Low-m Tearing Mode Studies on PEGASUS

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PEGASUS Toroidal Experiment

Abstract

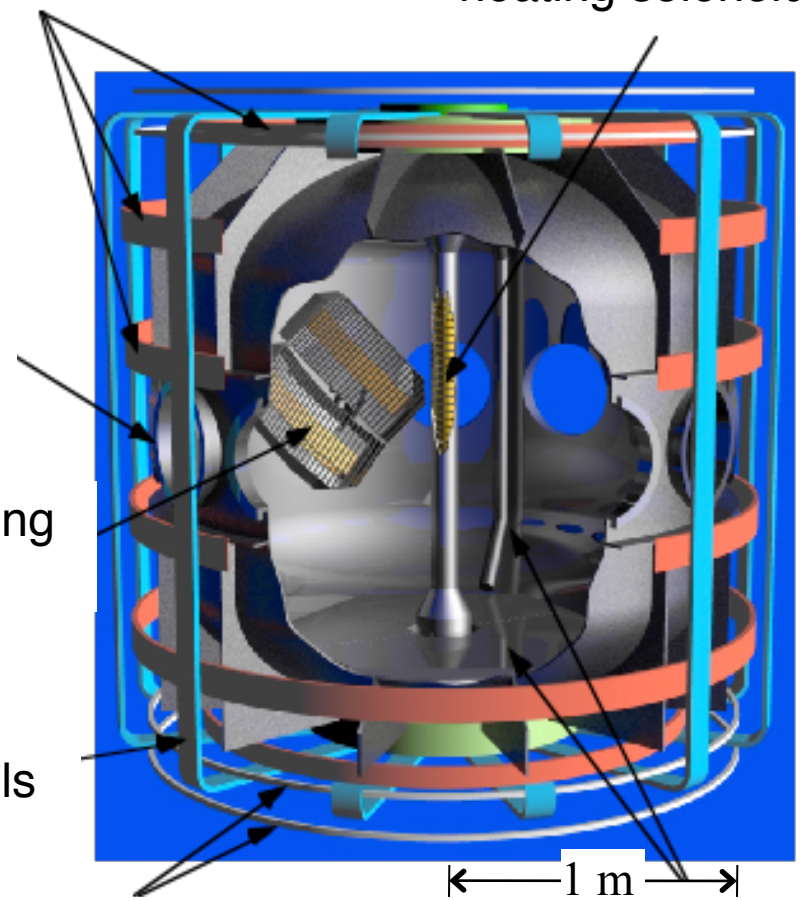
Large scale, low-m/n=1 tearing activity is commonly observed in ohmic discharges on Pegasus. Accentuated by broad regions of low magnetic shear, this tearing activity can limit performance in high TF utilization regimes ($I_p / I_{TF} \approx 1$) where q0 is a low-order rational. In addition to increasing TF to raise q_0 , tearing activity can be mitigated by: TF ramp-downs; electrostatic preioniziation 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.

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

PEGASUS Tearing Mode Studies Outline

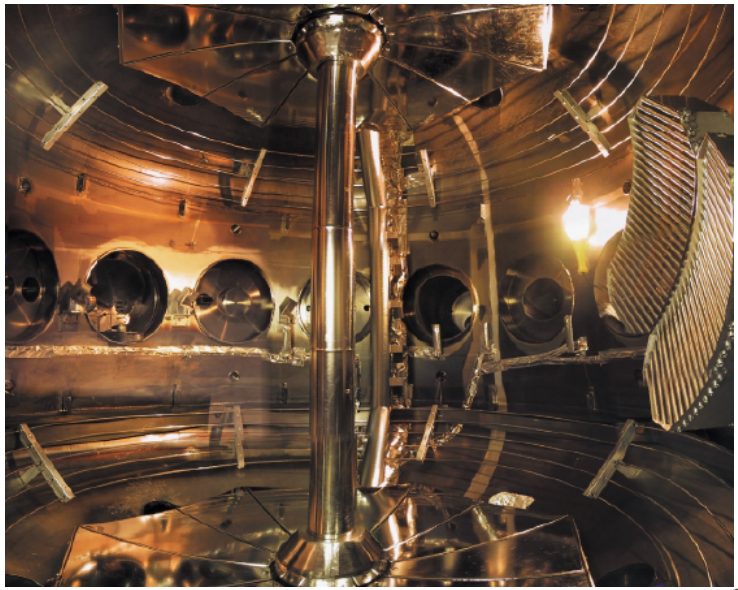
- 2/1 mode activity was a common problem in Phase I discharges
- n=1 modes persist in Phase II operation at higher toroidal field
- Characterizing and mitigating these modes is a goal motivating this and future work
- Switching noise complicates mode analysis
- 2/1 mode at Phase I levels of toroidal 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



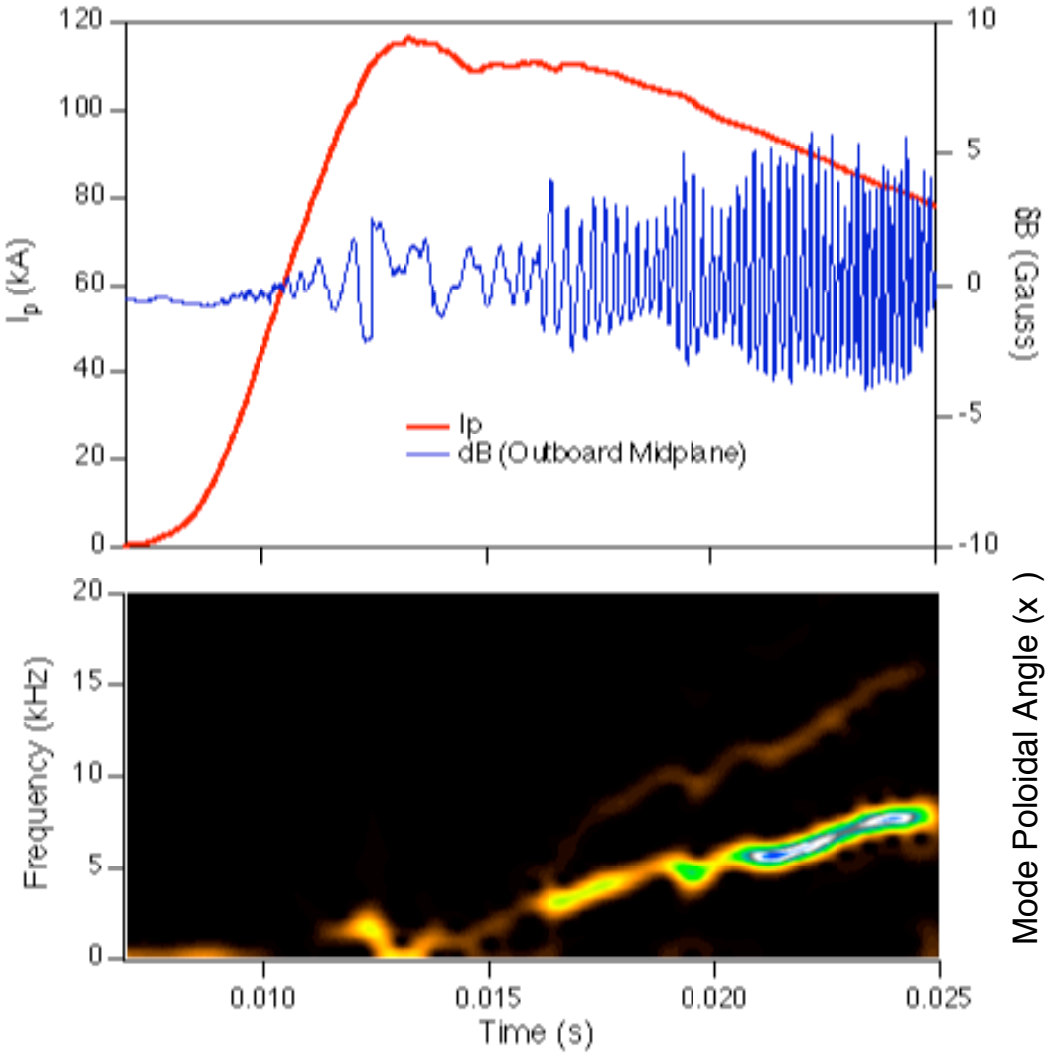
Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .22
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.0
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2

