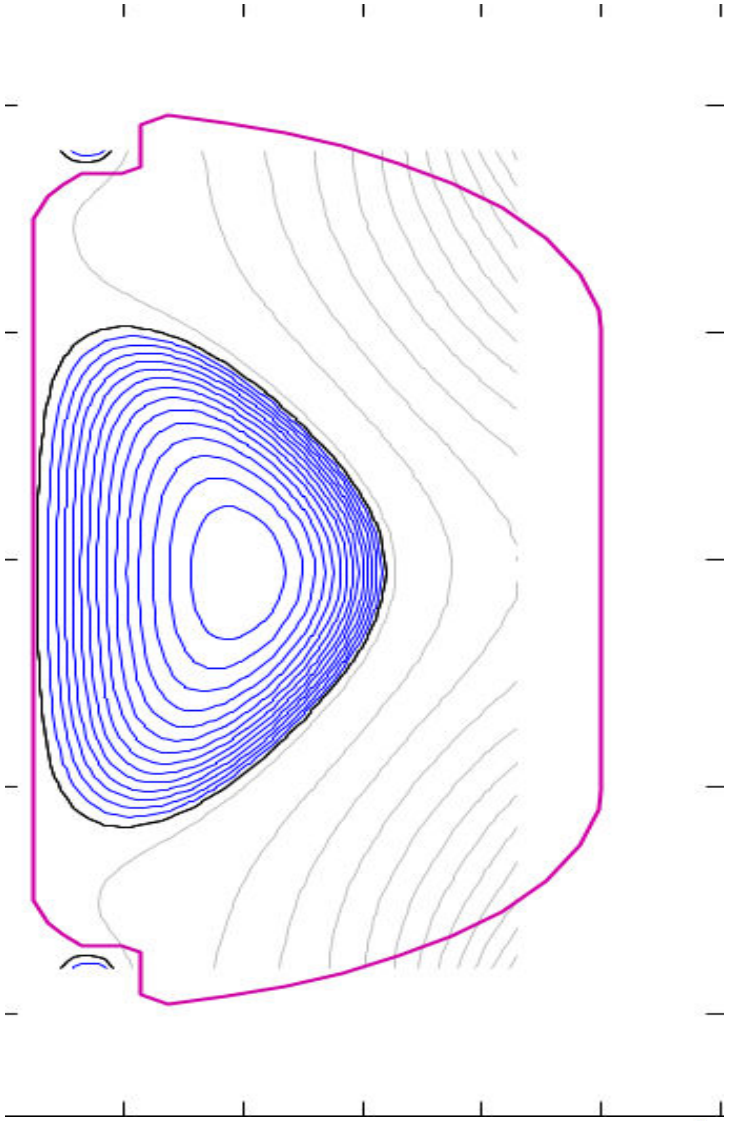
Major research thrusts include:

- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β stability limits*
  - *ELM-relevant edge MHD activity*

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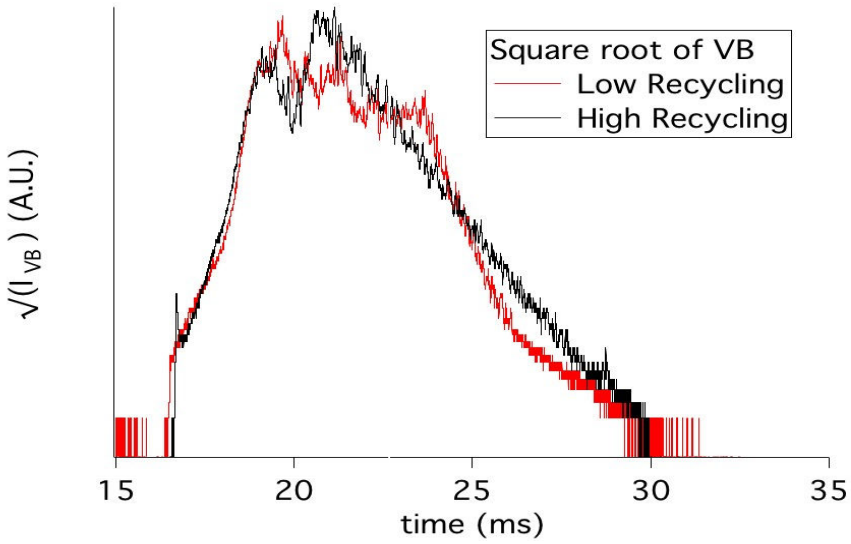
Vacuum Conditions

- Pumping
  - Cryogenic Pump 5000 Torr·L/s for N_2
    - Removes N_2, O_2, H_2O
  - Titanium gettering covers >80% of plasma facing components
    - 0.045 to 0.15 grams Ti sublimated per hour
    - Very difficult to passivate
- Base Pressure
  - Overnight base pressures < $3x10^{-9}$ Torr
  - Between shot base pressures < $4x10^{-8}$ Torr
- Wall far from plasma
  - Limiter 15 cm from vacuum vessel



Ohmic Plasmas have low Z_{eff} and very low Recycling

- Z_{eff} ~ 1
  - SPRED has very low signal levels and is dominated by O and D lines
  - Bolometers show very low $P_{RAD} \sim 0.6$ mW/cm^3
  - MIST used to estimate Z_{eff}



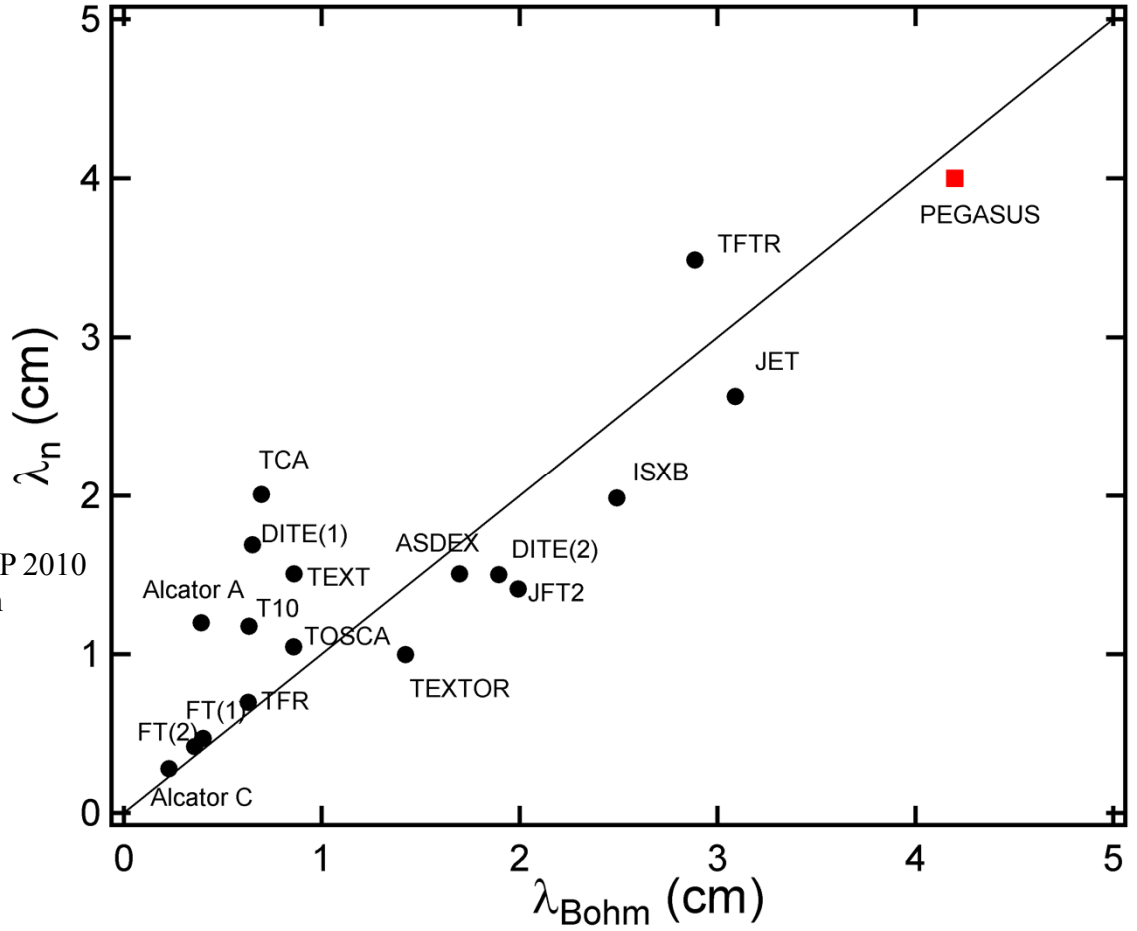
- R < .8
  - τ_p^* estimated from interferometer after terminating gas puffs for both low and high recycling in L-mode discharges
    - Low recycling τ_p^* ~ 2.8 ms
    - High recycling τ_p^* ~12 ms
  - τ_e estimated from reconstructions
    - Both cases $\tau_e \sim$ 1 ms
  - Assume $\tau_p \approx \tau_e$

