Low-m Tearing Mode Studies on PEGASUS

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PEGASUS Toroidal Experiment
Large scale, low-m/n=1 tearing activity is commonly observed in ohmic discharges on Pegasus. Accentuated by broad regions of low magnetic shear, this tearing activity can limit performance in high TF utilization regimes ($I_p / I_{TF} \approx 1$) where $q_0$ is a low-order rational. In addition to increasing TF to raise $q_0$, tearing activity can be mitigated by: TF ramp-downs; electrostatic preionization to obtain OH breakdown at lower TF; and, DC helicity injection to provide strong edge current drive. Systematic scans of TF, $I_p$, and $\partial I_p / \partial t$ are presently being conducted to characterize these modes under a range of operational conditions. Measurements of magnetic activity via internal Mirnov probes are complicated by electrostatic noise arising from Pegasus’ high-frequency switching power supplies. This noise can be mitigated somewhat by shielding and signal processing, but can be eliminated altogether by freewheeling all power supplies for a brief period.

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• 2/1 mode activity was a common problem in Phase I discharges

• n=1 modes persist in Phase II operation at higher toroidal field

• Characterizing and mitigating these modes is a goal motivating this and future work

• Switching noise complicates mode analysis

• 2/1 mode at Phase I levels of toroidal field has been recreated

• Scan of $I_p$ at Phase II’s maximum toroidal field shows decreasing MHD virulence with decreasing $I_p$ until reaching mitigation

• First level mode analysis points to higher poloidal mode number (m) at high toroidal field
Pegasus is a Compact Ultralow-A ST

**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>To Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>1.15 – 1.3</td>
</tr>
<tr>
<td>$R(m)$</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>≤ 0.22</td>
</tr>
<tr>
<td>$I_N$ (MA/m-T)</td>
<td>6 – 12</td>
</tr>
<tr>
<td>$l_i$</td>
<td>0.2 – 0.5</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>1.4 – 3.0</td>
</tr>
<tr>
<td>$\tau_{shot}$ (s)</td>
<td>≤ 0.025</td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>≤ 25</td>
</tr>
<tr>
<td>$P_{HHFW}$ (MW)</td>
<td>0.2</td>
</tr>
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2/1 Tearing Activity was Prevalent in PEGASUS Phase I operation

- m=2/n=1 tearing mode activity was a common feature of Phase I plasmas
- This tearing activity limited performance and field utilization

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m=2/n=1 tearing activity limited Phase I Pegasus discharge performance to a soft $I_p/I_{tf} \sim 1$ limit

This limit corresponds to having $q(0) \sim 2$
q(r) Manipulation Increased Shear and Decreased MHD Activity

- q(r) manipulation to increase shear was found to be an effective method of limiting tearing mode virulence and delaying its onset to later in the discharge.

- Achieved through discharge development (plasma current profile manipulation)

![Graph showing the relationship between shear and mode amplitude](image-url)
Phase II Facility Upgrades Provided Tools to Mitigate n=1 Activity

- Phase II included upgrades to mitigate n=1 modes:
  - Toroidal field coils doubled to 288 kA-turns to raise \( q(0) \) and keep \( q=2 \) surface out of the plasma; center-rod replaced with low inductance assembly for fast current ramping
  - \( \frac{dI_p}{dt} \) control via \( V_{\text{loop}} \) control to heat up plasma interior and lower resistivity to prevent resistive tearing activity
  - Fast, programmable switching power supplies for shaping control

Cross-section of center-stack

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n=1 activity still observed in most OH discharges in Phase II with increased 288 kA-turns of toroidal field current

These modes motivate more detailed study of n=1 activity in expanded Phase II operating space

Toroidal phase-slope
$I_{tf}=288$ kA-turns; $I_p=133$ kA
shot 49398 (3.0 kHz, 21-24 ms)

\[\text{Toroidal physical angle } \phi \]
Methods for lessening and delaying tearing activity on Pegasus have successfully expanded operating space to $I_p/I_{tf} > 1$:

- TF ramp-downs
- $q$-profile manipulation through discharge tailoring
- Plasma-gun pre-ionization
- Non-inductive helicity injection with plasma guns
• To explore $I_p/I_{tf} > 1$ and increase OH-only operating space, our goals include:
  – Characterize the structure of performance-limiting $n=1$ modes
  – Develop effective mitigation techniques

• $I_p$ scanned to vary $q_0$:
  – First, recreated plasma at $I_p/I_{tf} \sim 1$ limit at Phase I’s max TF current ($I_{tf}=288$ kA-turns, $I_{p-max}=119$ kA)
  – Scanned $I_p$ at Phase II max TF current ($I_{tf}=288$ kA-turns, 90 kA < $I_{p-max}$ < 163 kA)

• 1st level analysis in mind:
  – Map out virulence and parameter space of mode activity
  – Map out structure (namely, mode numbers $m$ and $n$)
Switching Power Supplies Add Noise to Mirnov Coil Diagnostics

- Mirnov arrays constructed in Phase I were routinely used for MHD analysis, but not built with switching noise considerations.

- Switching noise is in the same frequency range as MHD activity observed on Pegasus:
  - Core Mirnov coils are currently too noisy for measuring MHD signals.
  - Outer Mirnov coils are used to measure phase shifts of MHD activity, but require filtering.

