Initial Edge Stability Observations In the PEGASUS Toroidal Experiment

M.W. Bongard, D.J. Battaglia, G.D. Garstka,
A.C. Sontag, E.A. Unterberg, G.R. Winz

49th Annual APS-DPP
Orlando, FL
Nov. 15, 2007



University of
Wisconsin-Madison



PEGASUS
Toroidal Experiment

Abstract

Edge stability is an important consideration for design of fusion experiments, as transient heat loads generated by edge instabilities may damage the first wall. Such instabilities are now believed to include peeling (current driven) and ballooning (pressure driven) components. Peeling instability may be expected for high values of edge $j_{\|}/B$ and low edge pressure gradient. This matches the operating space of Pegasus, with typical $\langle j_{\|} \rangle \sim 100$ kA/m^2, $|B| \sim 0.1$ T, and an L-mode edge. A new camera system has observed filamentary structures in the edge of nearly all ohmically-heated discharges. Ideal stability analysis of these discharges with DCON indicates marginal stability to resistive interchange for $\psi_N \geq 0.95$. Modification of triangularity during startup is observed to delay instability onset. A plasma control system based on that used on DIII-D will allow study of the influence of plasma shaping on mode stability characteristics. An array of magnetic probes capable of insertion into the scrape-off layer and plasma edge is being developed to provide a local constraint on the edge current profile.

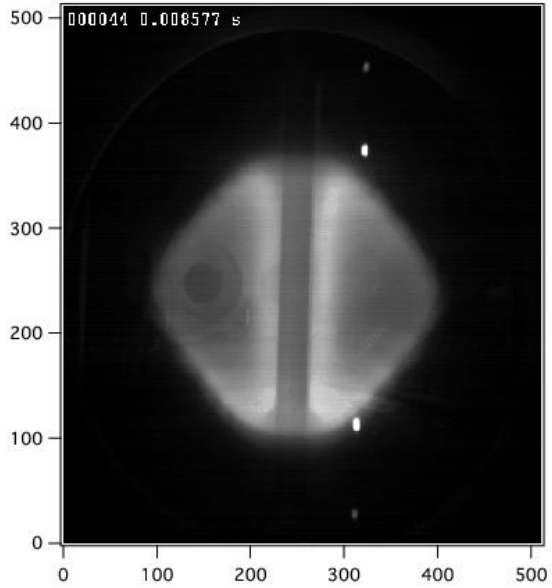
Work supported by U.S. DOE Grant DE-FG02-96ER54375

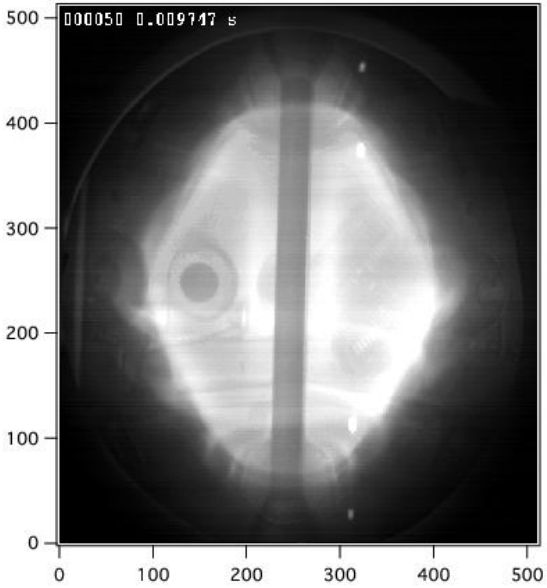
Motivation

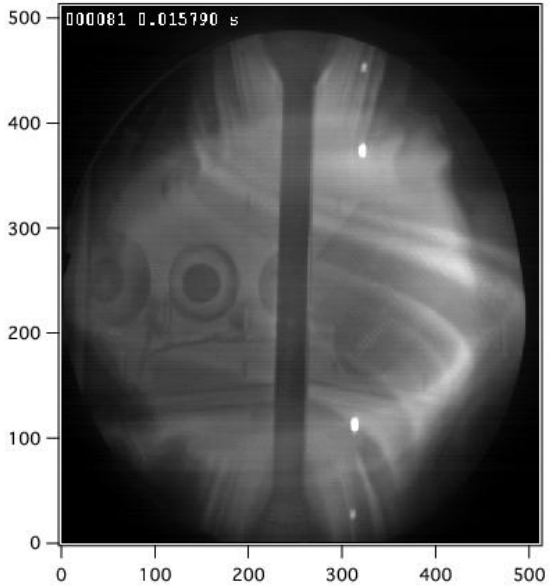
- Edge Stability Critical to Next-Step Devices
  - Transient ELM heat loads → PFC damage
  - Filamentary structures transiently studied during ELMs in large devices
- Peeling-Ballooning Theoretical Framework
  - Balance between edge current, pressure gradient
  - Edge pressure profile well-known experimentally
  - Accurate current profile constraints extremely desirable
  - Strong stabilizing influence of shaping
- Pegasus: Filamentary edge instability visually similar to ELMs
- Research goal: Characterize instability in Pegasus

Filamentary Structures Observed

- Seen in OH and gun operations
- Appear early, persist throughout shot







36117

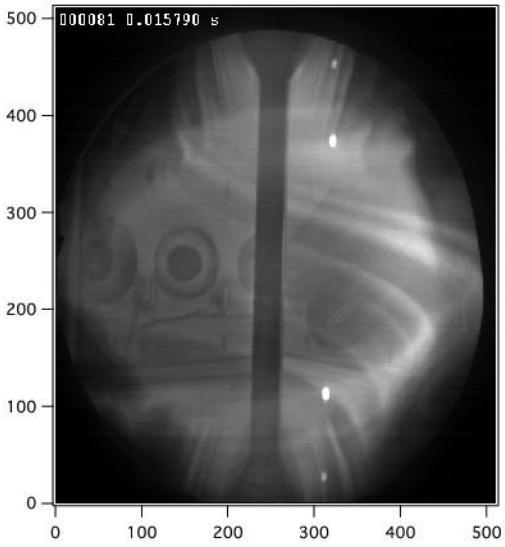
15.577 ms

18.747 ms

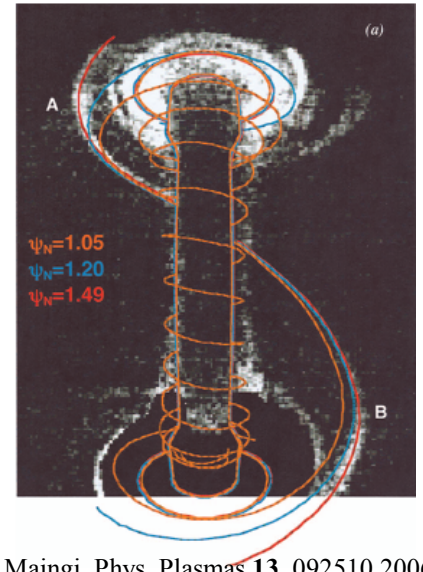
24.789 ms

THE UNIVERSITY of WISCONSIN MADISON

Edge Filaments Visually Similar to ELMs

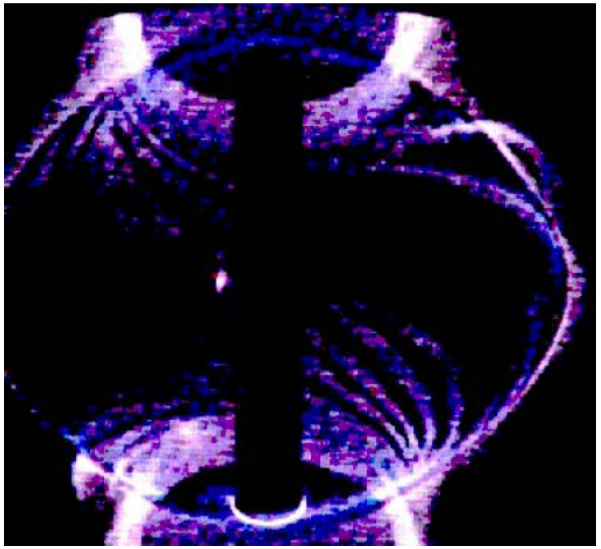


Pegasus



Maingi, Phys. Plasmas **13**, 092510 2006

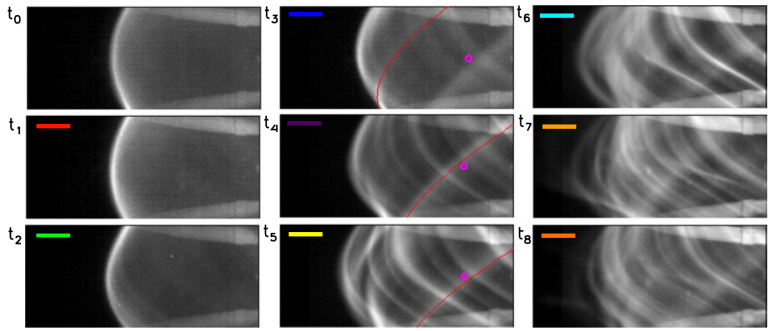
NSTX



Kirk, 2004 Proc. 20th Int. Conf. on Fusion Energy 2004

MAST

- Follow field lines
- Pegasus likely has L-Mode edge
  - No clear indication of H-mode
  - Filamentation continuous in time, unlike strong ELM burst behavior
- Might be same mechanism as ELMs