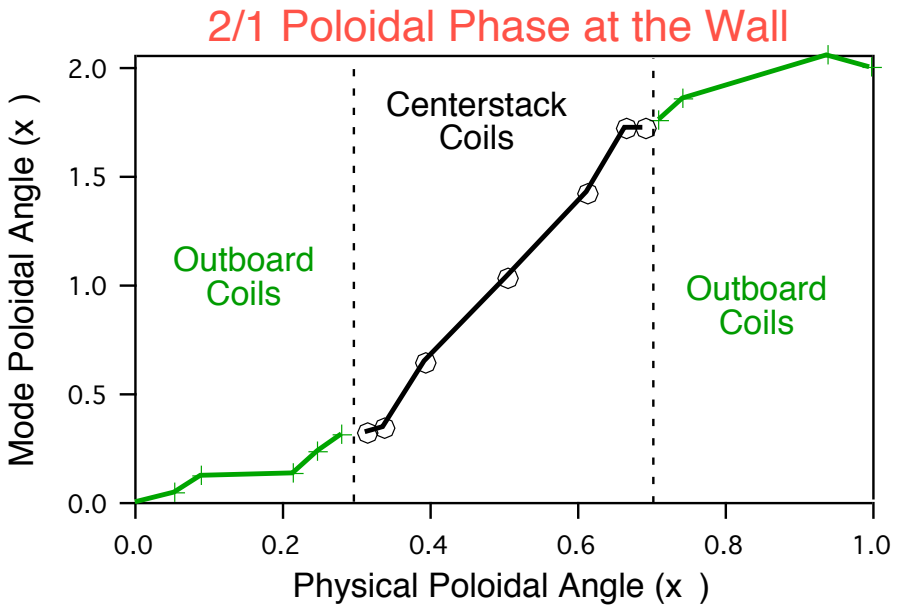


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2/1 Tearing Activity was Prevalent in PEGASUS Phase I operation



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

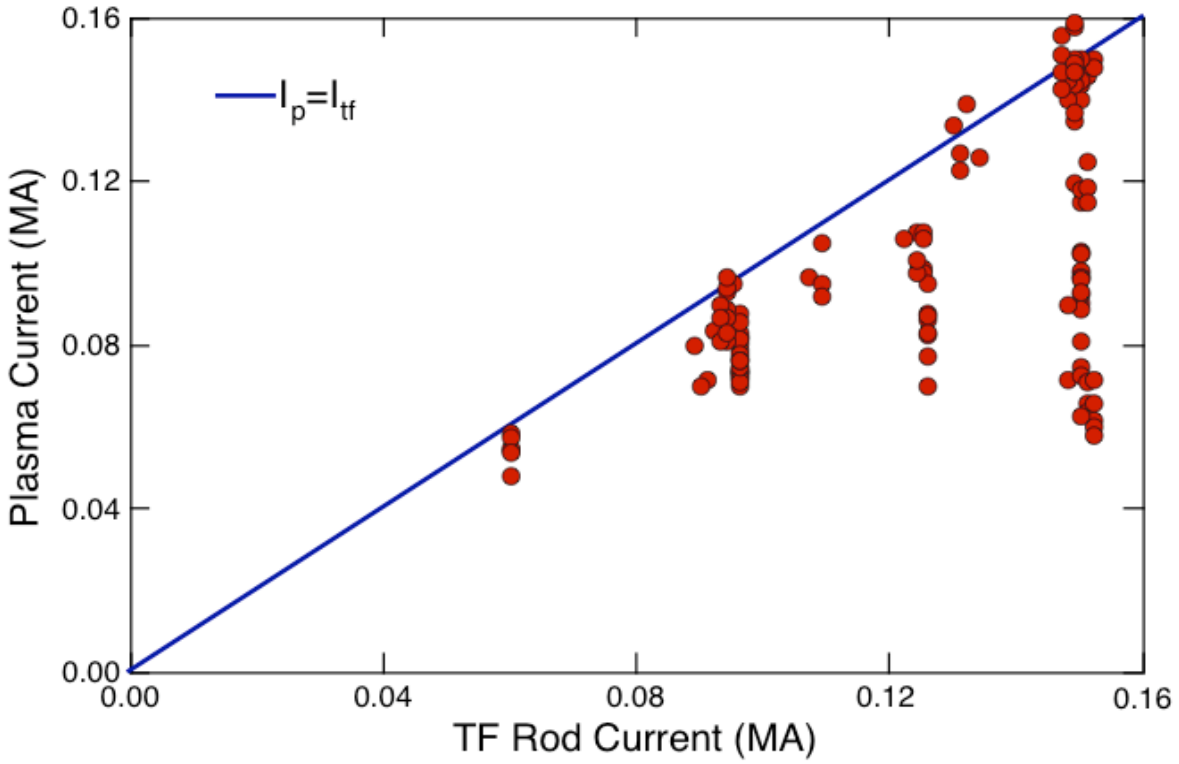


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2/1 Activity Limited Phase I to a Soft Operating Limit of I_p/I_{tf} ~ 1