$$\tau_p^* = \frac{n_e}{\frac{dn_e}{dt}} = \frac{\tau_p}{1-R}$$

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Broad n_e profiles observed in PEGASUS SOL

See E. T. Hinson's APS-DPP 2010 poster for more information

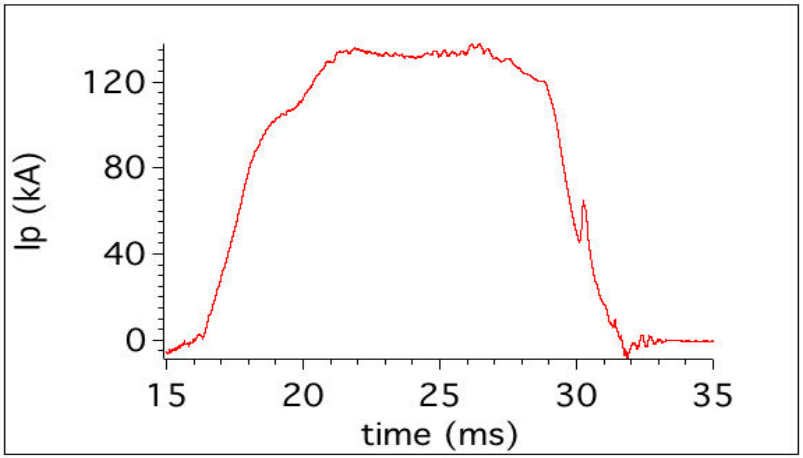


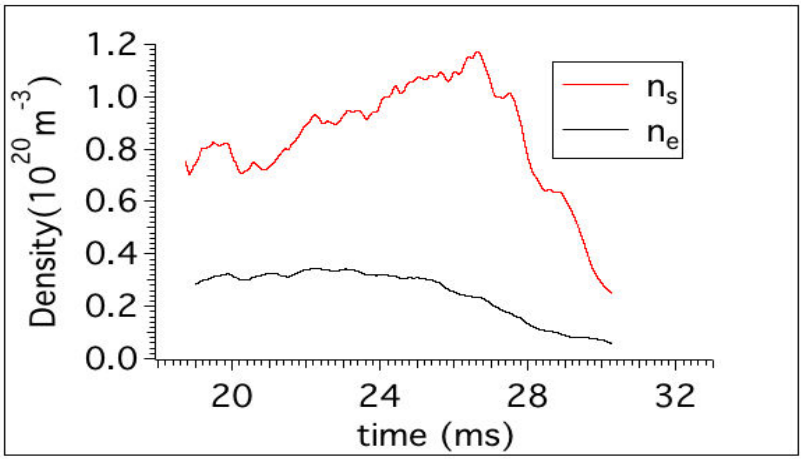
P.C. Stangeby, G.M. McCracken, Nuclear Fusion, Vol.30, No.7 (1990)

- Low field in Pegasus L-Mode leads to extended SOL scale lengths

Previously all Fueling was Provided with LFS External Valves

- Old external valves
  - Ganged Three PV-10s
    - 1000-5500 Torr*L/s
    - Located about midplane
  - Single PV-10
    - 200-4000 Torr*L/s
    - Located about z= - 20 cm



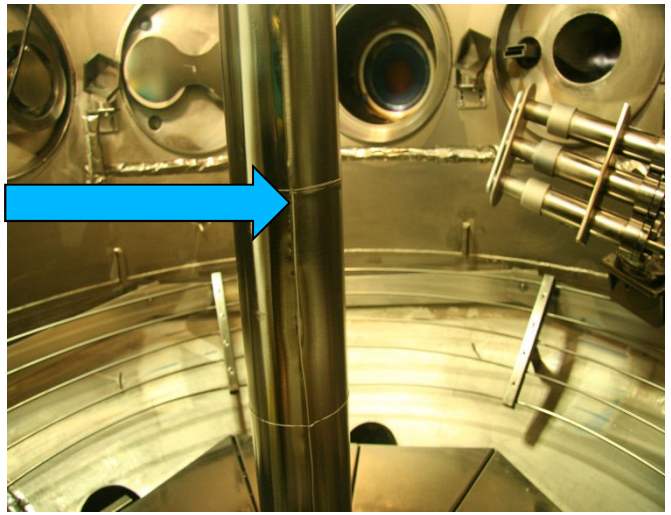


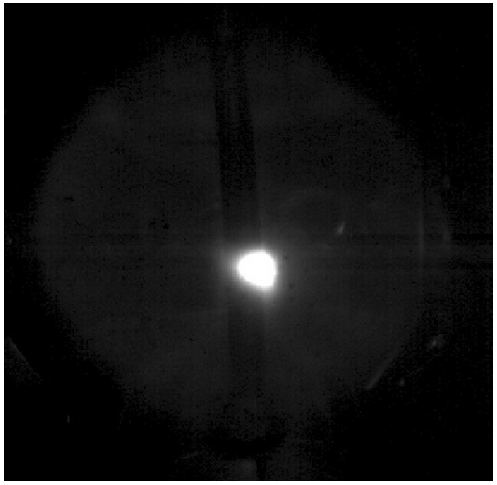
- Greenwald density 3-8 x10^{19} m^{-3}
- Achieved density is estimated to be 1-3 x10^{19} m^{-3}
  - External Valves fuels to ~30% n_e/n_g
  - Interferometer has known noise issues and more accurate will be available once this is remedied

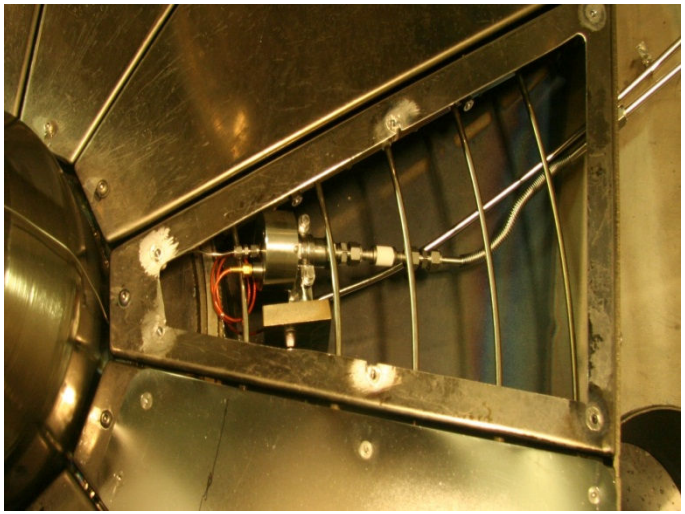
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Implemented Internal High-field Side Gas Valve