![Graph showing auto power and time series of Mirnov signal noise](image)
Noise-Proofing Techniques for Magnetic Diagnostics Have Been Developed

- A toroidal Mirnov probe array built in Phase II has been built to be switching-noise free
  - This diagnostic demonstrates that switching noise can be eliminated on Mirnov diagnostics and will guide upgrades to the machine for this purpose.
  - The probe array aids in current analysis, but is not sufficient for poloidal structure identification

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For Now, Switching Noise Temporarily Limits Available Magnetics

- Switching noise temporarily limits mode analysis to outboard toroidal and poloidal Mirnovs

- Future work will relieve this constraint

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“High-Res” Core Mirnov Coils (21)
Poloidal Mirnov Coils (22)

LFS Toroidal Mirnov Coils (6)
HFS Toroidal Mirnov Coils (7)
First level mode analysis of MHD activity with outboard Mirnov probes has been done at various levels of $I_p$

- Digital band-pass filtering is always applied in order to remove noise
- Applying a digital integration to Mirnov signals diminishes switching noise, especially in filtering the noisier poloidal coils on the top and bottom of the machine which are closer to the core
  - Integration introduces a constant phase shift of 90° to the signal, which is applied to all the Mirnovs
- Standard phase-slope analysis techniques are used, with the addition of a straight-field-line mapping approximation
To estimate \( m \), a shifted-cylinder approximation (which uses the Merezhkin approximation for the magnetic fields via an aspect ratio expansion) was used to estimate the straight-field-line (SFL) mappings in phase-slope analysis

\[
\theta_{\text{Mer}} \approx \theta - \lambda \sin(\theta) \quad \text{where} \quad \lambda = \frac{r_{mn}}{R} \left\{ \beta_p + 0.5 \ell_i + 1 \right\}
\]

using typical Pegasus values of \( \beta_p \approx 0.1 \), \( \ell_i \approx 0.35 \) and estimating \( r_{mn} \approx a/4 \)

Example SFL mapping from a KFIT reconstruction:

Example shifted-cylinder approximation of SFL poloidal angle:


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At Phase I’s maximum toroidal field (144 kA-turns, half of current capability), the 2/1 tearing mode observed in Phase I was recreated.

\[ I_{tf} = 144 \text{ kA-turns}; \; I_p = 119 \text{ kA} \]
Shot 49522 (24-27 ms, 3.7 kHz)

![Graph showing phase angle vs. toroidal physical angle and meridional approximation of SFL angle.](image-url)
Decreasing $I_p$ Significantly Reduced MHD Activity at High Toroidal Field

- Scanning $I_p$ at maximum toroidal field (288 kA-turns) showed clear decrease in MHD activity

- Below 90 kA, MHD activity appears to be completely mitigated
Poloidal Mode Number Higher at High TF

- Poloidal mode number $m \sim 4-5$ estimated for 3 levels of $I_p$ at high toroidal field.

- These results suggest larger-$m/n=1$ modes can limit performance at $A \sim 1$.

$I_{tf} = 288$ kA-turns; $I_p = 156$ kA
Shot 49393 (2.5 kHz, 20-25 ms)

$I_{tf} = 288$ kA-turns; $I_p = 133$ kA
Shot 49398 (3.0 kHz, 21-24 ms)

$I_{tf} = 288$ kA-turns; $I_p = 138$ kA
Shot 49399 (2.2 kHz, 21-24 ms)
Conclusions

- 2/1 tearing activity was a performance-limiting problem in Phase I and inspired several major upgrades in Phase II to mitigate tearing activity

- $n=1$ activity at times can still limit performance in Phase II, motivating this and further study to fully characterize these modes to develop mitigation techniques
  - This suggests j-profile manipulation as a tool for future mitigation work.

- At Phase II’s increased toroidal field, first level mode analysis shows an increase in poloidal mode number to $m \sim 4-5$, suggesting that higher-$m/n=1$ modes can limit performance at $A$ approaching $A \sim 1$.

- In a scan of $I_p$ at 288 kA-turns of toroidal field current, $n=1$ mode virulence diminished as $I_p$ decreased until fully suppressed at $I_p \sim 90$ kA
Future Work

• Noise-proofing electronics
  – Replacing external signal lines to be completely shielded
  – Add analog integrators and line drivers to signal trains

• New methods of temporarily stopping switch events is under development
  – This method involves forcing individual power supplies to stop switching, and naturally coast down in current for a short period of time (~several ms).

• A soft x-ray wave array will soon be under development
  – A soft x-ray wave array will make it possible to directly locate perturbations’ location in the plasma, and offer another method for mode structure characterization.

• Model the effect of a helical perturbation on various resonant surfaces to account for shaping effects on measured mode structure
The Forced-Freewheel Method Dramatically Reduces Switching Noise

- The method of forcing individual power supplies to stop switching has had preliminary testing:
  - The test included stopping the ohmic inductive drive as well as the toroidal field coils from producing switch events.
  - However, freewheeling the toroidal field coils and the ohmic drive together caused temporary loss of plasma performance.
  - Further testing involving only forcing the toroidal field coils to stop switching may be a simple solution.
  - Changing the switching frequency for a short period of time where a coil’s waveform does not change greatly could significantly reduce switching noise.