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

- This limit corresponds to having q(0) ~ 2

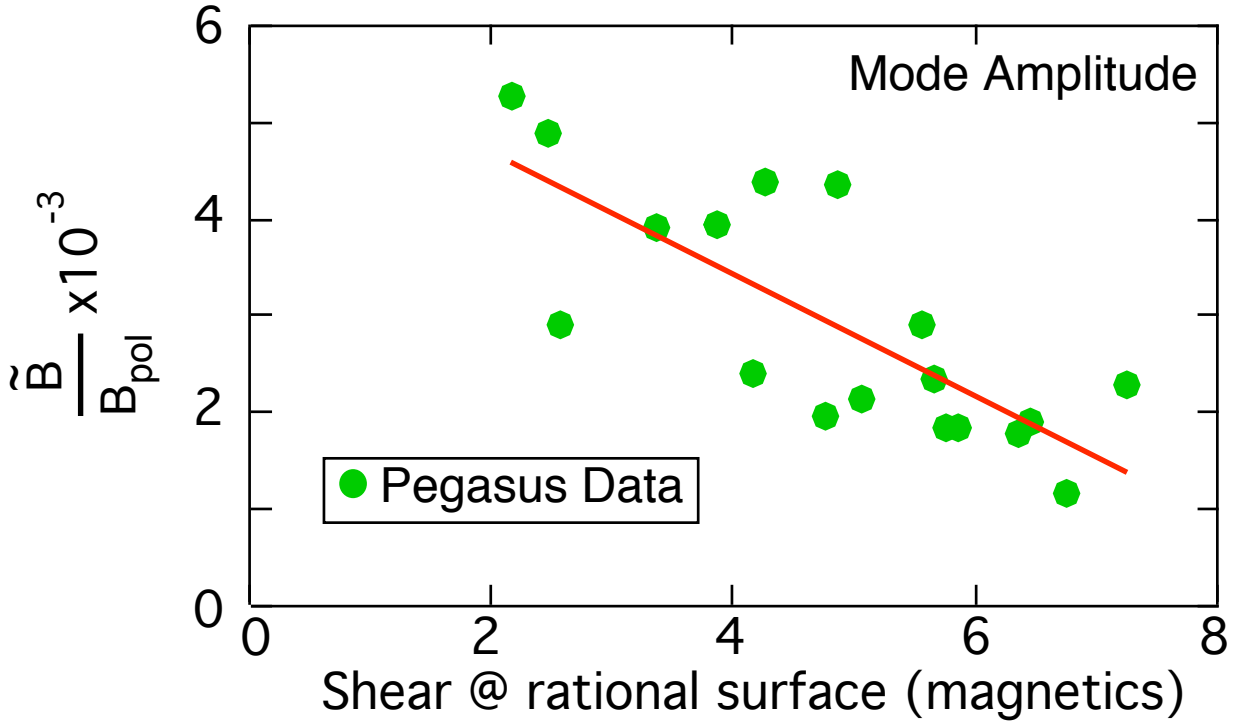


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q(r) Manipulation Increased Shear and Decreased MHD Activity

- 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

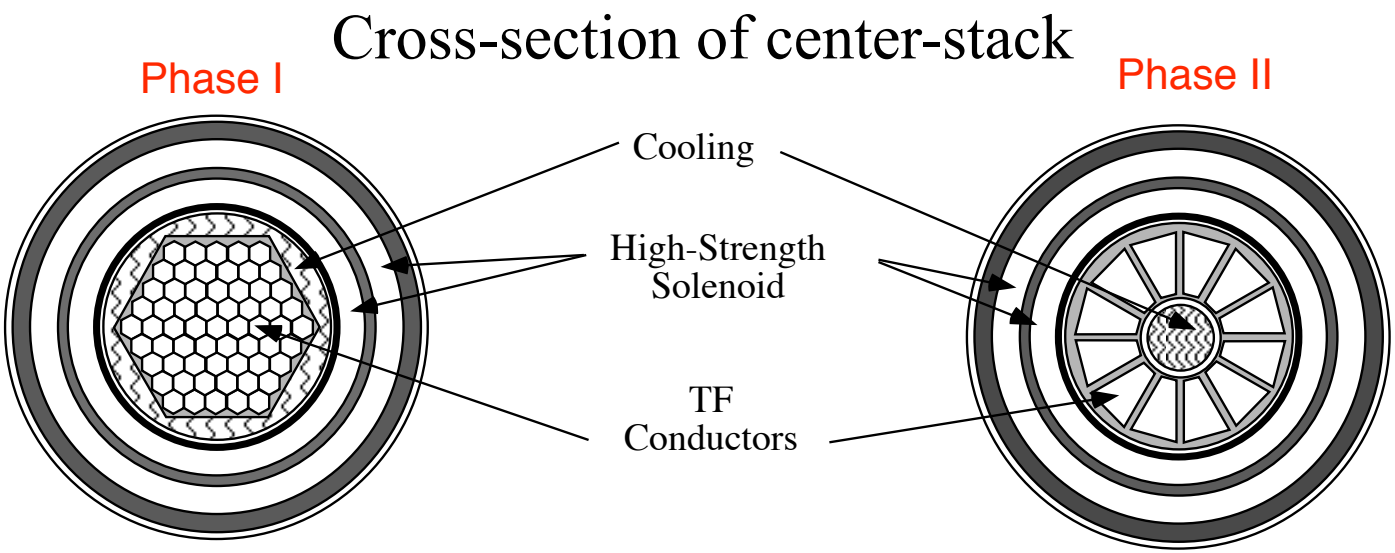
- Achieved through discharge development (plasma current profile manipulation)



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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
  - dI_p/dt control via V_{loop} control to heat up plasma interior and lower resistivity to prevent resistive tearing activity
  - Fast, programmable switching power supplies for shaping control

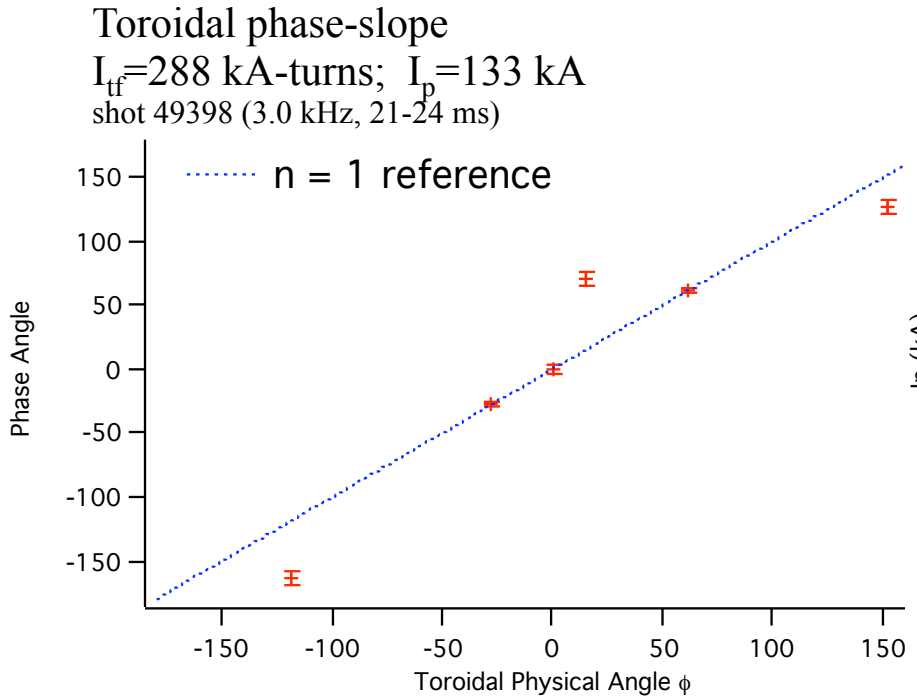


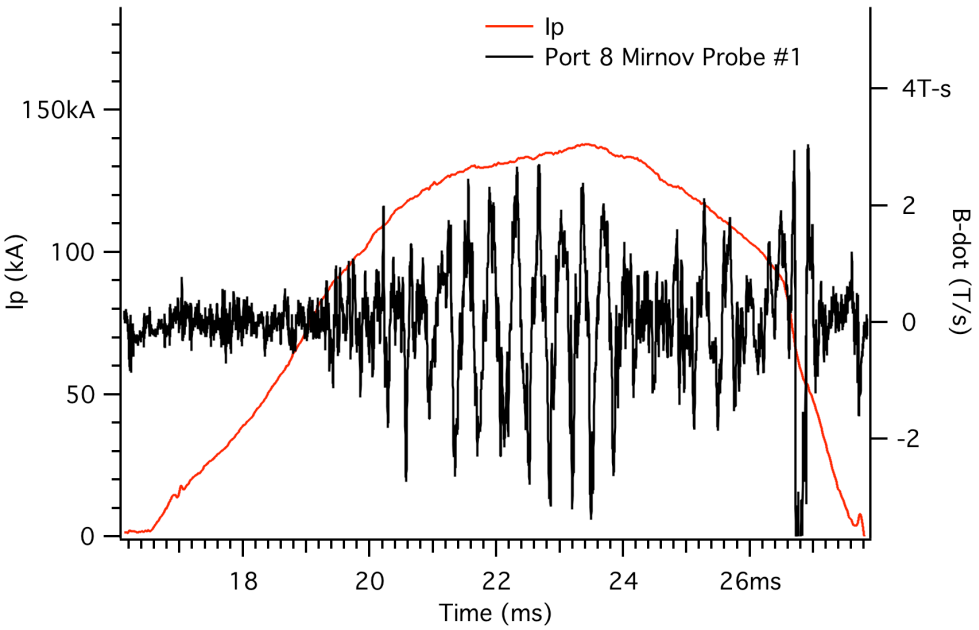
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n=1 Activity Persisted after Facility Upgrades