- Characteristics
  - Internal PV-10
  - 33” long .046” ID tube
  - z= - 30 cm
  - Gas continues to dribble out after puffing terminated
  - Throughput 300-3000 Torr*L/s
  - Throughput affected by gettering (temperature), overcome by increasing applied voltage



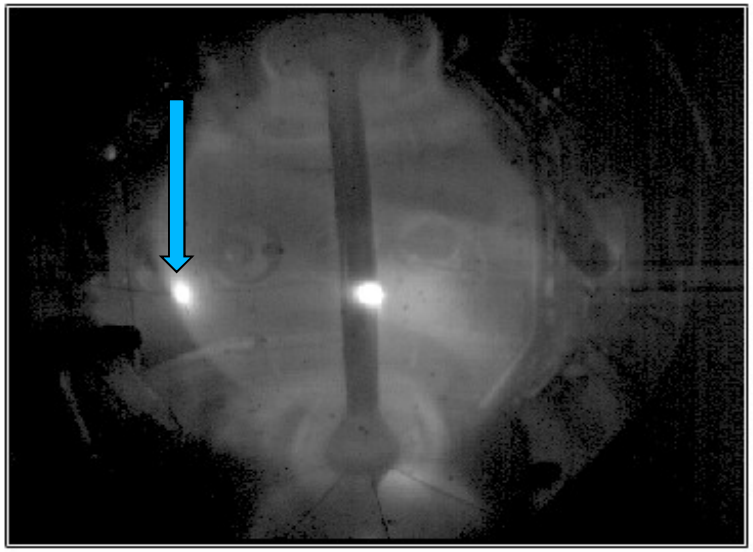


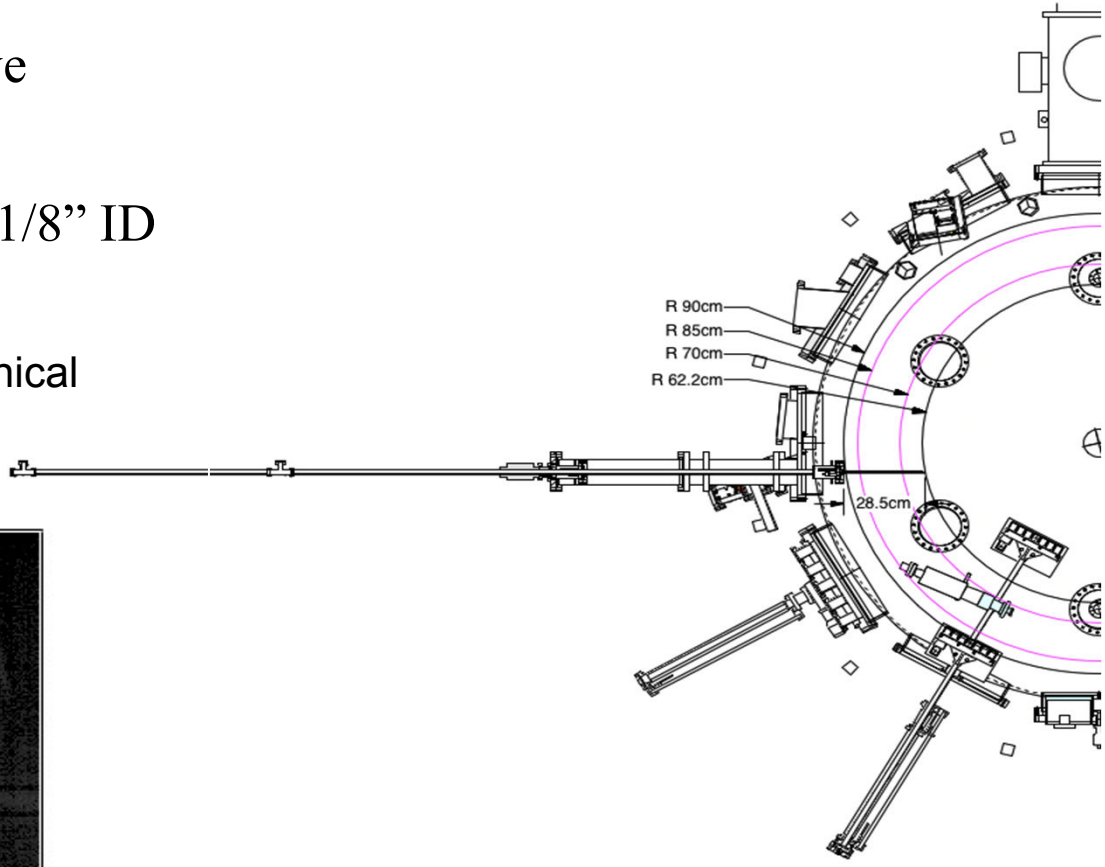


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Also Implemented Internal Poker Gas Valve

- Characteristics
  - Movable, and on a Gate Valve
  - PV-10
  - 28.5 cm long Graphite Tube 1/8” ID
  - 2500-5000 Torr*L/s
    - Need lower throughput-technical issue needs to be resolved
  - z= - 5.5 cm



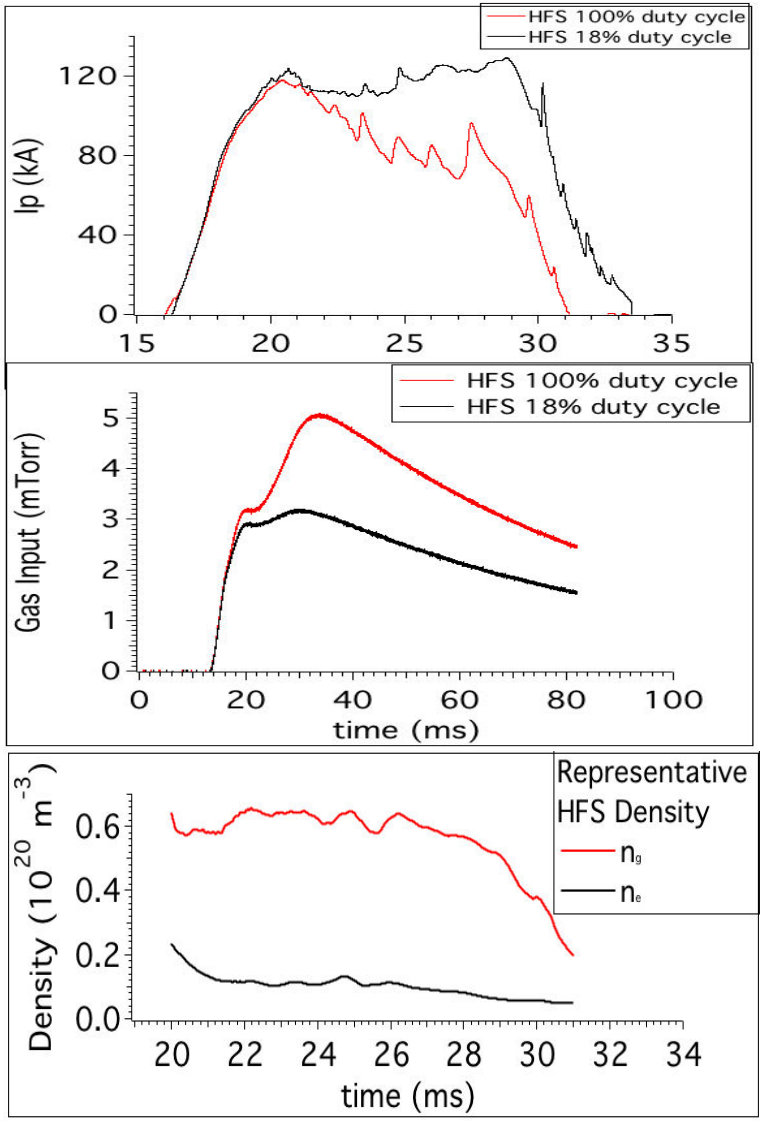


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HFS Valve Results

- HFS throughput can be varied
- Currently estimated to fuel to 1 x10^{19} m^{-3}
  - In either duty cycle
  - ~20% n_e/n_g
- Can be used to transition to H-mode (see later slides for details)
  - Similar to MAST, NSTX, COMPASS-D