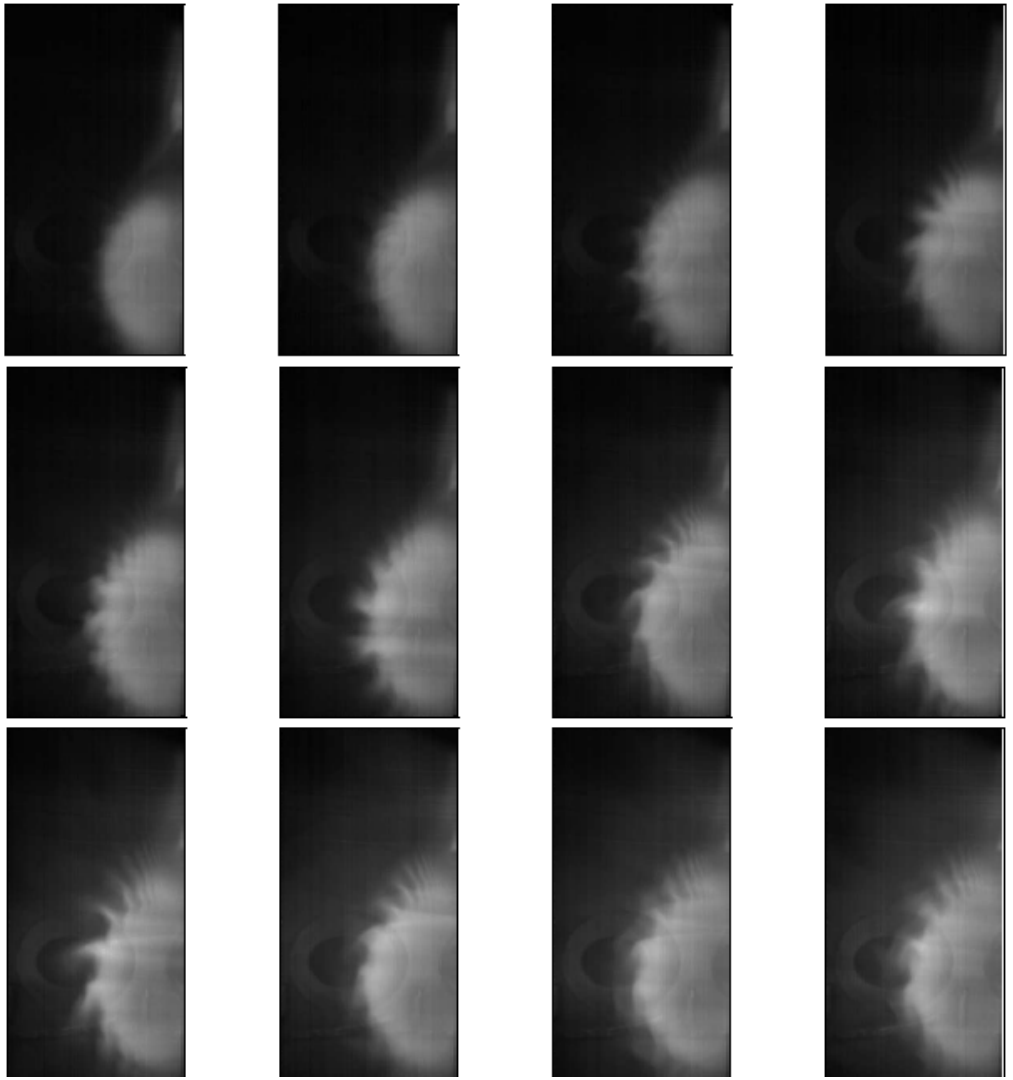


Scannell, Plas. Phys. Controlled Fus. **49**, 2007

THE UNIVERSITY of WISCONSIN MADISON

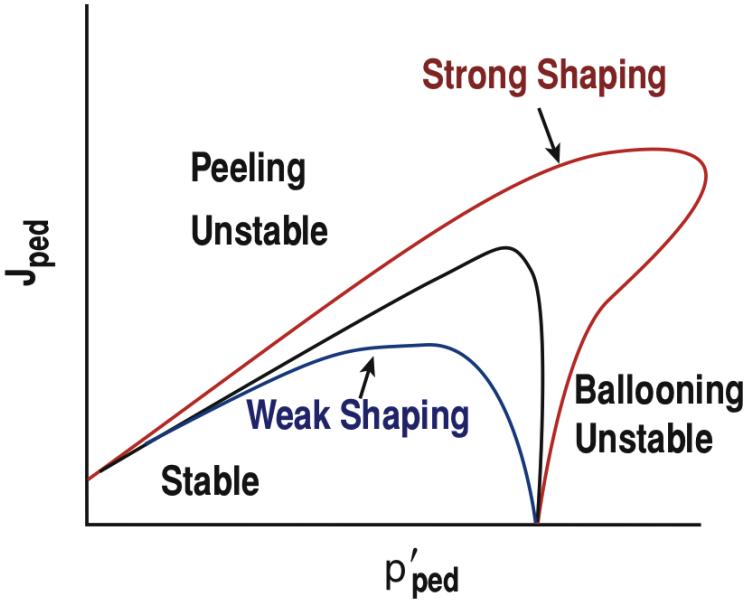
High Speed Imaging Reveals Structure

- First 2 ms of shot
  - 12 kHz framerate
  - 16 μs exposure
  - Small size
- High m structure
- "Fingers" can propagate radially, appear to rotate poloidally



Candidate Instability: The Peeling-Ballooning Mode

- Proposed mechanism for ELMs
- Localized edge instability
- Peeling
  - Edge current, current gradient drive
  - Stabilized by pressure gradient
- Ballooning
  - Normal pressure gradient drive
  - Stabilized by shear
- Strong stabilizing influence of shaping
  - Decouples current, shear

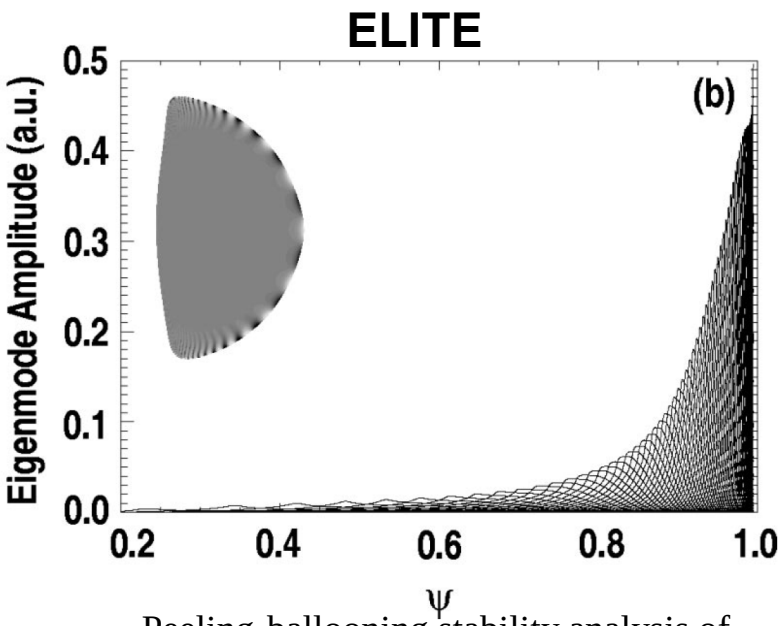


Snyder, Phys. Plasmas **12**, 056115, 2005

THE UNIVERSITY of WISCONSIN MADISON

Ballooning Stability Numerically Determined

- Ballooning stability problem more difficult
  - Complementary codes commonly utilized to study low, intermediate-high n regimes
- DCON: Ideal & low-n stability
  - Computes $D_M(\psi)$, $D_R(\psi)$
  - Poloidal Fourier components
  - n > 3-5 becomes numerically intensive
    - Local CPU processor constraint
- ELITE: peeling-ballooning stability
  - Well-validated; "industry standard"
  - Efficiently computes 5 < n < 50 edge stability
  - Poloidal Fourier components



Peeling-ballooning stability analysis of DIII-D ELM
Snyder, Phys. Plasmas **9**, 2002