- 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

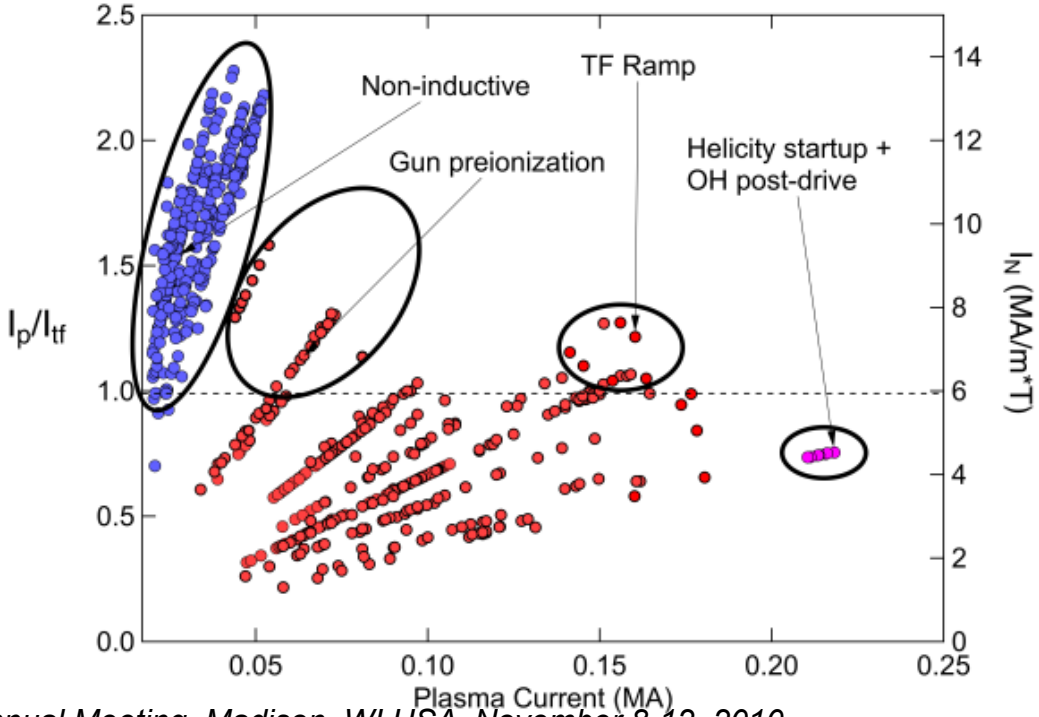




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Tearing Activity Diminishing and Delay Techniques Have Been Developed

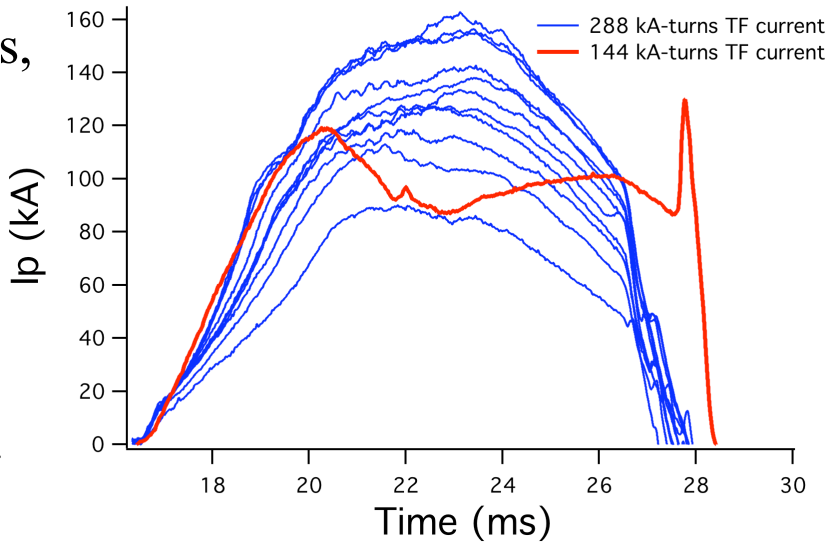
- Methods for lessening and delaying tearing activity on Pegasus have successfully expanded operating space to $I_p/I_{tf} > 1$:
  - TF ramp-downs
  - q-profile manipulation through discharge tailoring
  - Plasma-gun pre-ionization
  - Non-inductive helicity injection with plasma guns



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I_p Scanned to Characterize n=1 Activity at High TF in OH-only Plasmas

- 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}~1 limit at Phase I's max TF current (I_{tf}=288 kA-turns, $I_{p\text{-}max}$=119 kA)
  - Scanned I_p at Phase II max TF current (I_{tf}=288 kA-turns, 90 kA <$I_{p\text{-}max}$< 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)