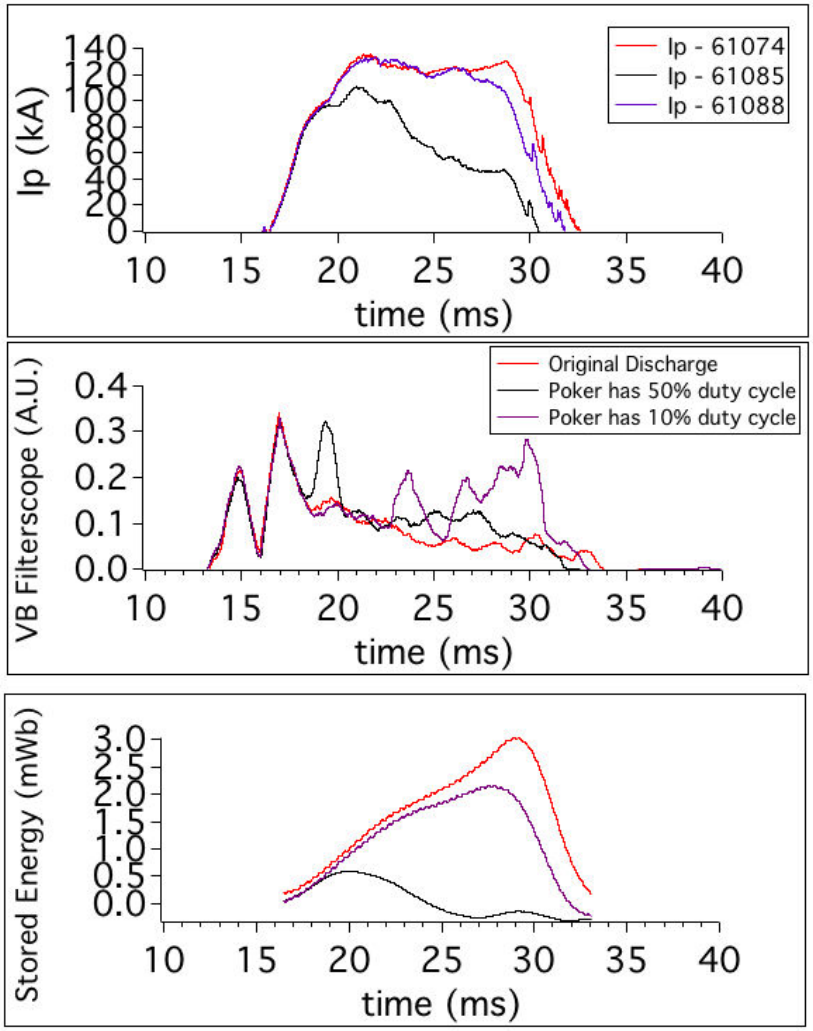
*A. R. Field, et. al, Plasma Phys. Controlled Fusion **46**, 981 2004.



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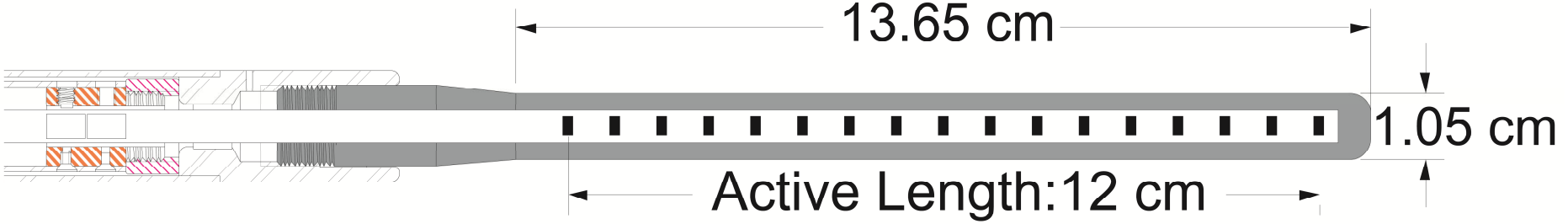
Poker Valve Results

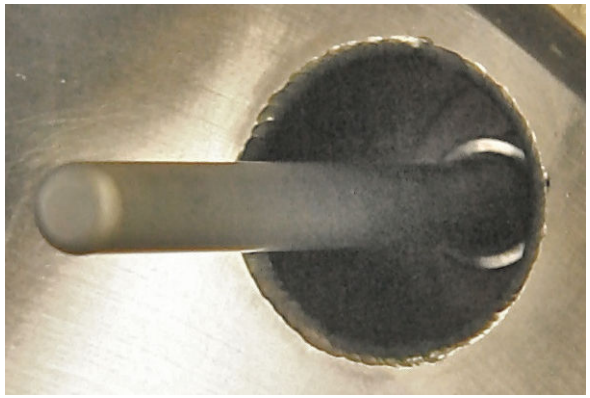
- Poker successfully inserted to r/a ~.6
  - Slightly degrades plasma performance
- Throughput from poker is currently too much
  - Degrades plasma performance, I_p, stored energy
  - Need to resolve this technical issue

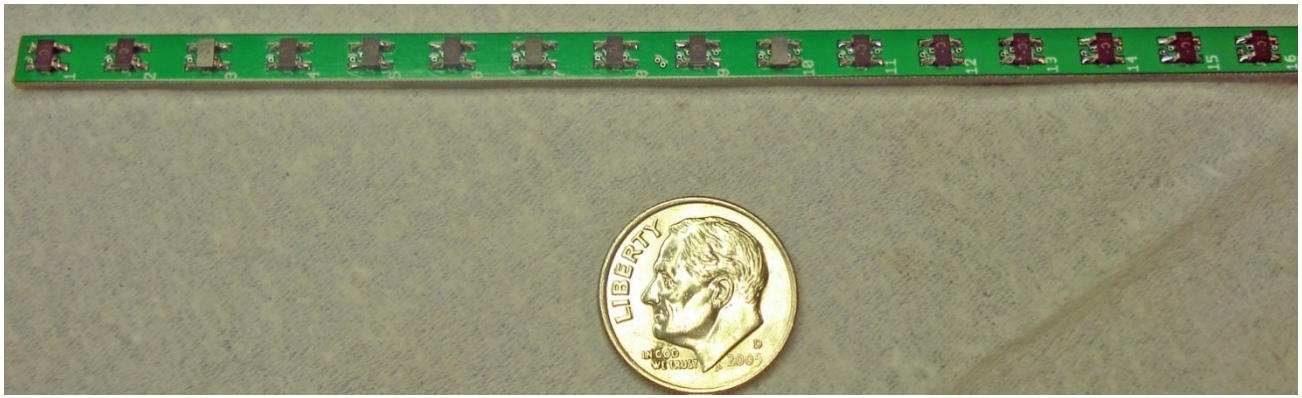


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PEGASUS Hall Probe Used to Investigate Current Profiles