THE UNIVERSITY of WISCONSIN MADISON

Peeling Mode Destabilized by Increased $(j_{||}/B)_{edge}$

- Necessary peeling stability criterion: (Connor, PoP 5, 1998)

$$2\sqrt{-D_I} = \sqrt{1 - 4D_M} > 1 + \frac{2}{2\pi q'} \oint \frac{j_{||} B}{R^2 B_p^3} dl$$

where

  - $D_M \propto p'$ = Mercier coefficient (< 0)
  - q' = Magnetic shear
  - $j_{||}$ = Parallel edge current density

- Stability in high A, low-β, low ν, weak shaping limit:

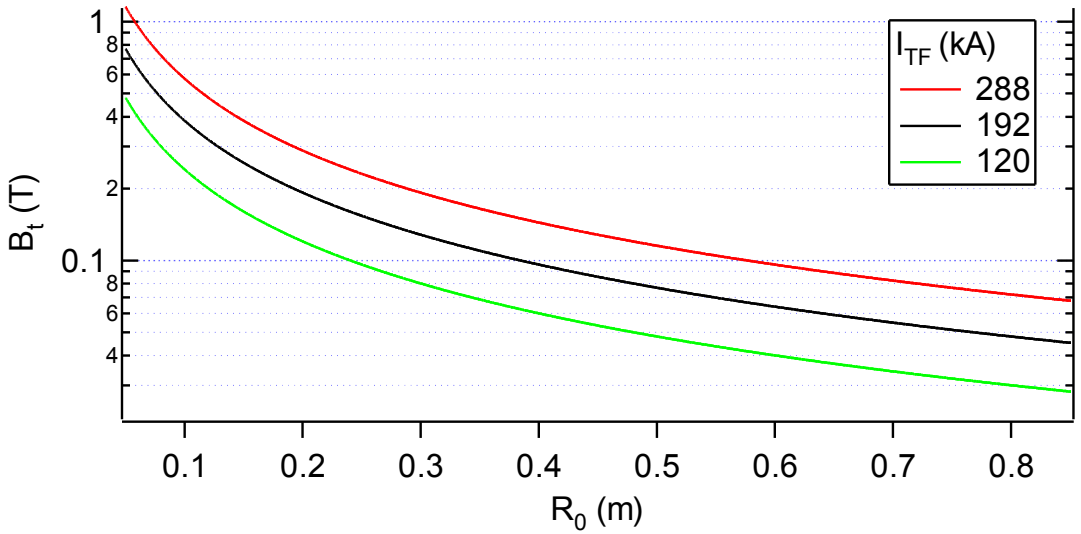
$$-D_R > \frac{Rq}{s} \left(\frac{\bar{j}_{||}}{B} \right)_{edge}, \quad s \equiv \frac{r}{q} \frac{dq}{dr}$$

with D_R (< 0) = GGJ resistive interchange coefficient

THE UNIVERSITY of WISCONSIN MADISON

Pegasus: High $(j_{||}/B)_{edge}$ Typical

- Normal Operations:
  - Large $dI_p/dt \sim 25\text{-}100$ MA/s
    - Strong j_{edge} drive
  - Low Toroidal Field
    - $|B_{\varphi,0}| \sim 0.1$ T
  - Strong Toridicity
    - $|B_{HFS}/B_{LFS}| > 10$

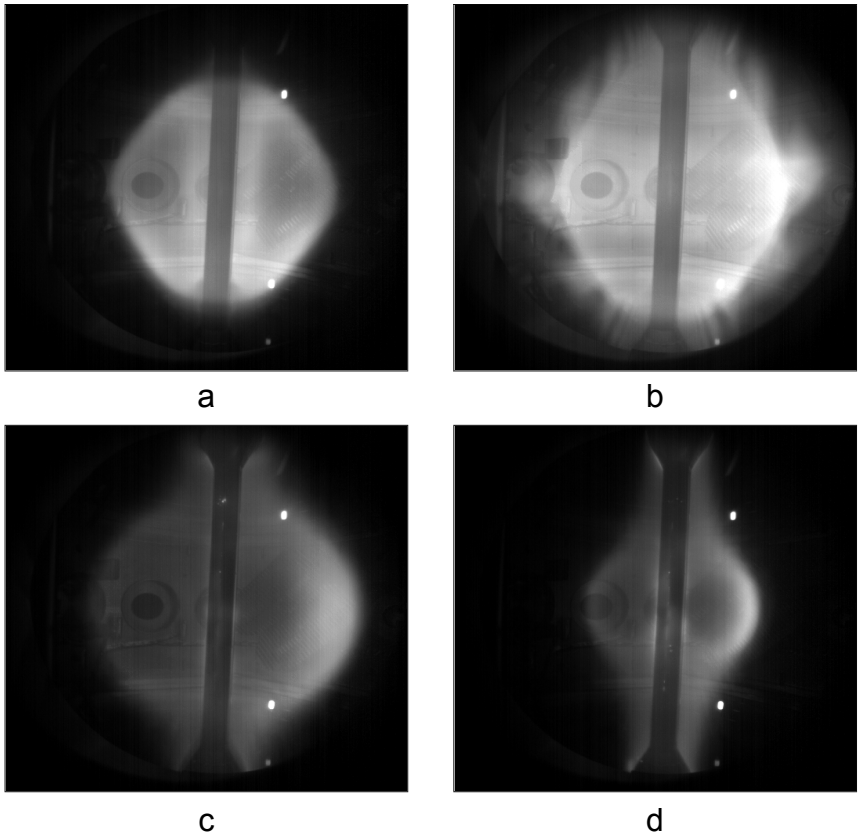


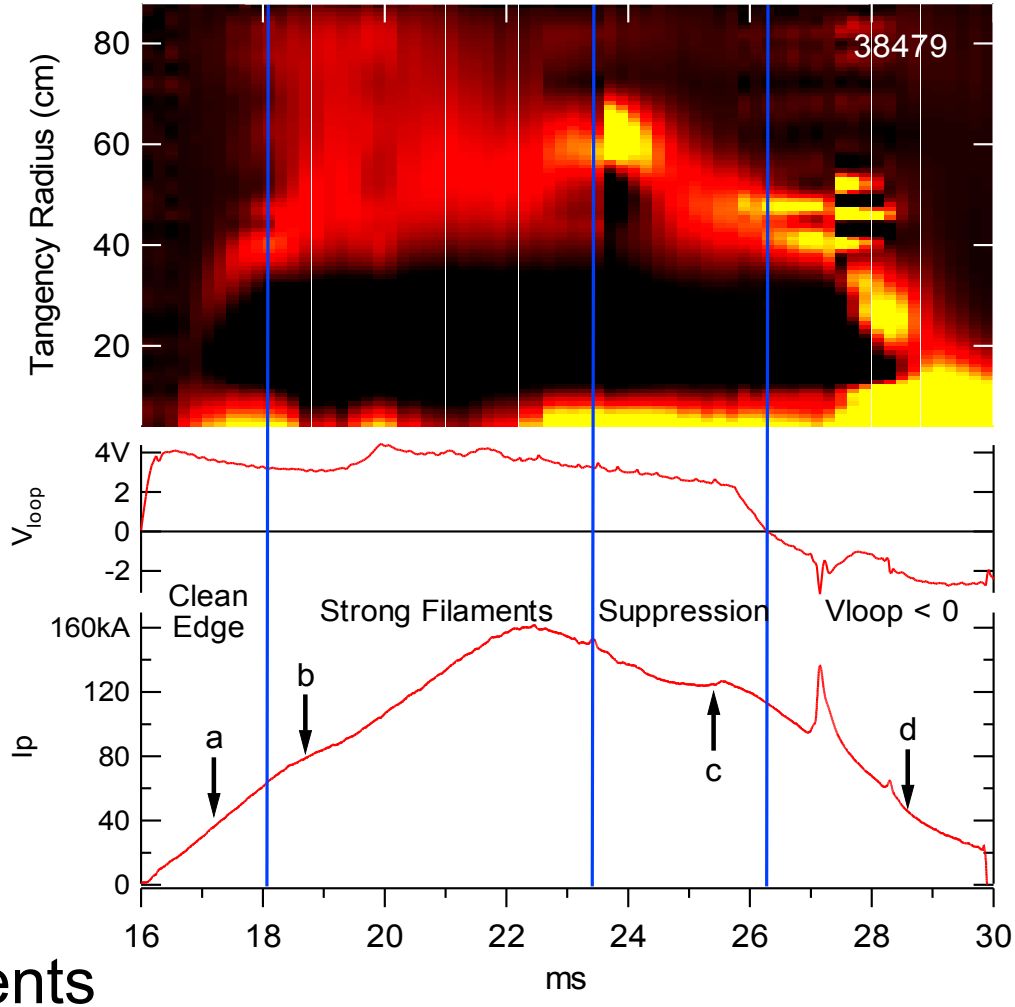
- $j_{||}/B$ Comparable to Larger Devices; strong peeling drive
  - Pegasus: $\langle j_{||} \rangle \sim 10^5$ A/m^2, $B_{\varphi,0} \sim 0.1$ T $\rightarrow j_{||}/B \sim 1\text{x}10^6$ A/(m^2-T)
  - DIII-D*: $\langle j_{||} \rangle \sim (1\text{-}2)\text{x}10^6$ A/m^2, $B_{\varphi,0} \sim 2$ T $\rightarrow j_{||}/B \sim (0.5\text{-}1)\text{x}10^6$ A/(m^2-T)
- Pegasus offers unique, university-scale opportunity for high $j_{||}/B$ experiments

