Initial Edge Stability Observations
In the PEGASUS Toroidal Experiment

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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.

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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

15.577 ms
18.747 ms
24.789 ms
Edge Filaments Visually Similar to ELMs

- 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

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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_
• 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
Necessary peeling stability criterion: 

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

where

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

Stability in high \( A \), low-\( \beta \), low \( \nu \), weak shaping limit:

\[ -D_R > \frac{Rq}{s} \left( \frac{j_{||}}{B} \right)_{edge} \quad s \equiv \frac{r dq}{q dr} \]

with \( D_R \ (< 0) = \text{GGJ resistive interchange coefficient} \)
Pegasus: High $(j_{||}/B)_{\text{edge}}$ Typical

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

- $j_{||}/B$ Comparable to Larger Devices; strong peeling drive
  - Pegasus: $<j_{||}> \sim 10^5$ A/m$^2$, $B_{\phi,0} \sim 0.1$ T $\rightarrow j_{||}/B \sim 1x10^6$ A/(m$^2$-T)
  - DIII-D*: $<j_{||}> \sim (1-2)x10^6$ A/m$^2$, $B_{\phi,0} \sim 2$ T $\rightarrow j_{||}/B \sim (0.5-1)x10^6$ A/(m$^2$-T)

- Pegasus offers unique, university-scale opportunity for high $j_{||}/B$ experiments

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*: Thomas, Phys. Plasmas 12, 056123 2005
• Midplane bolometry reveals edge degradation with filaments
• Sharper edge during $I_p$ rampdown
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
• $\rho(\psi)$ typically well-known via multichannel TS
  – Currently unavailable on Pegasus

• $J(\psi)$ more difficult, equally important
  – $T_e \to$ noninvasive methods
  – Ex: Li beam polarimetry, DIII-D

• Accurate $J(\psi)$ measurement technique desired

• Typical alternative: compute $J$
  – Assumes bootstrap current drive
  – Questionable assumptions in edge

Thomas, Phys. Plasmas 12, 056123 2005
Edge Conditions Can Be Measured With Probes in Pegasus

• Pegasus plasmas compatible with probes
  – Short pulse ($\tau_{\text{shot}} < 50$ ms)
  – Low $T_{e,\text{edge}}$

• 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
• Filament magnetic signature detected
  – Probe inserted to plasma boundary, \( R_a = 65 \text{ cm} \)

• Frequency bursts coincide with filament onset

• Probe detects high frequency components unseen by existing magnetics
  – Likely due to high radial separation (\(~ 20 \text{ cm}\)
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
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

Key

- Existing Component
- New Component
- Post-shot Information Flow
- Real-time Information Flow

Power Supply Control

Power Supplies

Coils

PEGASUS

Diagnostics

12-bit CAMAC Digitizers

Data Archive

MDSplus

Real-time Analog Outputs

Real-time Computer

Power Supply Model

Control Algorithms

User-input Plasma Parameters

Errors

Desired Coil Response

Plasma Parameter Estimators

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Initial Control Algorithm Development

- Existing Control Replicated
  - PWM Demand Generator
  - Gas Puff Demands

- PS System Identification
  - EF Response Times $\sim 1$ ms $\tau_R$
  - OH $G_p$ Tests $\rightarrow 1.2$ V/MA-s

![Graphs and charts showing measured and achieved demand, normalized current, and ratio vs. time and current change rate.](image)
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
Backups
Suggestive: Mode Onset Delay with Shaping

- Preliminary, cursory, modification of $\delta$ 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

$\delta$ increasing

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Pegasus Mirnov Locations

Probe Insertion Path (Nominal)

(R(cm), Z(cm), Phi(°))

CTA: Core Toroidal Mirnov Array
NCTA: Non-core Toroidal Mirnov Array
HRM: High Resolution Mirnov Coils
LRM: Low Resolution Mirnov Coils
PDX: Poloidal Mirnov Coils

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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