- Solid-state InSb Hall Effect sensors
  - Sypris model SH-410
  - Weak variance with T_{sensor} and $B_{||}$ are correctable with calibration
- 16 channels, 7.5 mm radial resolution
- Slim C armor as low-Z PFC
  - Minimizes plasma perturbation
- 25 kHz bandwidth
  - Innermost sensor R> 50.8 cm
- Used to diagnose both PEGASUS OH and HI plasmas

*See M.W.Bongard, et al., Rev. Sci. Instrum. 81. 10E105, 2010

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Local $J_\varphi(R)$ Estimated From On-Midplane Hall Sensor Array B_z Measurements

- Petty, *et al.** showed that J_φ for a plasma with elliptical cross-section can be calculated from an on-midplane B_z measurement:

$$\mu_0 J_\varphi = -\left(\frac{B_Z}{\kappa^2 (R - R_0)} + \frac{\partial B_Z}{\partial R} \right)$$

*Petty, C. C., *et al.*, Nuclear Fusion, 42, 1124, 2002

- Assumes a Grad-Shafranov equilibrium

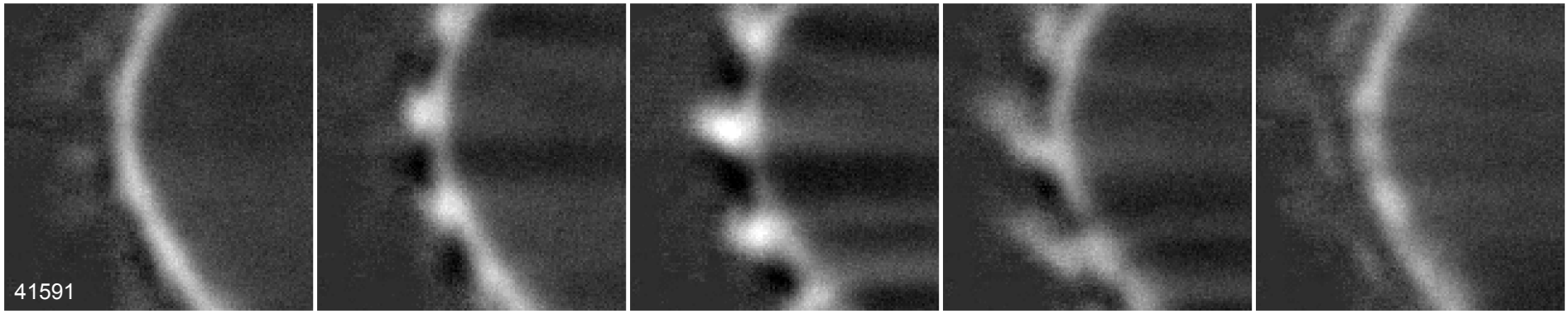
- Using typical PEGASUS shaping parameters (κ=1.75) and R_0=0.3m estimated from external magnetics, J_φ over the range of the Hall sensor array can be estimated
  - Note R_0 and κ change with time

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ELM Precursor: Peeling Mode Previously Investigated

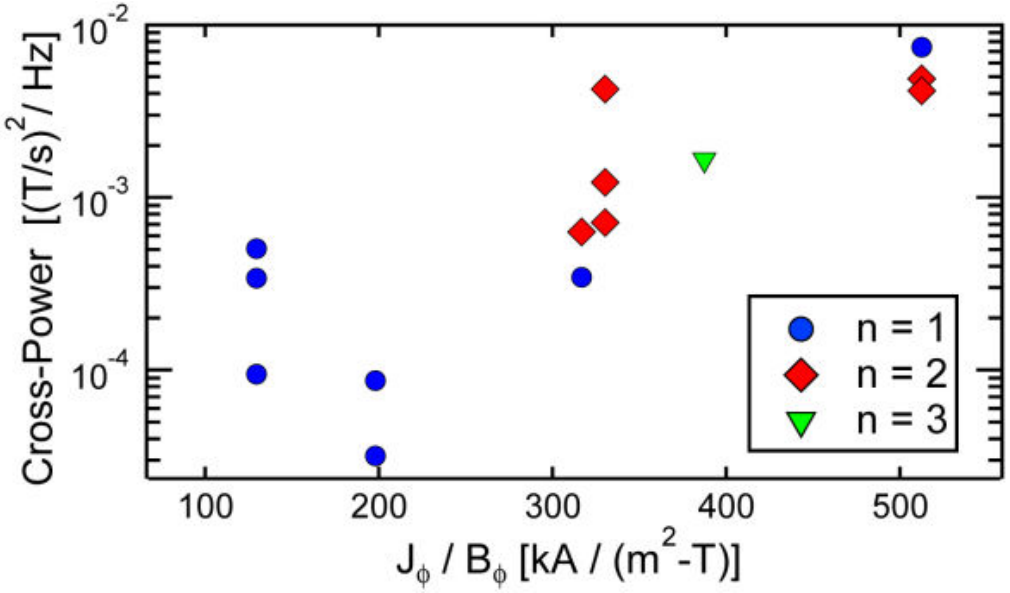
- Direct measurements of J_{edge} conducted with Hall probe
  - Direct analysis, equilibrium reconstruction
  - J_{edge} controllable with dI_p/dt
- Characteristics of peeling modes consistent with theory
  - Macroscopic features: Electromagnetic low-n, high-m edge-localized mode
  - Onset consistent with ideal MHD, analytic peeling stability theories
  - Observed MHD scales with measured J/B peeling drive
  - Coherent, propagating filaments
- J_{edge} dynamics supports current-hole & EM blob hypotheses
  - Nonlinear filaments generated from current-hole J_{edge} perturbation
  - Transient magnetostatic repulsion
  - Constant-V_R propagation in agreement with available EM blob theory