*: Thomas, Phys. Plasmas **12**, 056123 2005

THE UNIVERSITY of WISCONSIN MADISON

$J_{||}$ Suppression Reduces Filamentation

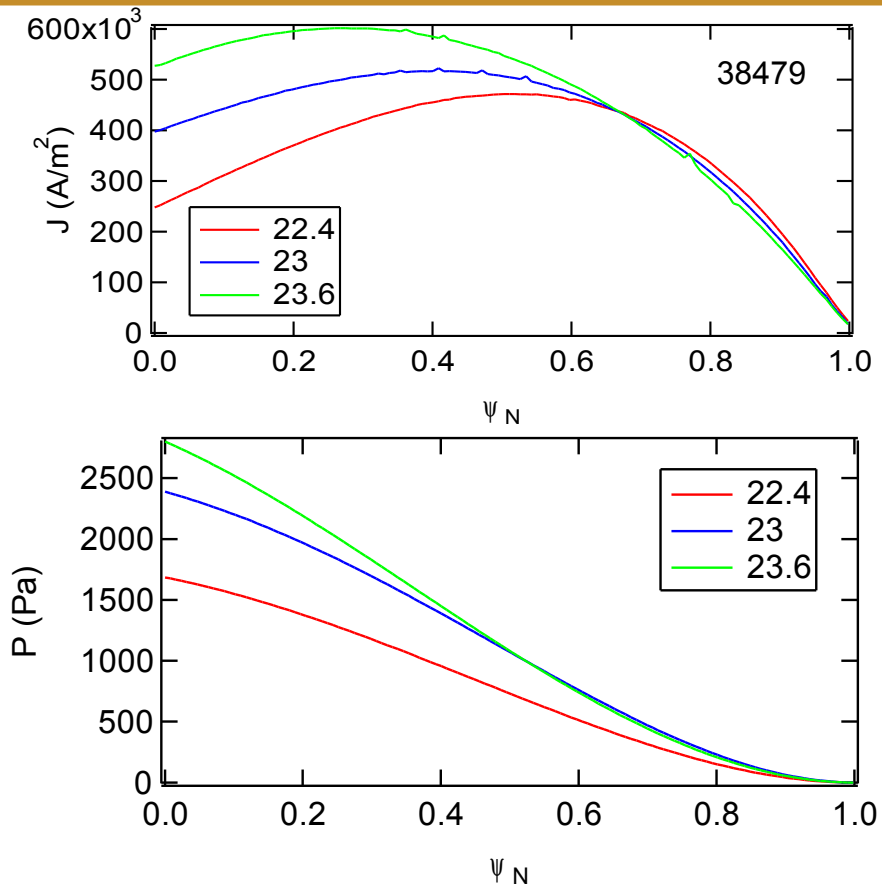


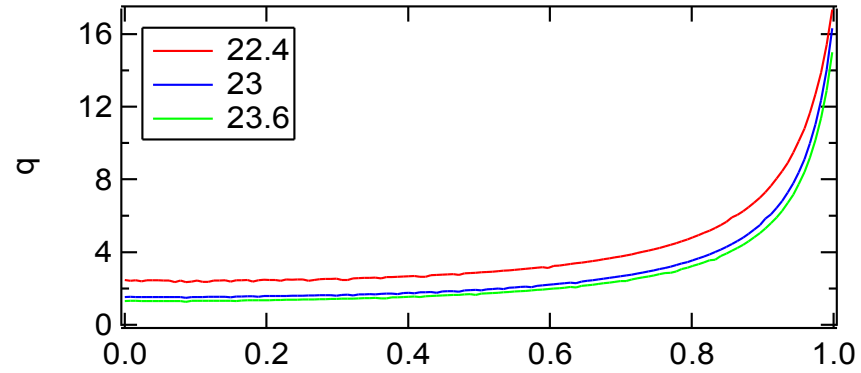


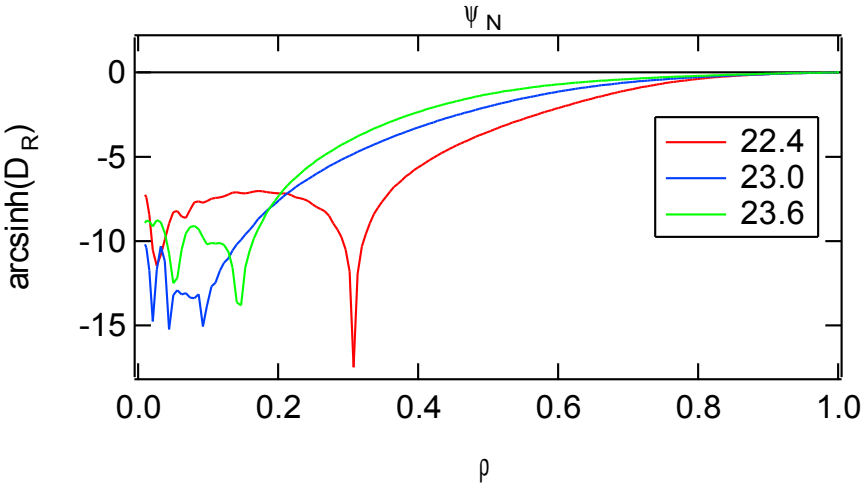
- Midplane bolometry reveals edge degradation with filaments
- Sharper edge during I_p rampdown

THE UNIVERSITY of WISCONSIN MADISON

DCON: Edge $D_R \sim 0 \rightarrow$ Marginal Peeling Stability





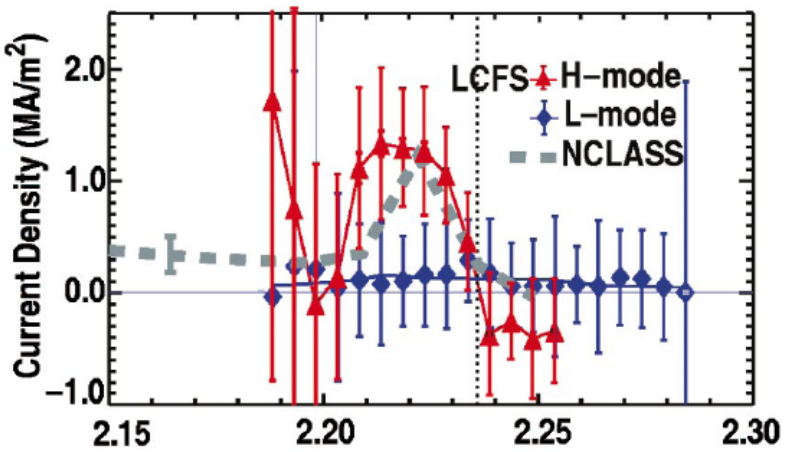


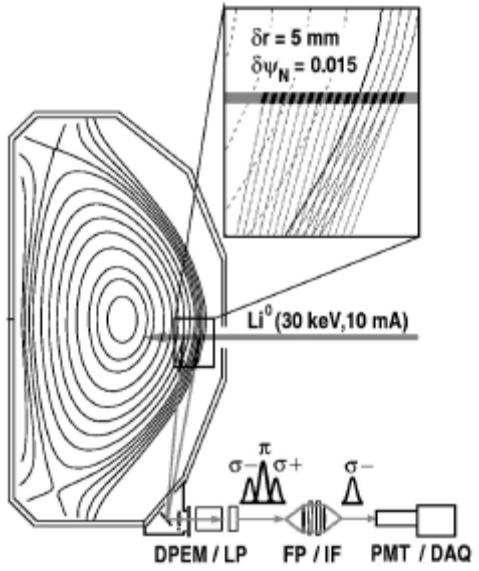
- 3 times amenable to KFIT reconstruction
  - External magnetics only
- Local profile constraints needed for detailed edge study

THE UNIVERSITY of WISCONSIN MADISON

Current Profile Constraint Desirable

- p(ψ) typically well-known via multichannel TS
  - Currently unavailable on Pegasus
- J(ψ) more difficult, equally important
  - High $T_e \rightarrow$ noninvasive methods
  - Ex: Li beam polarimetry, DIII-D
- Accurate J(ψ) measurement technique desired
- Typical alternative: compute J
  - Assumes bootstrap current drive
  - Questionable assumptions in edge