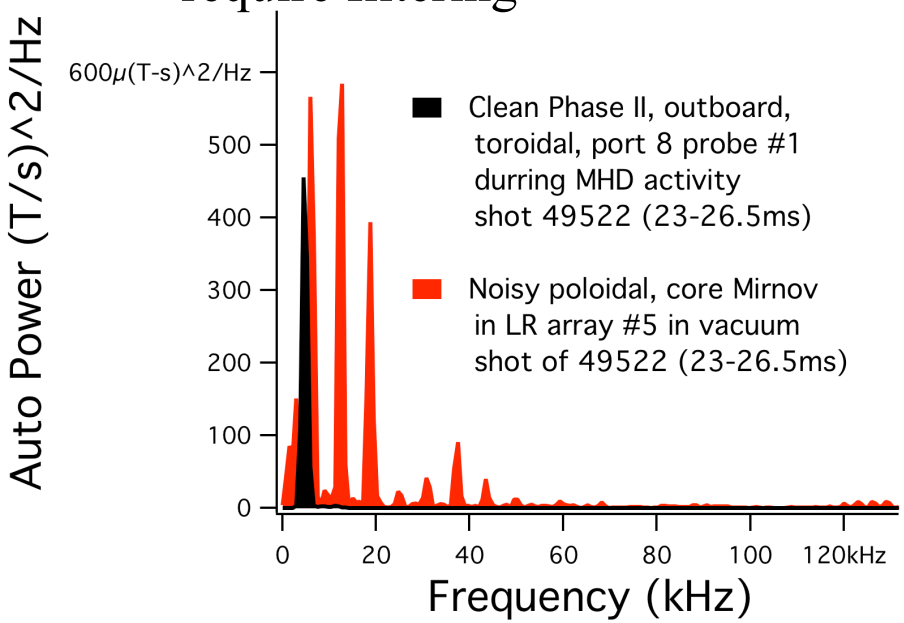


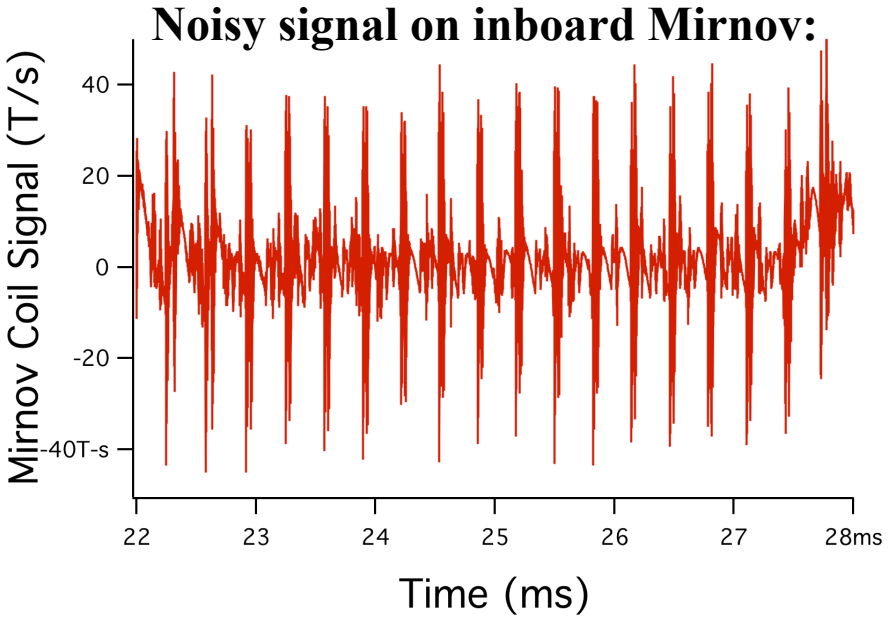
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Switching Power Supplies Add Noise to Mirnov Coil Diagnostics

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

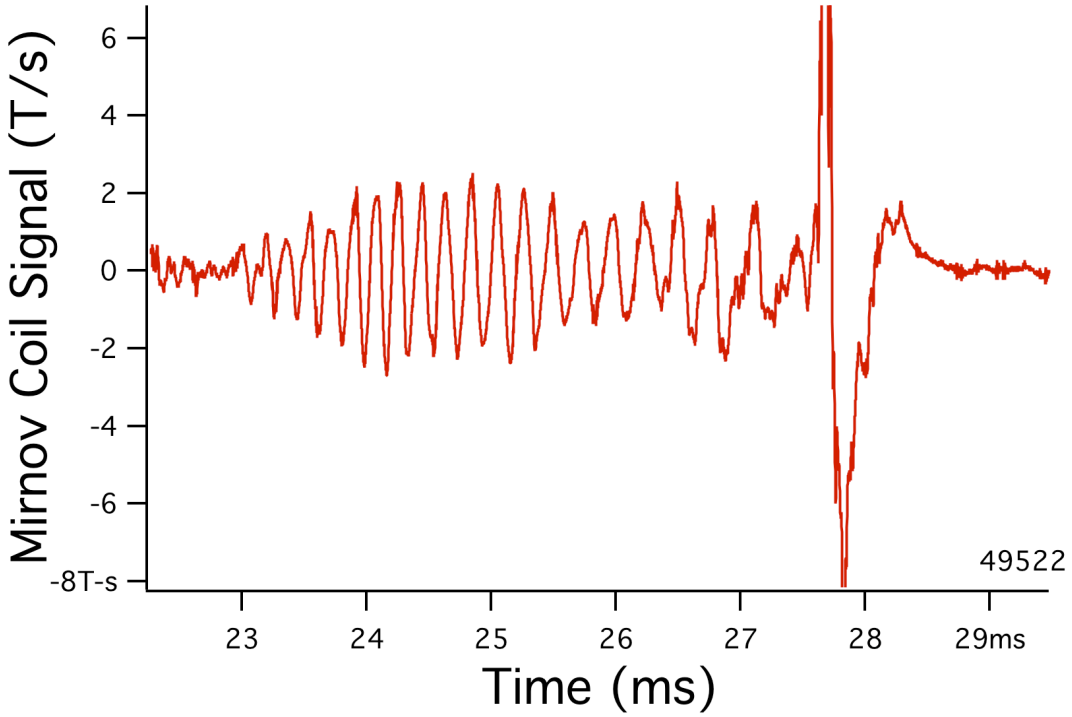
- Switching noise is in the same frequency range as MHD activity observed on Pegasus
  - Core Mirnov coils are currently too noisy for measuring MHD signals
  - Outer Mirnov coils are used to measure phase shifts of MHD activity, but require filtering





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

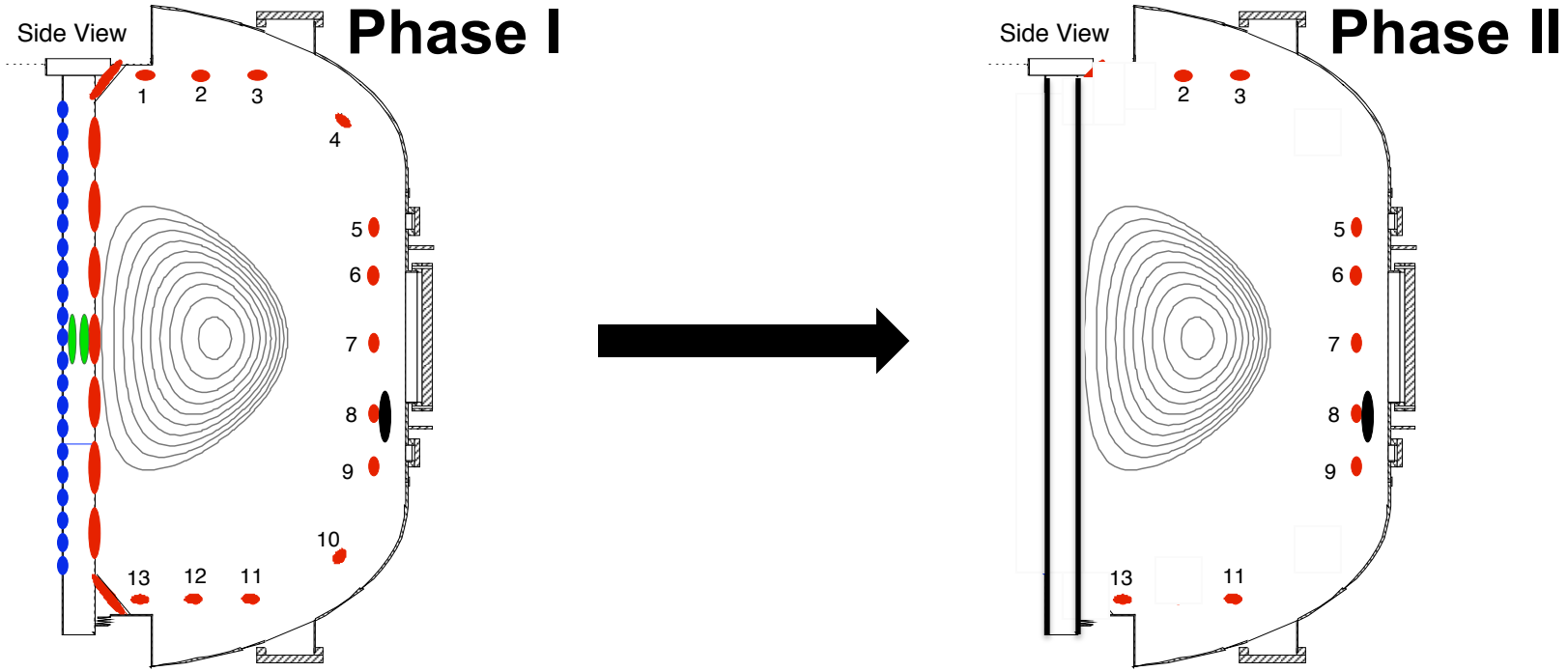


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For Now, Switching Noise Temporarily Limits Available Magnetics