PEGASUS Peeling Mode Features Match Empirical and Theoretical Expectations



0-9 μs 11-20 μs 22-31 μs 33-42 μs 44-53 μs

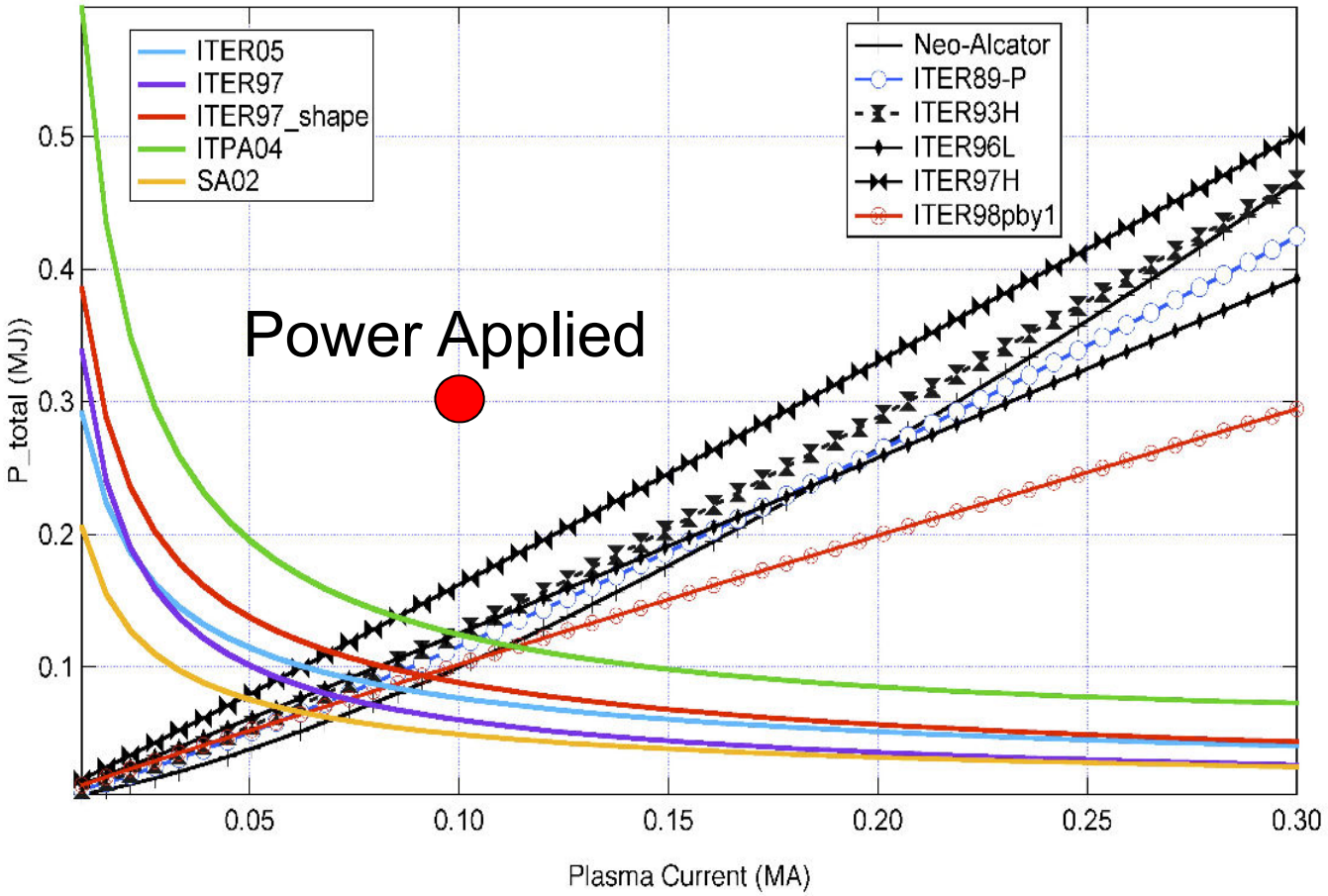
- Short lifetimes with high poloidal coherence
- Detachment, radial propagation of filaments
- High-m, low-n structure
- Mode amplitude increases with theoretical drive J/B



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

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PEGASUS is over the H-mode Power Threshold



R (cm)	34
r (cm)	30
A	1.13
κ	1.33
δ	0.15
B_{TF} (T)	0.155
I_{ROD} (kA)	264
n_e/n_g	0.9
P_{rad}/P_{heat}	0.5
Z_{eff}	2
T_i/T_e	0.5
H, ξ	1, 1
M_i (amu)	2
α_n, α_T	1, 2

Remember: P_{THR} for SN, ∇B aligned quiescent plasmas

*Thanks to D. Battaglia for this graph

K. E. Thome, 54th APS-DPP, Providence, Rhode Island, October-November 2012

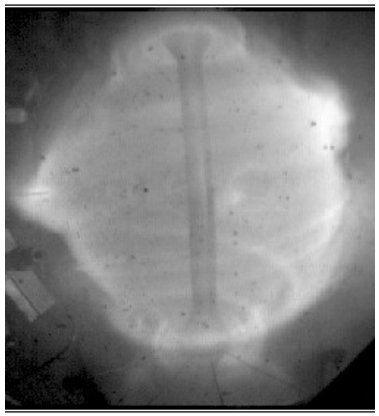
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Ohmic H-mode Achieved with HFS Fueling

H-mode

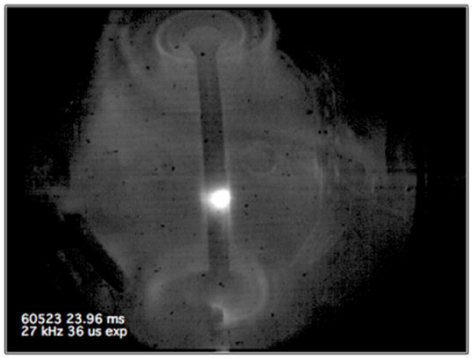


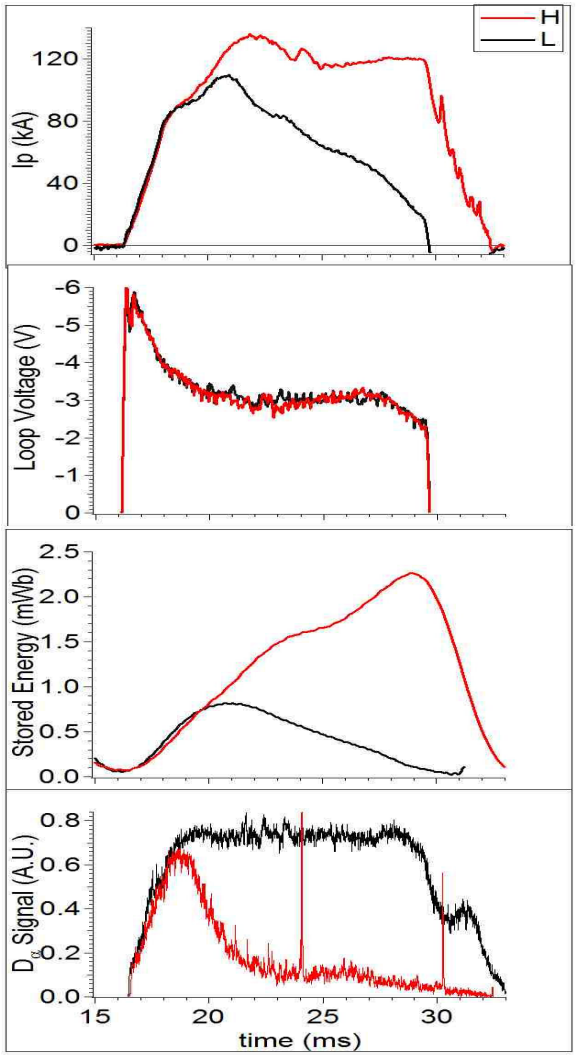
L-mode



- Standard H-mode signals seen
  - Reduced D_α emission
  - Quiescent edge between ELM events
  - Type I and III ELMs suggested
  - Improved confinement inferred
    - Increased diamagnetic flux signal
    - Improved V-sec consumption; increased T_e suggested