Thomas, Phys. Plasmas **12**, 056123 2005

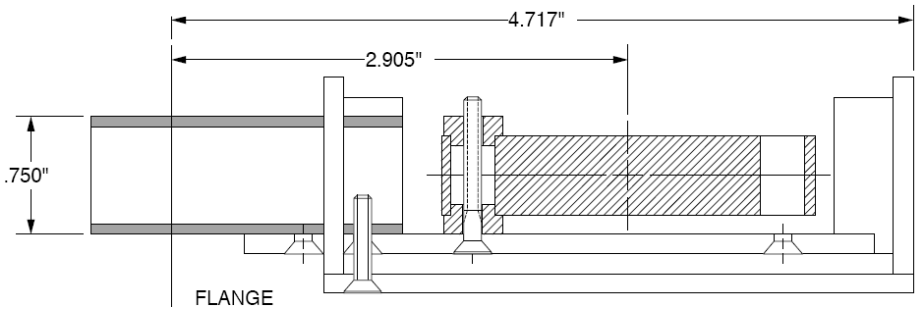
THE UNIVERSITY of WISCONSIN MADISON

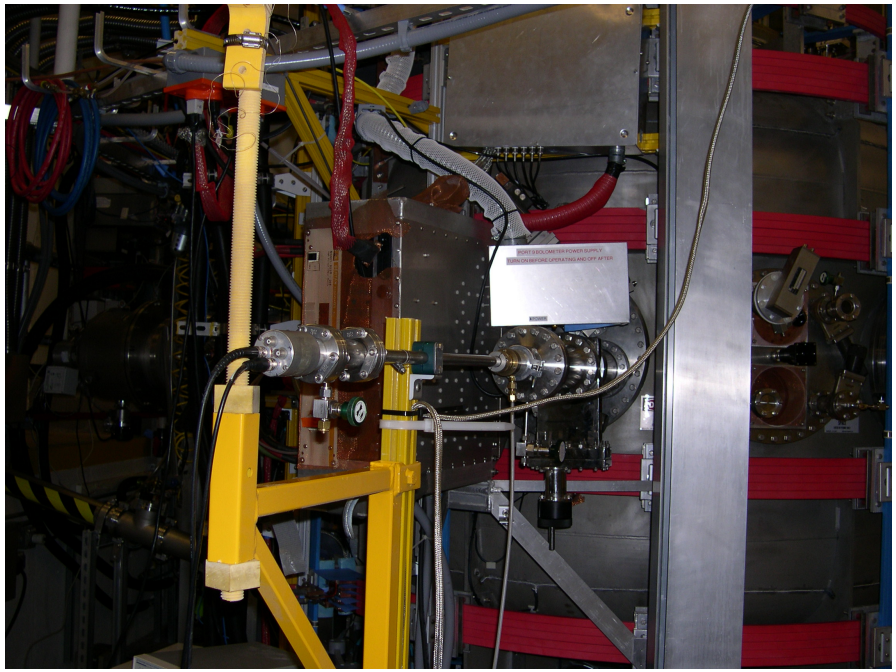
Edge Conditions Can Be Measured With Probes in Pegasus

- Pegasus plasmas compatible with probes
  - Short pulse ($\tau_{shot} < 50$ ms)
  - Low $T_{e,edge}$
- Magnetic Probes
  - Direct measurement of $B_\theta \rightarrow$ edge $J(\psi)$ constraint
  - Filament magnetic signature detection
  - Mode analysis
- Triple Langmuir Probes
  - n_e, $T_e \rightarrow p_e(\psi)$ in lieu of multichannel TS
  - High spatial, time resolution possible

Initial Magnetic Probe Deployed

- Insertable midplane mount structure developed
  - Multiple probe tips possible
- Differentially pumped O-ring vacuum seal
  - Ti gettering: low 10^{-8} torr routine
- On-hand Mirnov coil mounted
- BN probe shielding
  - Provides thermal protection
  - Low-Z PFC

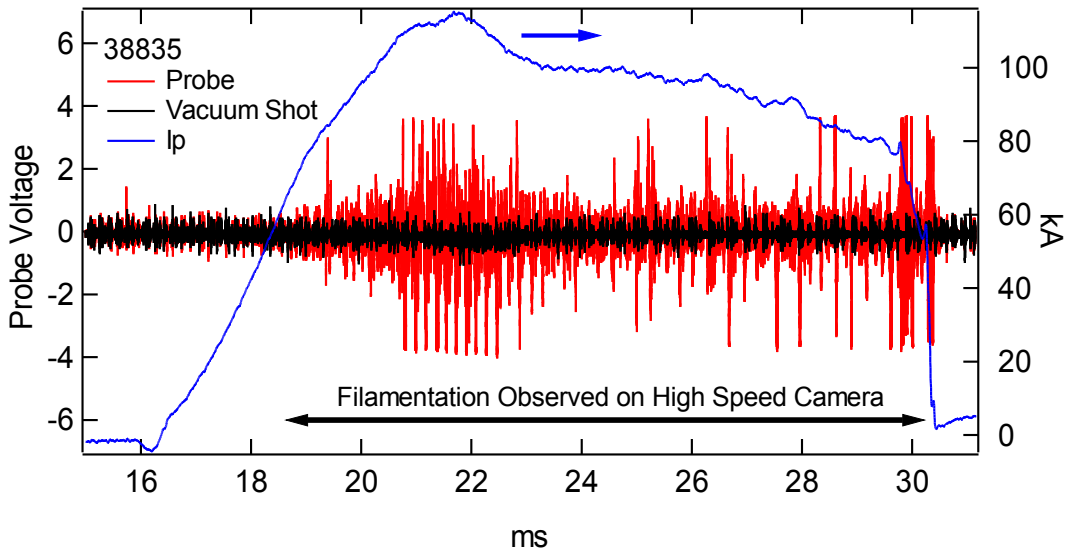


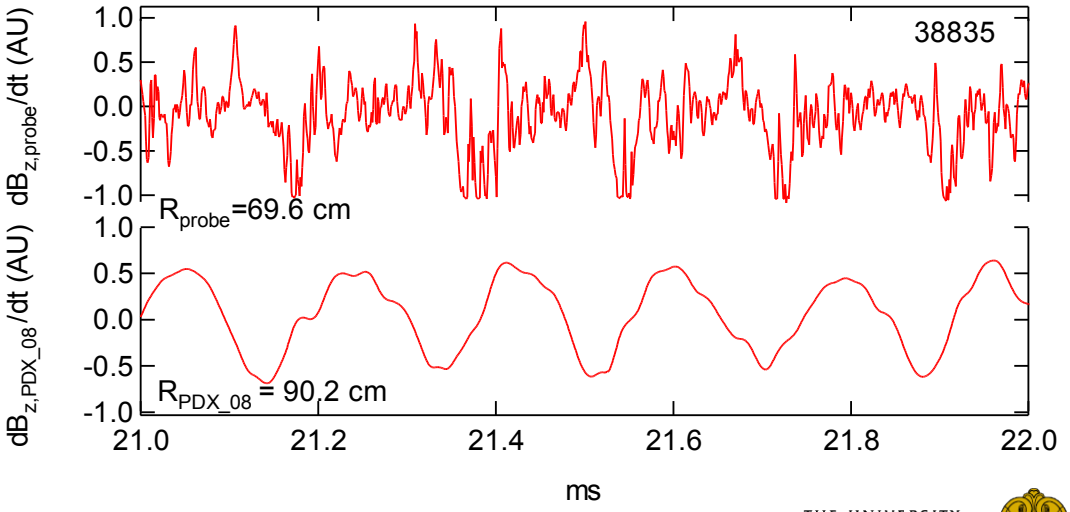


THE UNIVERSITY of WISCONSIN MADISON

Initial Magnetic Probe Data

- Filament magnetic signature detected
  - Probe inserted to plasma boundary, $R_a = 65$ cm
- Frequency bursts coincide with filament onset
- Probe detects high frequency components unseen by existing magnetics
  - Likely due to high radial separation (~ 20 cm)