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

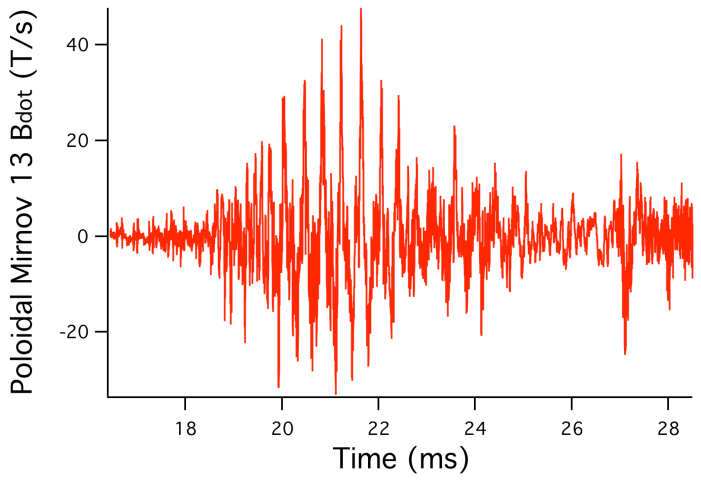
- Future work will relieve this constraint

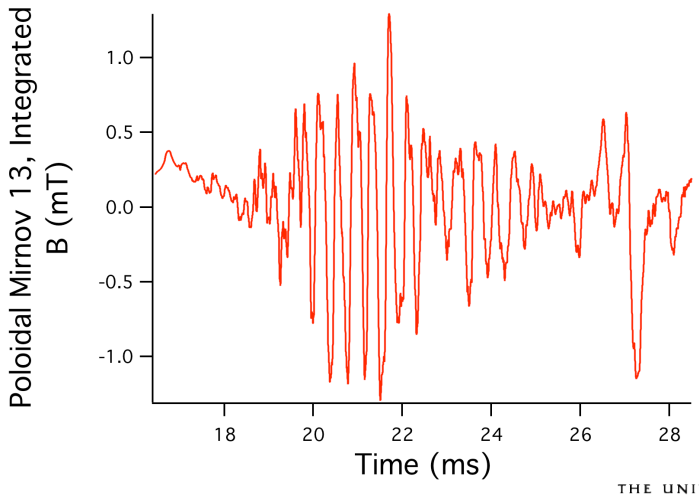


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First Level Mode Analysis is Performed with Outboard Mirnovs

- 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





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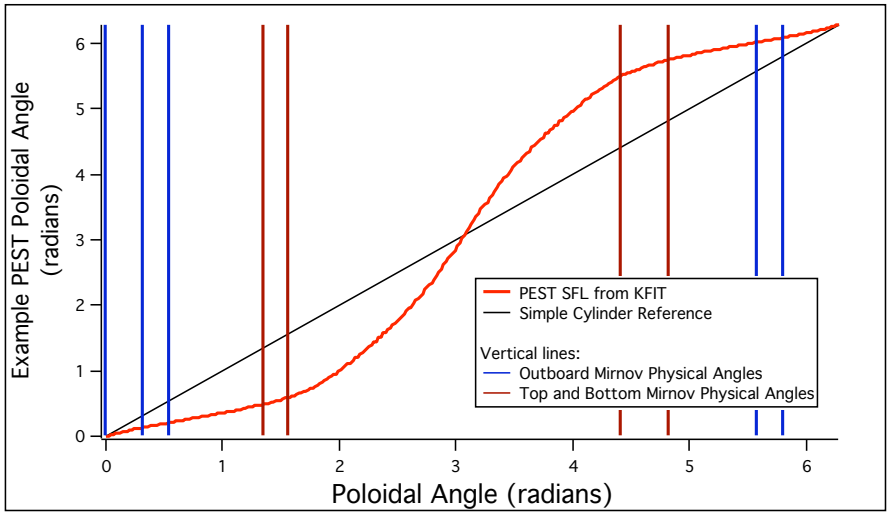
Straight Field Line Mappings and the Merezhkin Approximation

- 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

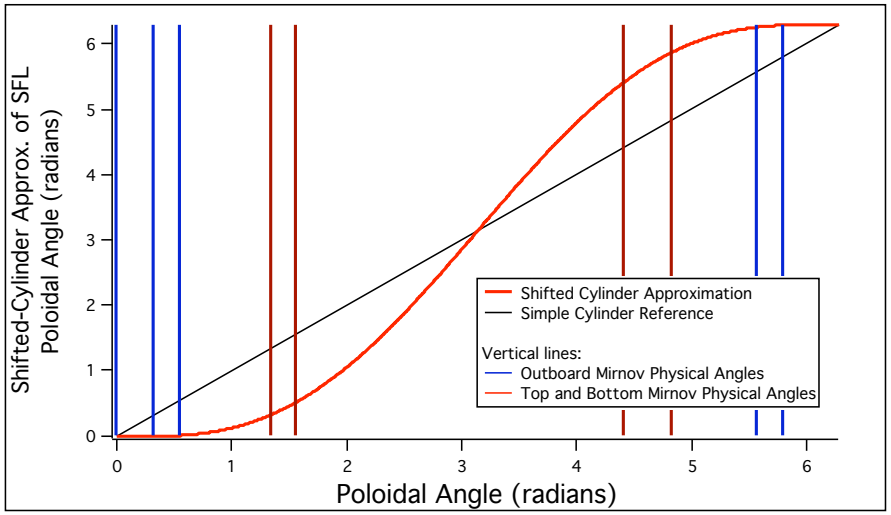
$$\theta_{Mer} \approx \theta - \lambda \sin(\theta) \qquad \text{where } \lambda = (r_{mn}/R)\ \{\beta_p + 0.5\ \ell_i + 1\}$$

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:



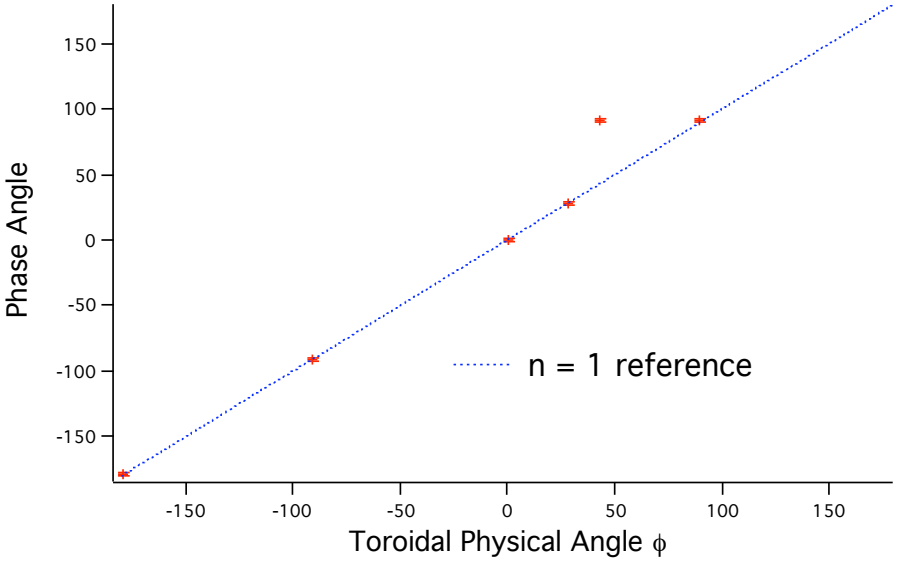
See Z. Unterberg, *Accessing High Normalized Current in an Ultra-Low-Aspect-Ration Torus*, UW-Madison NEEP (2007) for more information on this approximation.

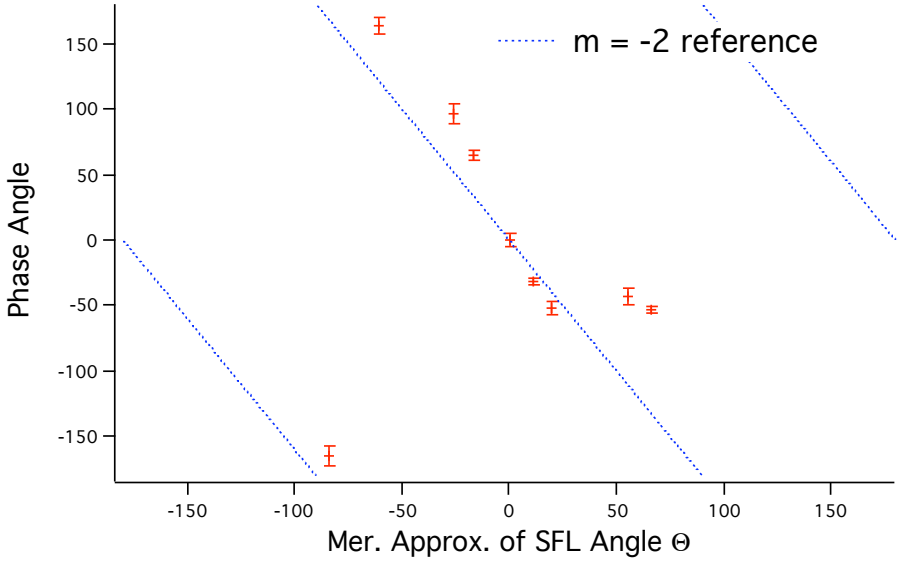
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2/1 Mode Reproduced at Low Toroidal Field

- 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 kA-turns; I_p=119 kA
Shot 49522 (24-27 ms, 3.7 kHz)



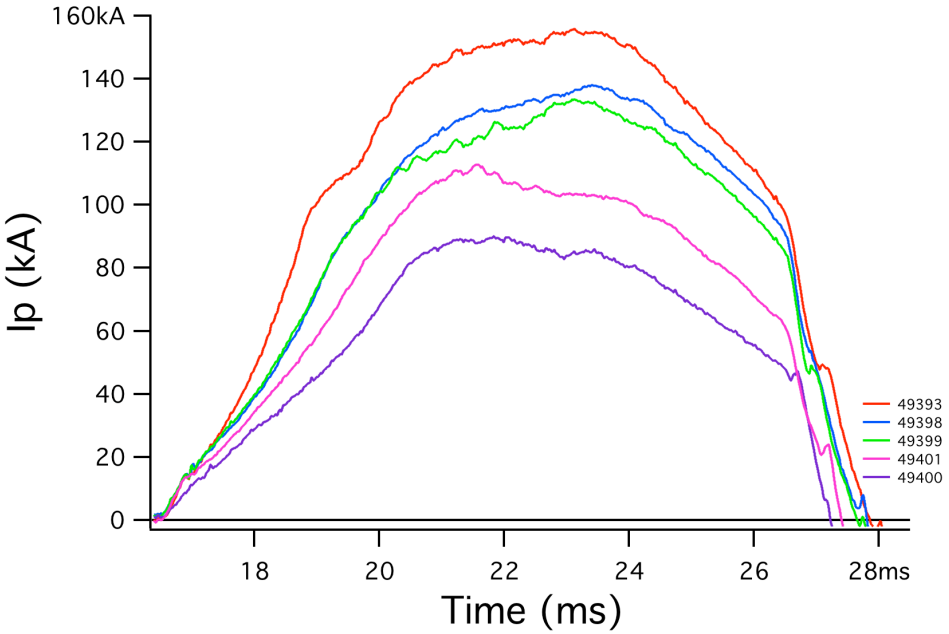


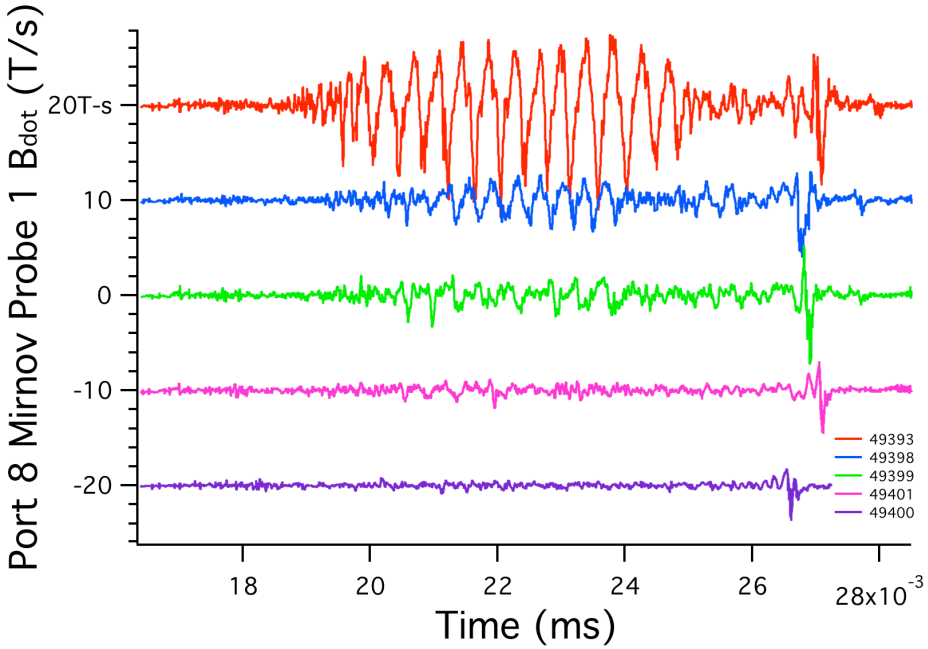
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Decreasing I_p Significantly Reduced MHD Activity at High Toroidal Field