ELM

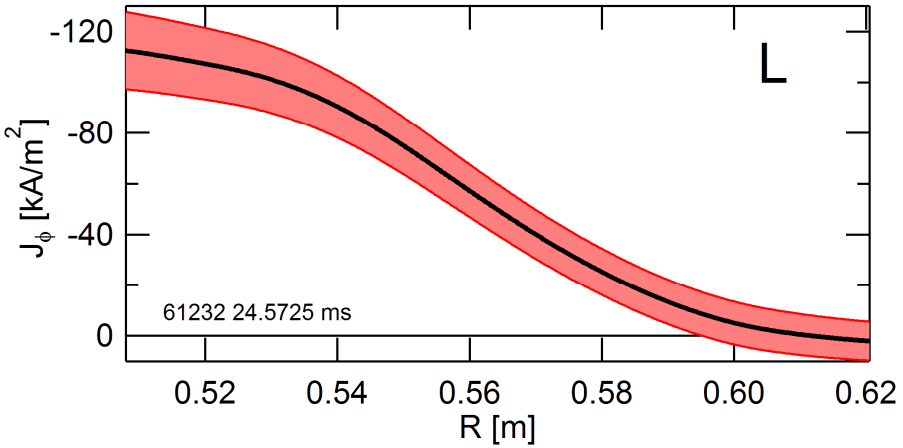




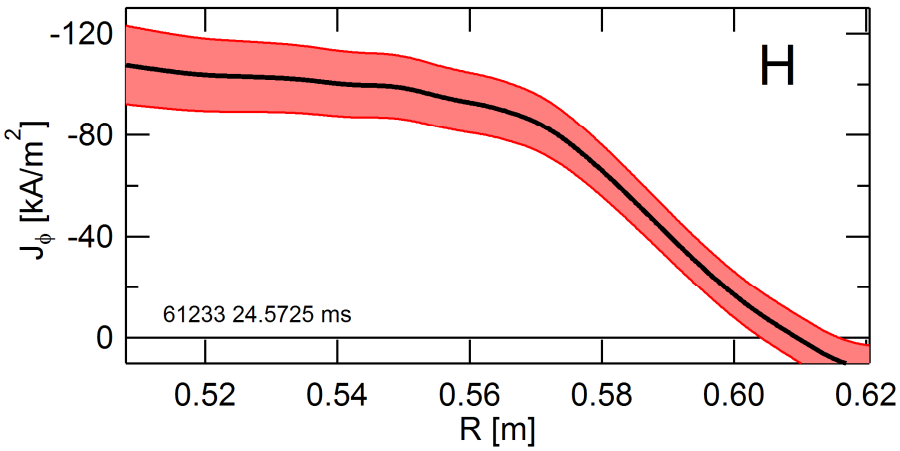
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Edge Current Pedestal Observed in H-mode

- Internal B measurements from Hall array yield local $J_\phi(R,t)$
  - Probe relocated to z = 0 to simplify interpretation



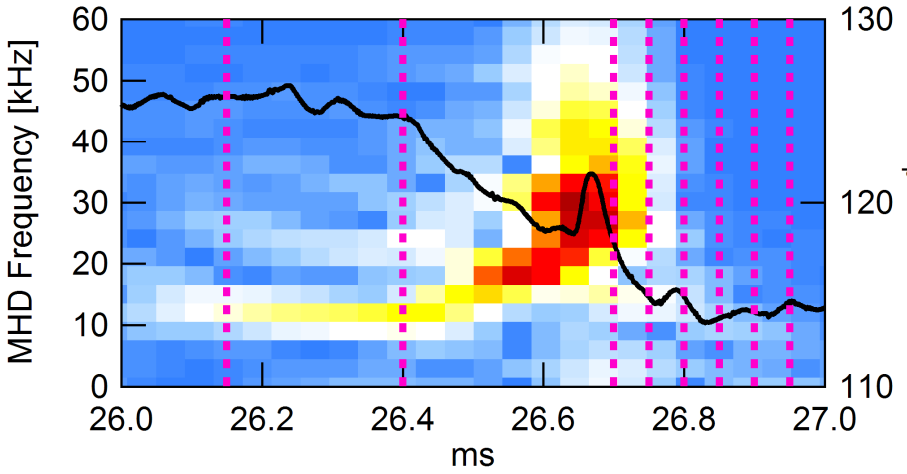
- Current gradient scale length significantly reduced in H mode
  - L → H: 6 → 2 cm
  - Ion gyroradius ~ 1.8 cm

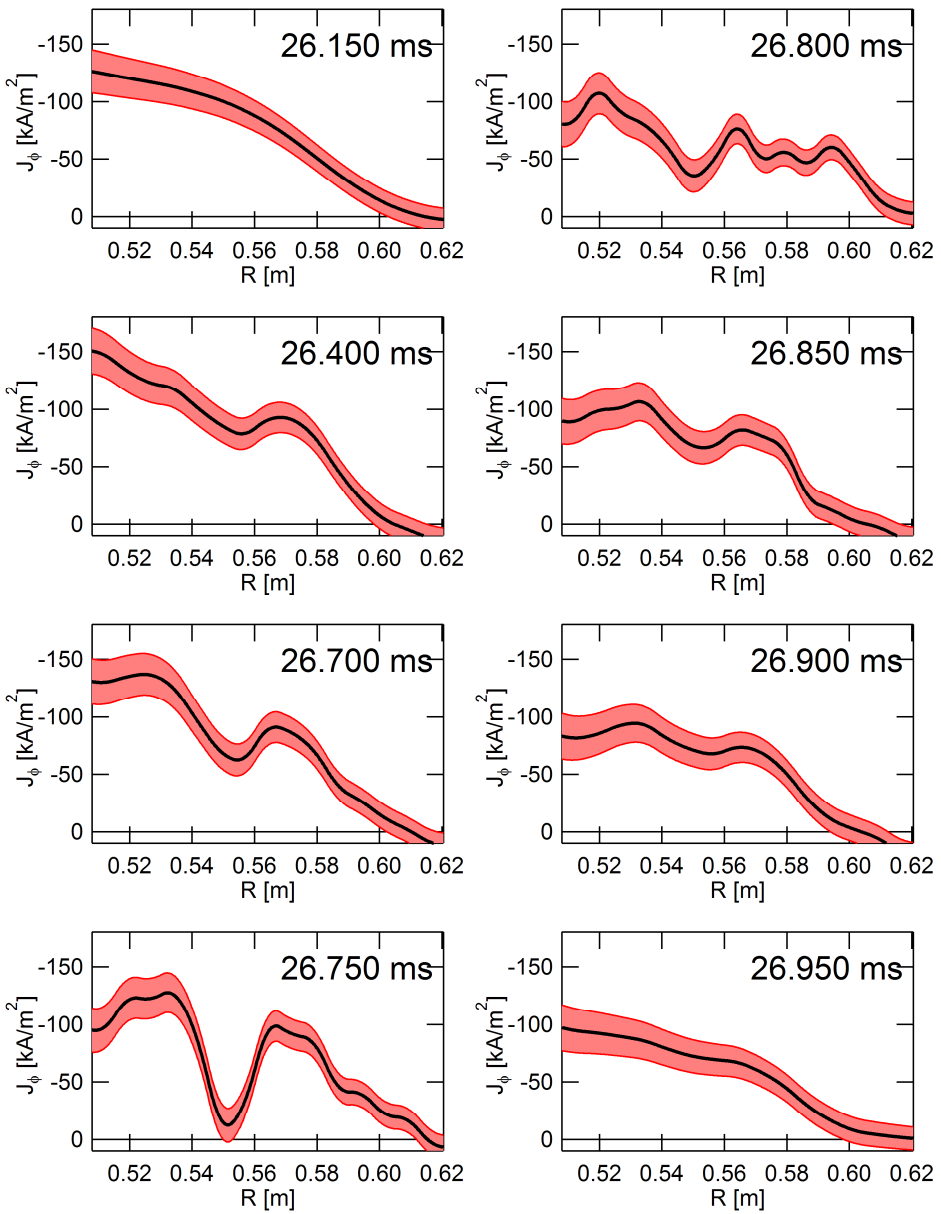


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J_{edge} ELM Dynamics Observed

- J(R,t) profiles measured throughout single Type III ELM
  - n = 1 EM precursor
  - ~10% I_p loss, negligible $\Delta\Phi$
- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in PEGASUS
- Rapid recovery to H-mode pedestal following event





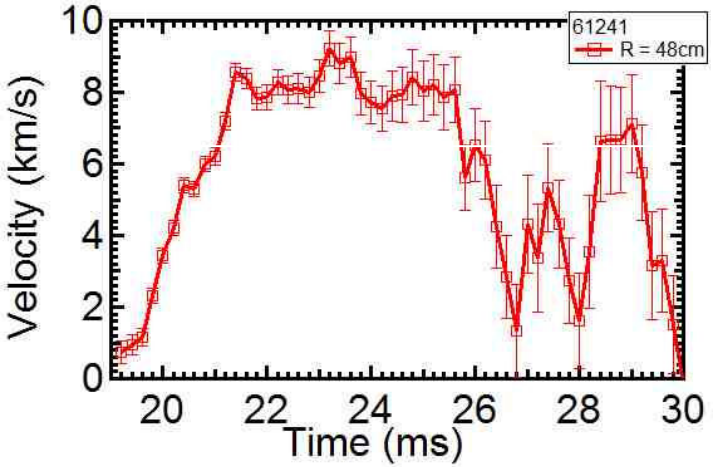
Toroidal Flow Reverses at Transition from L-mode to H-mode