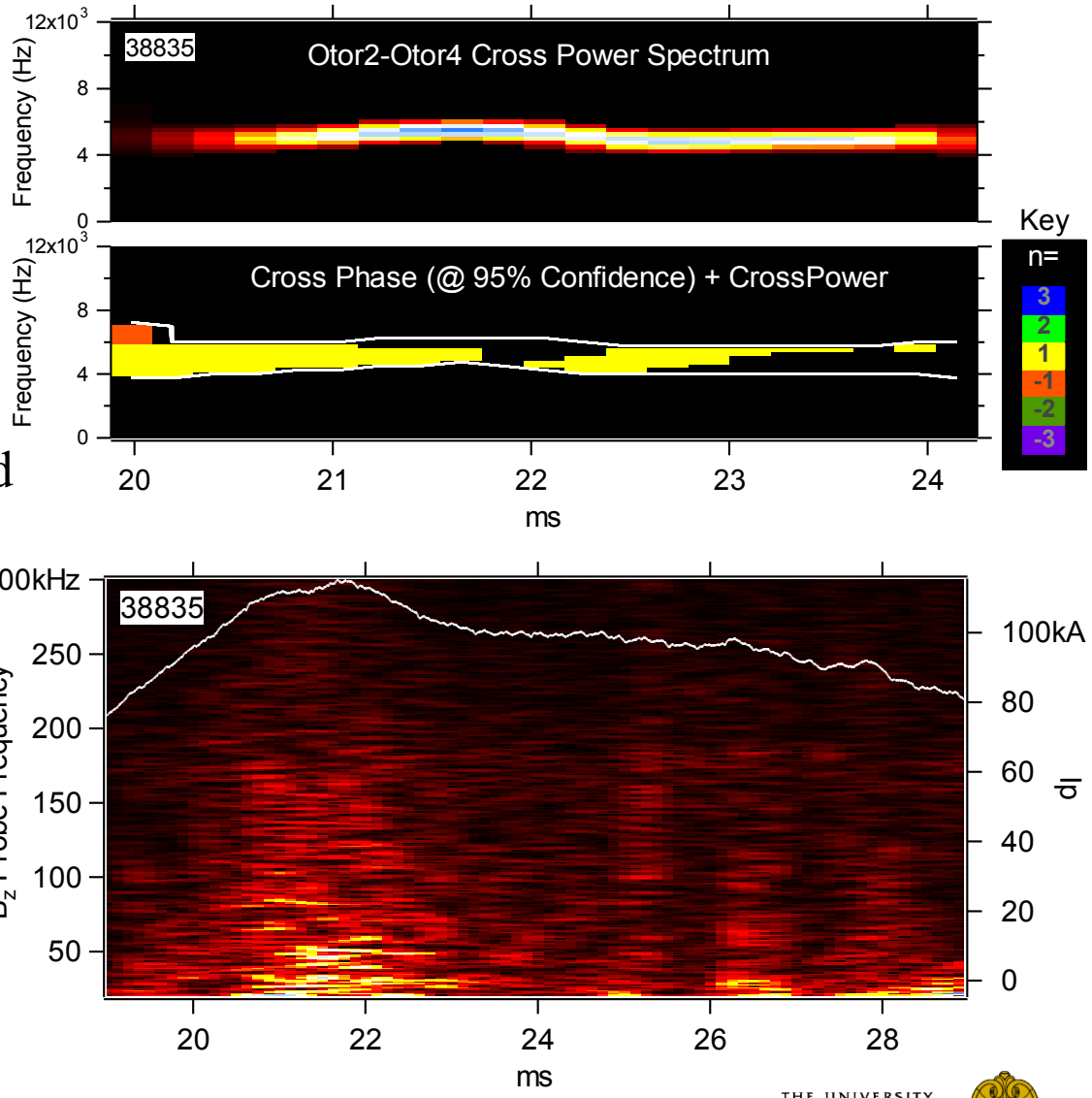




THE UNIVERSITY of WISCONSIN MADISON

Edge Probe: Filaments Intermediate n

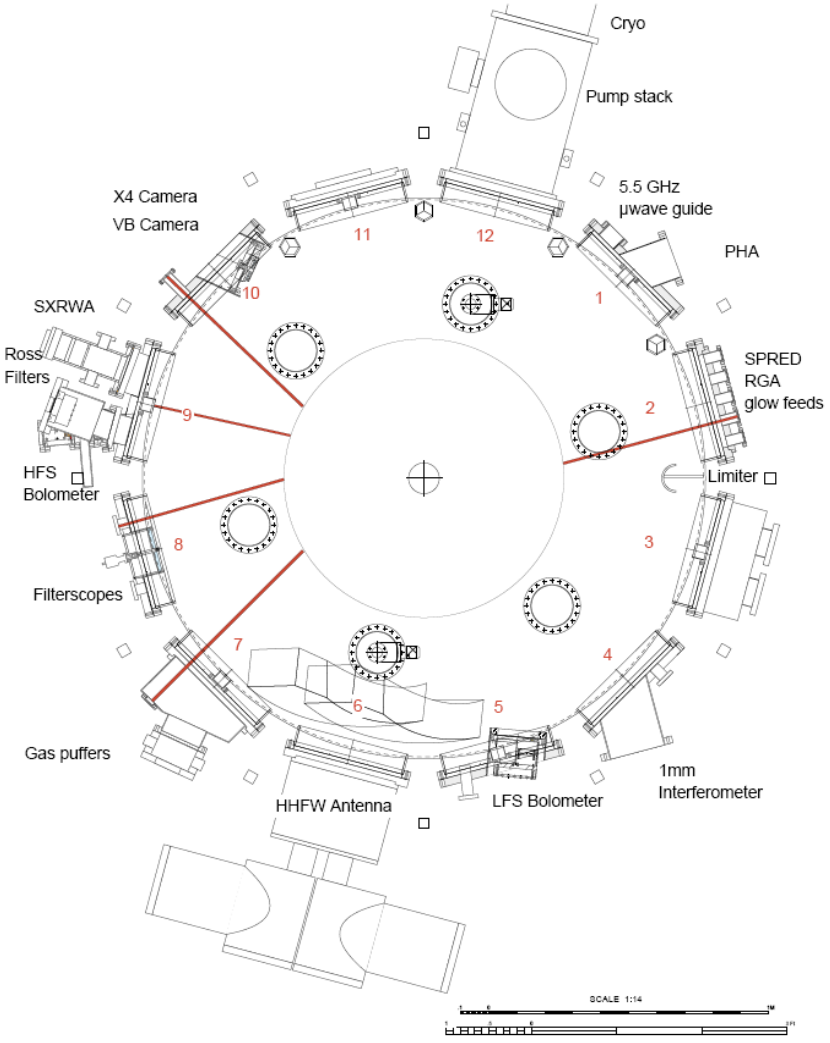
- n=1 tearing mode present
  - Typical in most OH discharges
  - Determined from outboard Mirnov coils
  - f ~ 5 kHz dominant; assumed intrinsic mode rotation frequency
- Probe at R=a: n=5-20 signatures present
  - No single dominant mode; likely a wide variety simultaneously present



THE UNIVERSITY of WISCONSIN MADISON

Future: Expansion to Multi-probe Array

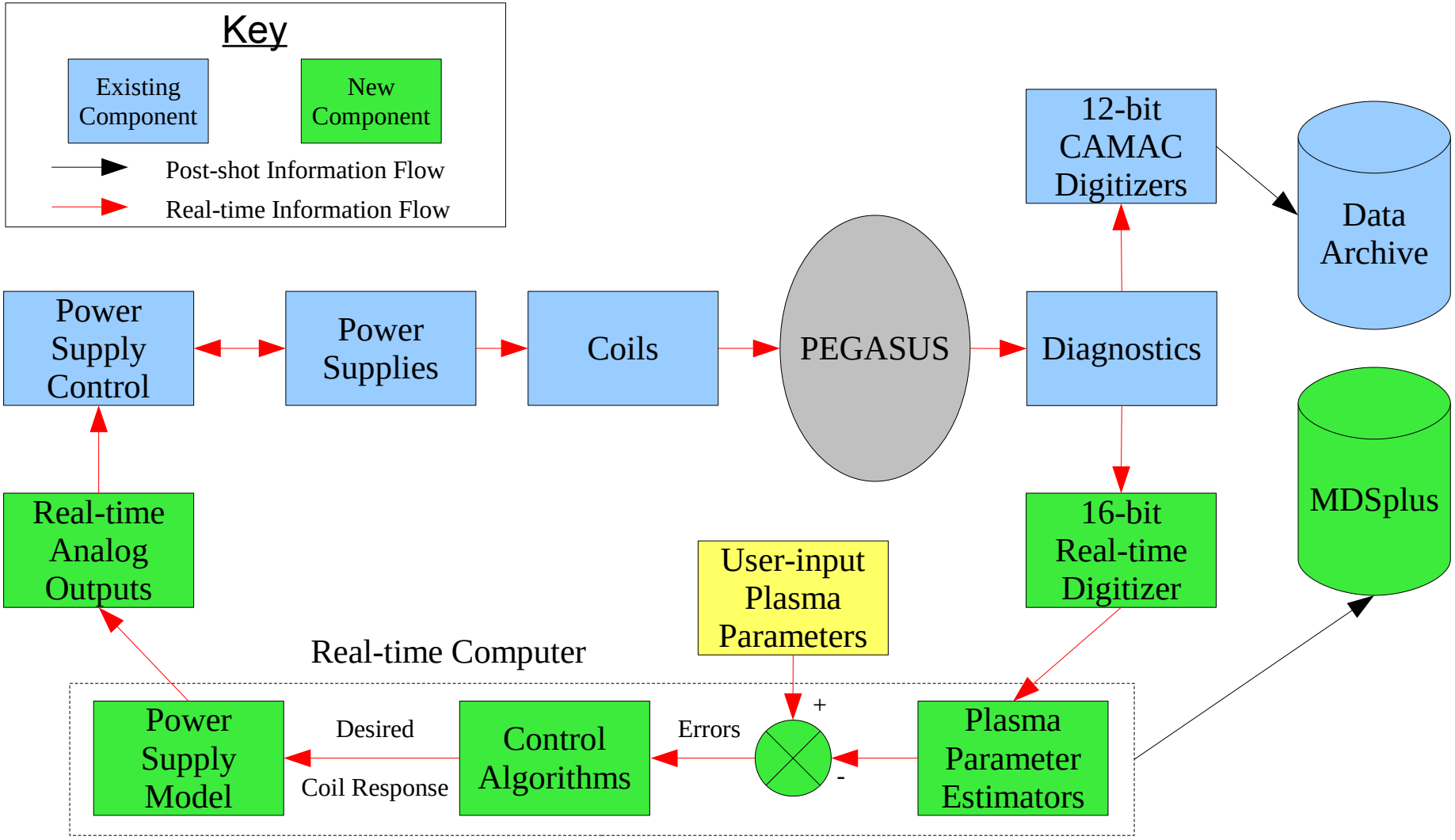
- Variety of probe locations viable on Pegasus
- Multiple toroidal angles for filament mode identification
- Compatible with existing port layout