- 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

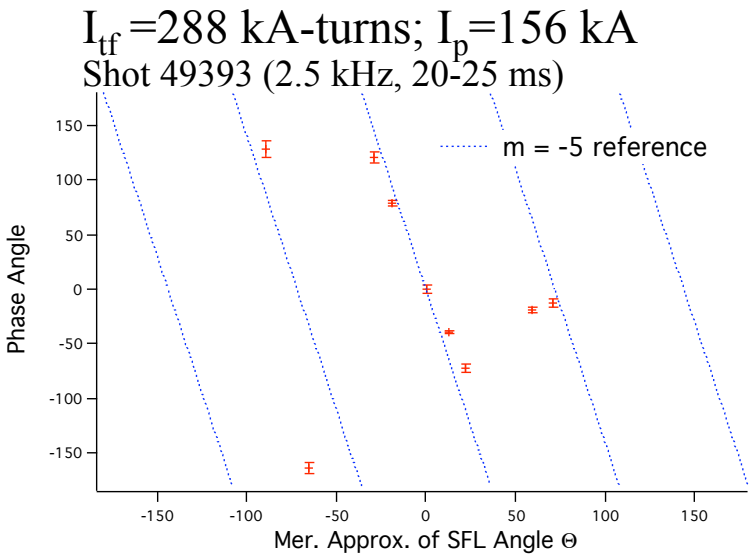


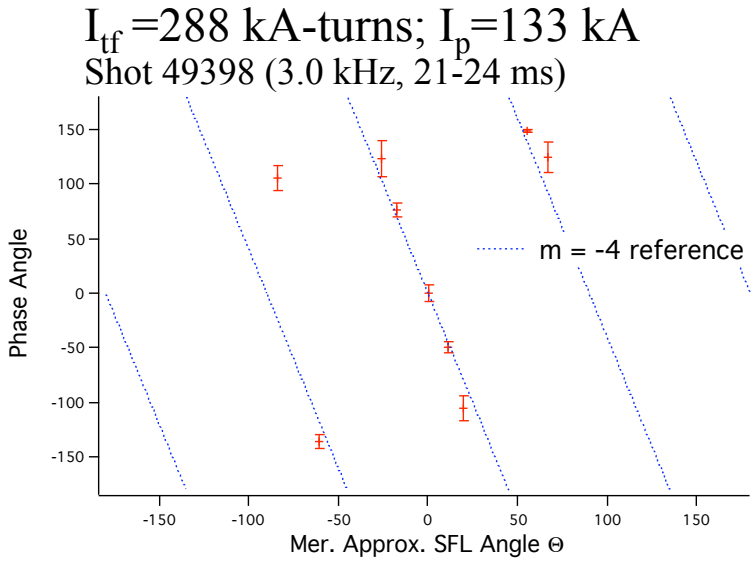


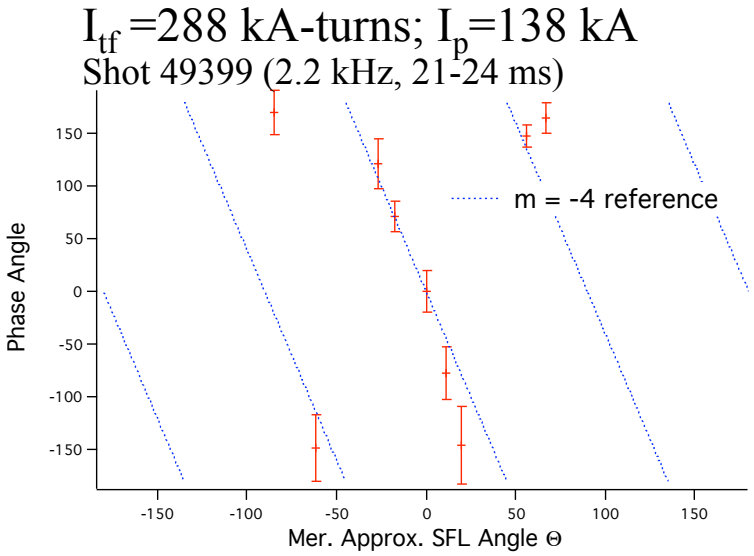
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Poloidal Mode Number Higher at High TF

- Poloidal mode number m~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 ~ 1







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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 ~ 4-5, suggesting that higher-m/n=1 modes can limit performance at A approaching A~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~90 kA

Future Work

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

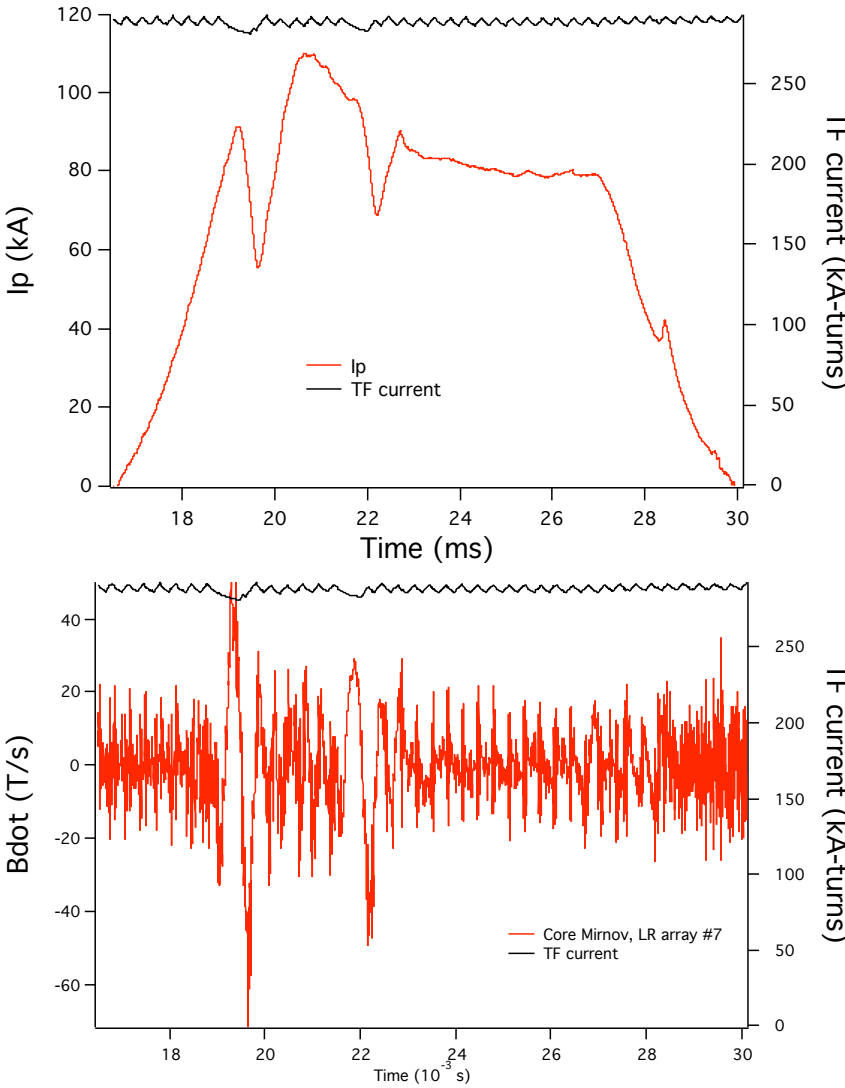
- New methods of temporarily stopping switch events is under development
  - This method involves forcing individual power supplies to stop switching, and naturally coast down in current for a short period of time (~several ms).

- 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



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