- Toroidal flow reverses direction at L to H transition
  - Flow is in the counter-current direction in L-mode
  - Originally flow is in counter-current direction and then it reverses to co-current direction in H-mode
  - Reversal previously seen on MAST and NSTX during HFS fueling

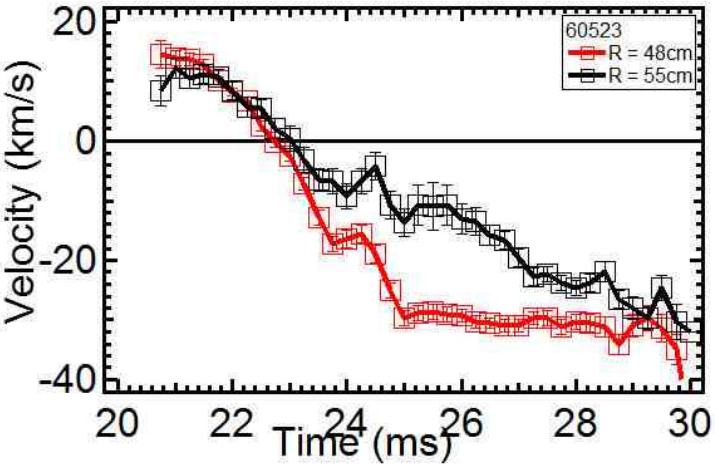
*Meyer H. *et al* 2008 *J. Phys.: Conf. Ser.* **123** 012005

- See NP8.00063 for more information

L-mode Shot



H-mode Shot

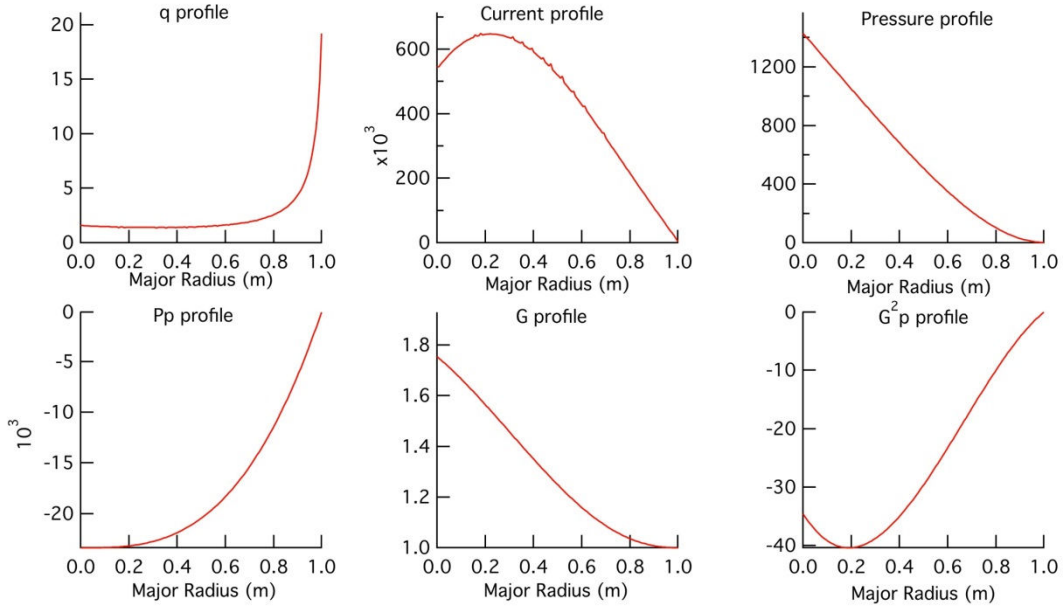


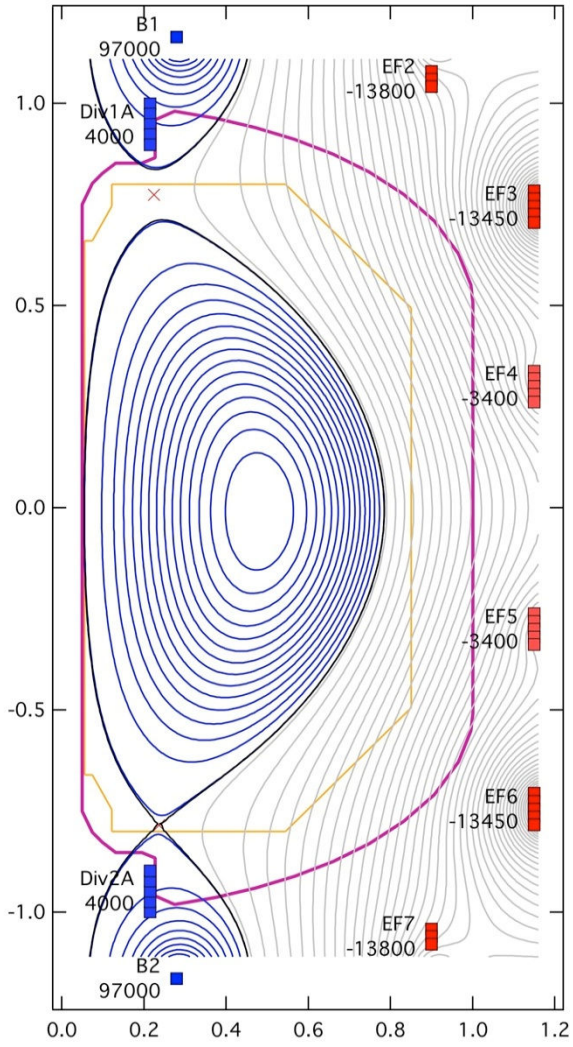
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New Divertors Will Provide Separatrix Operation

- 97 kA turns are required for double-null diversion
- 26 turn coil operating at 4kA with the ability to divert a 300kA plasma
- For further detail see NP8.00067

*Thanks to P.C. Shriwise for this slide





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Conclusions

- Two new internal gas valves have been implemented and used successfully
  - Future work will include improving diagnostics to better understand our density, ionization, impurities and gas flow
  - The HFS gas valve allows access to H-mode

- H-mode has been observed on PEGASUS for the first time
  - Trademarks include: reduced D_α emission, increased diamagnetic flux, type 1 and 3 ELMs observed, quiescent edge between ELM events, observation of pedestal, measurement of toroidal flow reversal at the transition from L to H-mode

Future Work

- Future Capabilities
  - Additional HFS valve
  - Divertor coils
  - Thomson Scattering System
    - Minimum adjustable 12 spatial channels (with capability of 24 depending on background needs)
    - Single 10 ns time point
  - Bolometers
    - Capable of measuring photons and neutrals
  - Langmuir Probes

- Future Studies
  - H-mode
    - Power threshold scalings at low A
    - ELM observation and characterization
    - Diverted Plasma
  - Stability Studies at low A
    - Non-solenoidal startup will allow access to high I_p, which will enable stability studies at low A

Reprints

Reprints of this and other PEGASUS presentations are available online at

http://pegasus.ep.wisc.edu/Technical_Reports

or via email kethome@wisc.edu

Work supported by US DOE Grant DE-FG02-96ER54375

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