Pegasus PCS to Assist Studies

- Pegasus Digital Plasma Control System Deployed
  - Enables realtime sample and adjustment of power supply demands
  - Based off versatile DIII-D PCS
  - Managed select run campaigns in 2007; wider adoption anticipated 2008
- Goals: I_p, R, Z control in ms timescale
  - I_p (V_{loop}) feedback highly desirable
  - R, Z more difficult due to effects of conducting vessel wall
- Low-drift integrator / signal processing modules developed
  - Improvement in signal processing electronics ongoing process
  - High quality, reliable analog measurements combat switching noise

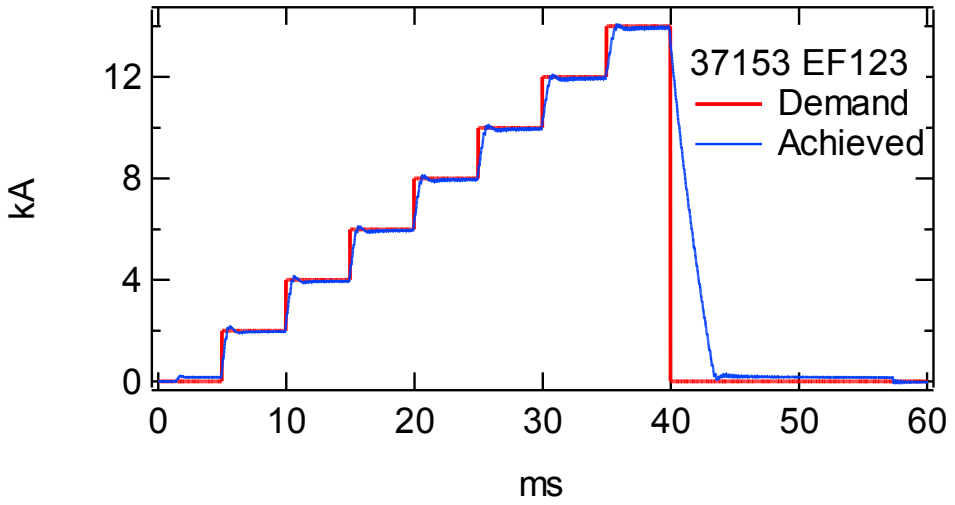
Pegasus PCS Enables Realtime Control

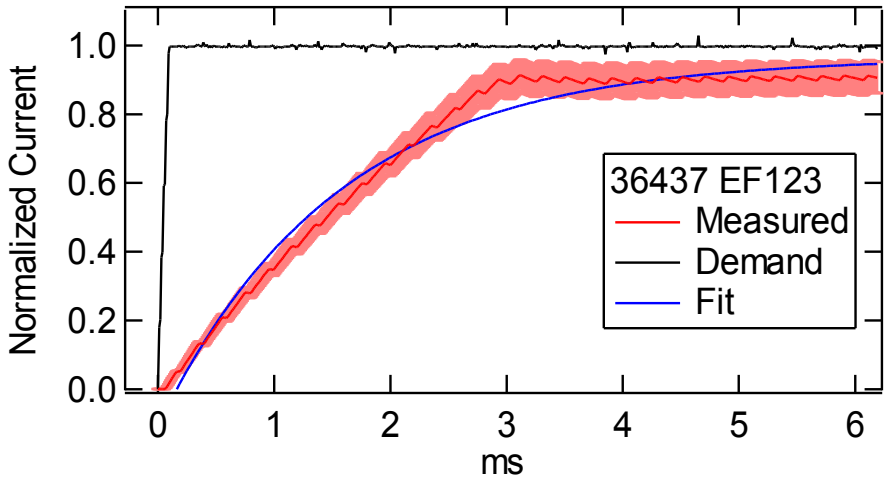


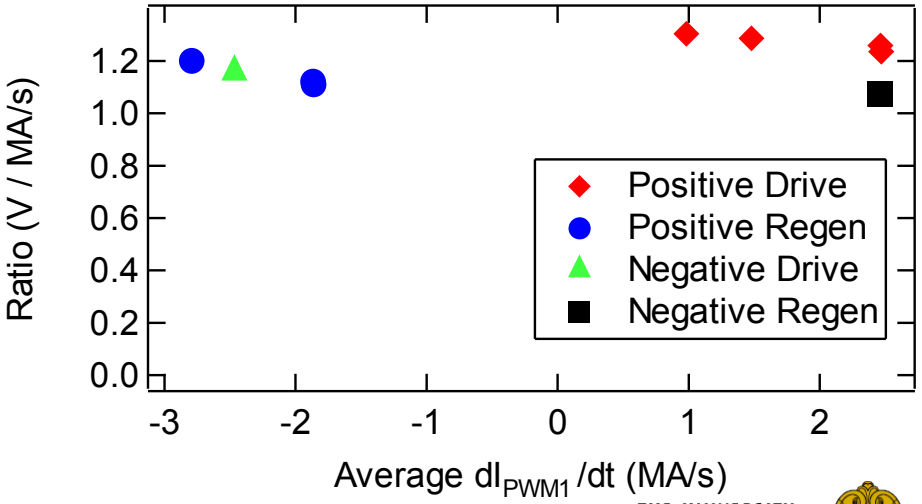
THE UNIVERSITY of WISCONSIN MADISON

Initial Control Algorithm Development

- Existing Control Replicated
  - PWM Demand Generator
  - Gas Puff Demands
- PS System Identification
  - EF Response Times ~ 1 ms τ_R
  - OH G_p Tests → 1.2 V/MA-s







THE UNIVERSITY of WISCONSIN MADISON

Summary

- Persistent edge filaments observed in Pegasus
  - Visually similar to ELM bursts in larger machines
- Initial observations consistent with peeling mode
  - High m, intermediate n
  - Suppression with reduced $j_{\|}$
- Pegasus' characteristic high edge current, low |B| suggest strong peeling drive
- Edge probes intended to constrain reconstruction, allow for meaningful stability analysis
- Increased control capabilities to aid shaping, Ip ramp studies

Reprints

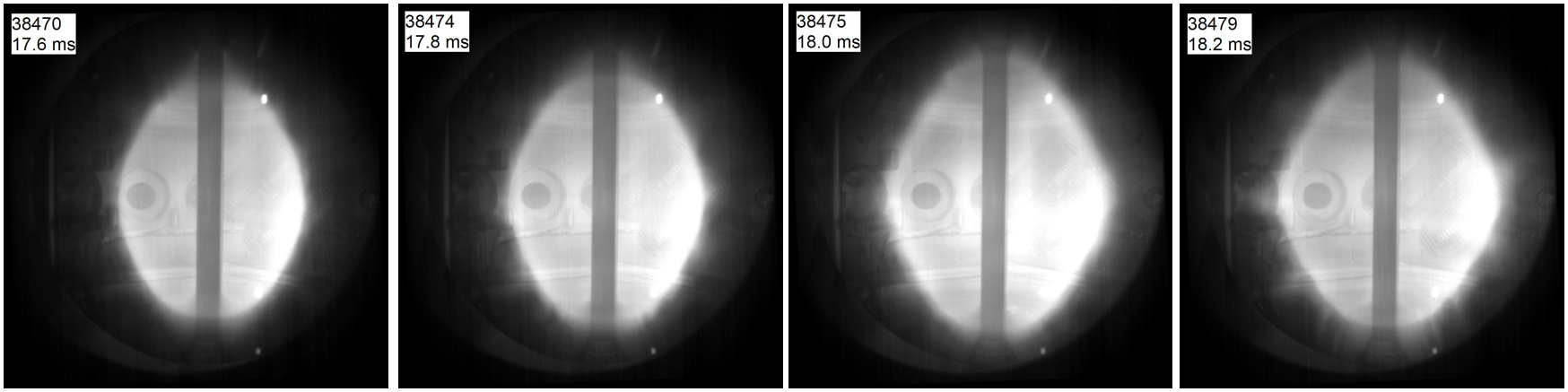
Backups

Suggestive: Mode Onset Delay with Shaping

- Preliminary, cursory, modification of δ via outboard midplane coil set effects slight delay in filamentation onset

- Difficult to discriminate influence of shape vs. |B| without very careful discharge tailoring

Visual Images at Onset of Filamentation

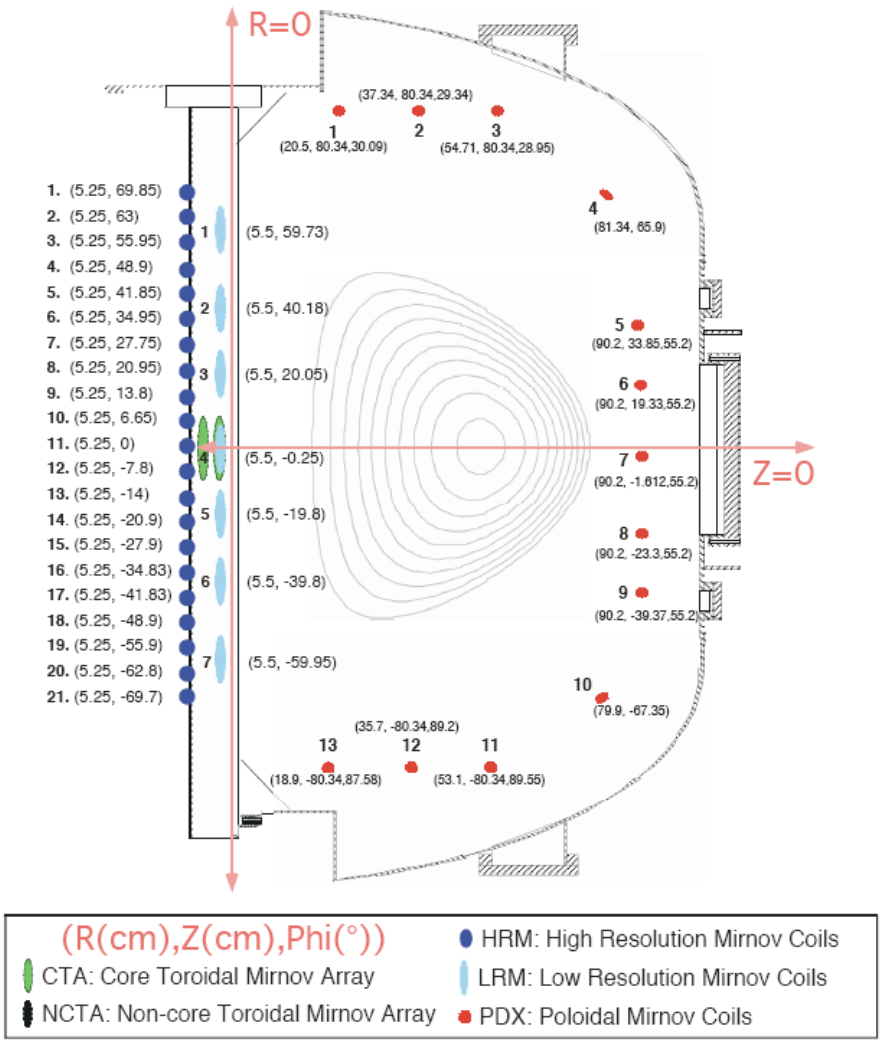


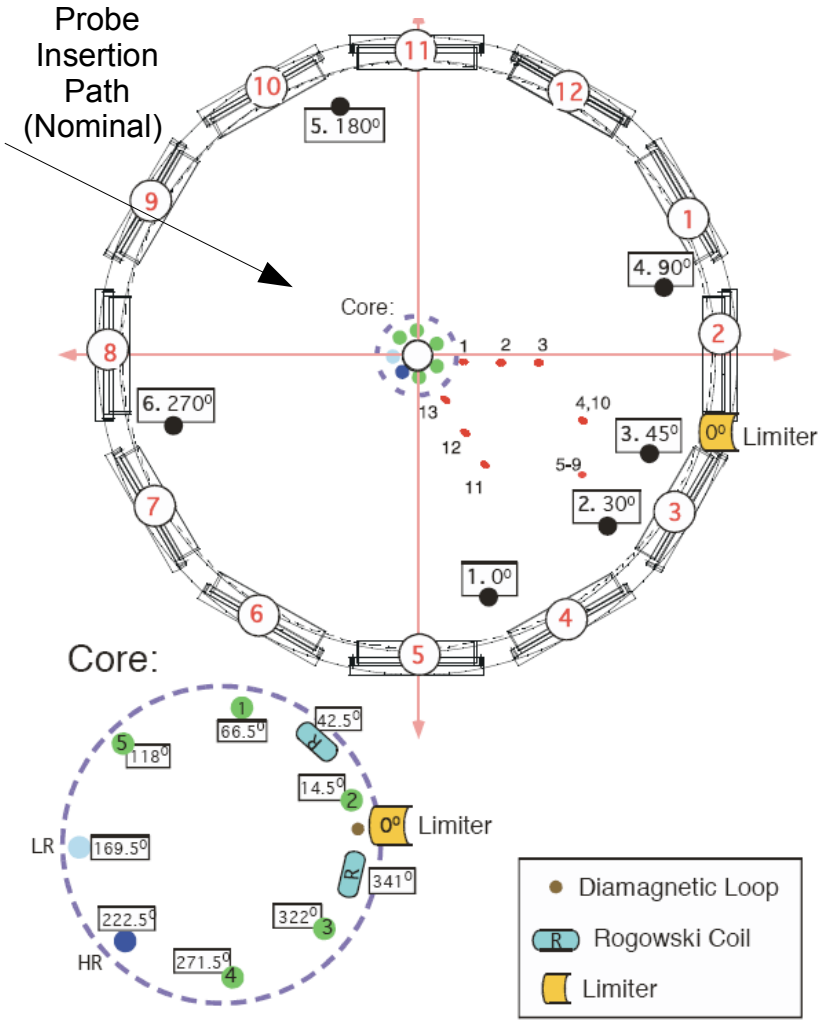
t_{onset} = 17.6 ms 17.8 ms 18.0 ms 18.2 ms

δ increasing →

THE UNIVERSITY of WISCONSIN MADISON

Pegasus Mirnov Locations

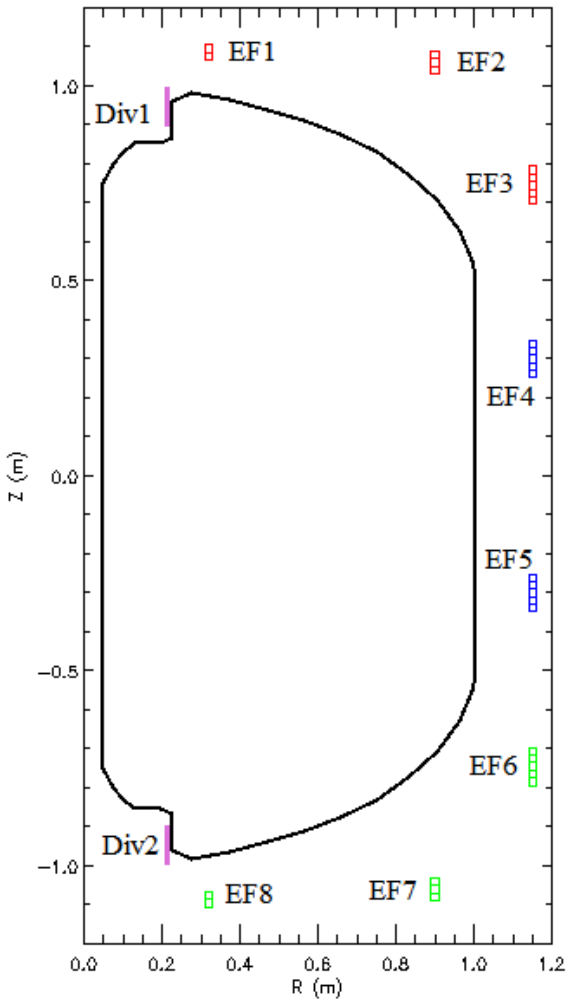




THE UNIVERSITY of WISCONSIN MADISON

EF Coil Sets are Primary Actuators

- 12 Independent Coil Sets Available
  - 8 EF, 2 Divertor, OH, TF
- Sets typically coupled for **B** control
  - 2-3 coil sets in series per group
  - Connections provided via patch panel
- Coil current control utilized
  - 5 coil groups capable of independent operation
    - 3 EF, TF, OH
  - Provides operator control without unwieldy machine operation space
  - Current ratings dependent on power supply configuration



Pegasus poloidal coil system (to scale). A typical configuration of EF123,45,678 is shown.

THE UNIVERSITY of WISCONSIN MADISON