Characterization of Intermittent Fast Ion Transport in DIII-D

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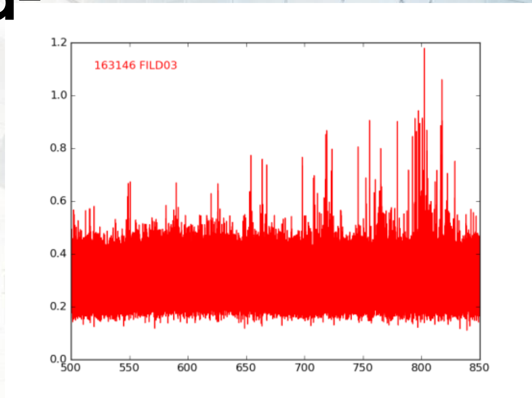

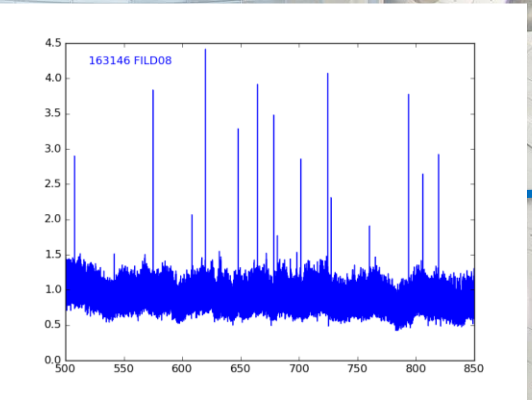

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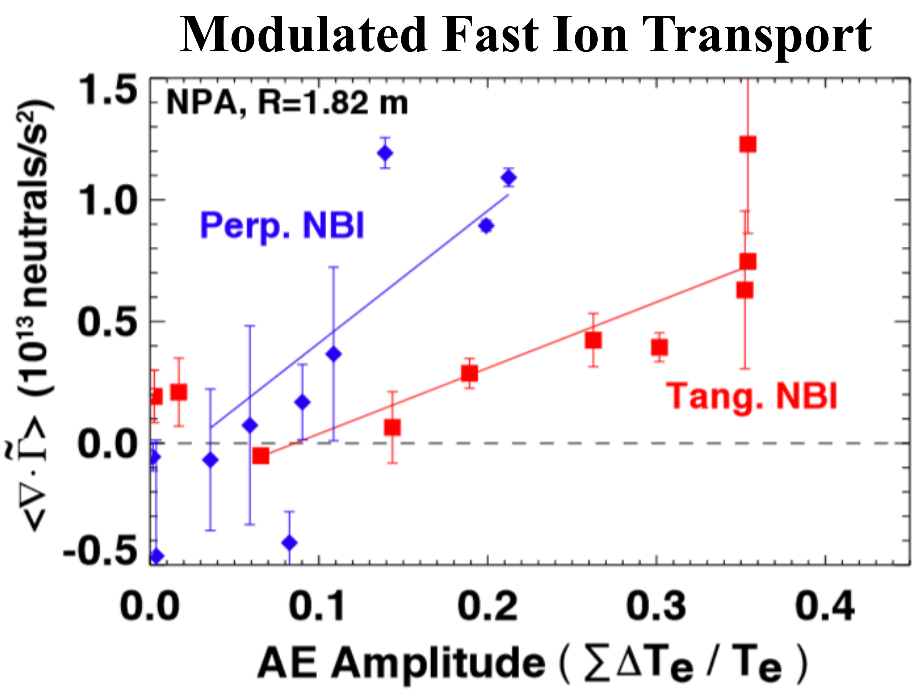
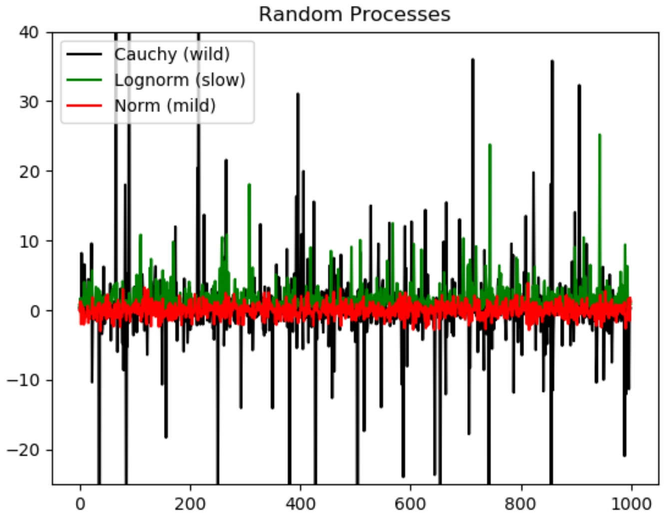
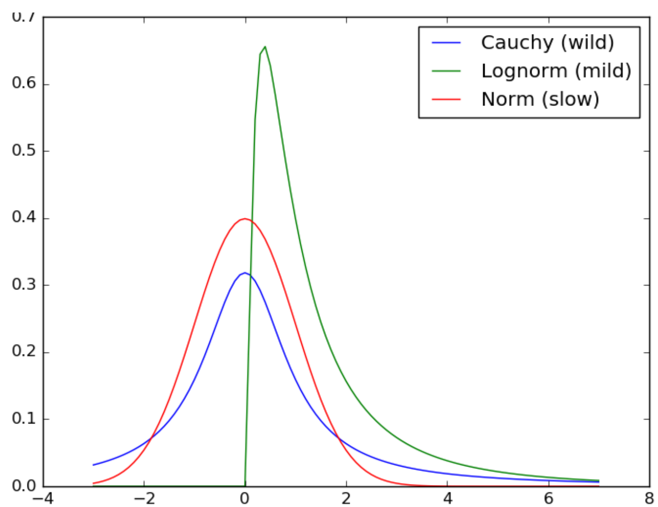
Alfvén Eigenmodes (AEs) can cause undesirable energetic particle (EP) transport

- In general, fast ion transport and confinement are important to the heating efficiency of a device
- Fast Ions that are lost to the wall increase the heat load applied to the plasma facing surface, potentially causing damage
- Validation of AE driven transport in simulations is important in preparation for future reactors



Plasma simulations specifically require validation of intermittent behavior



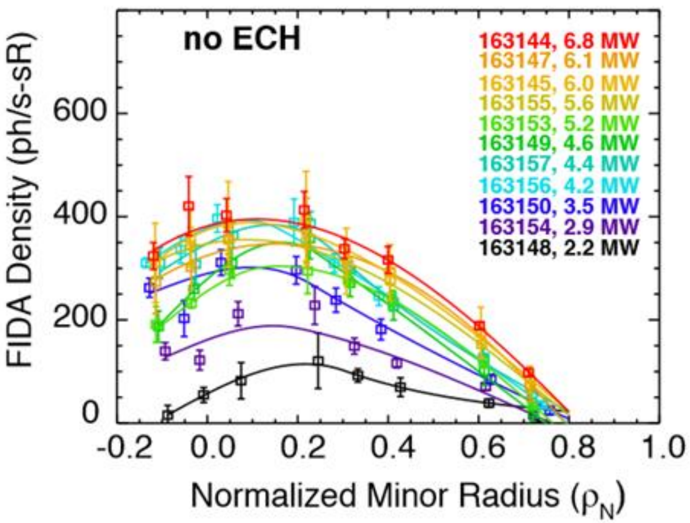


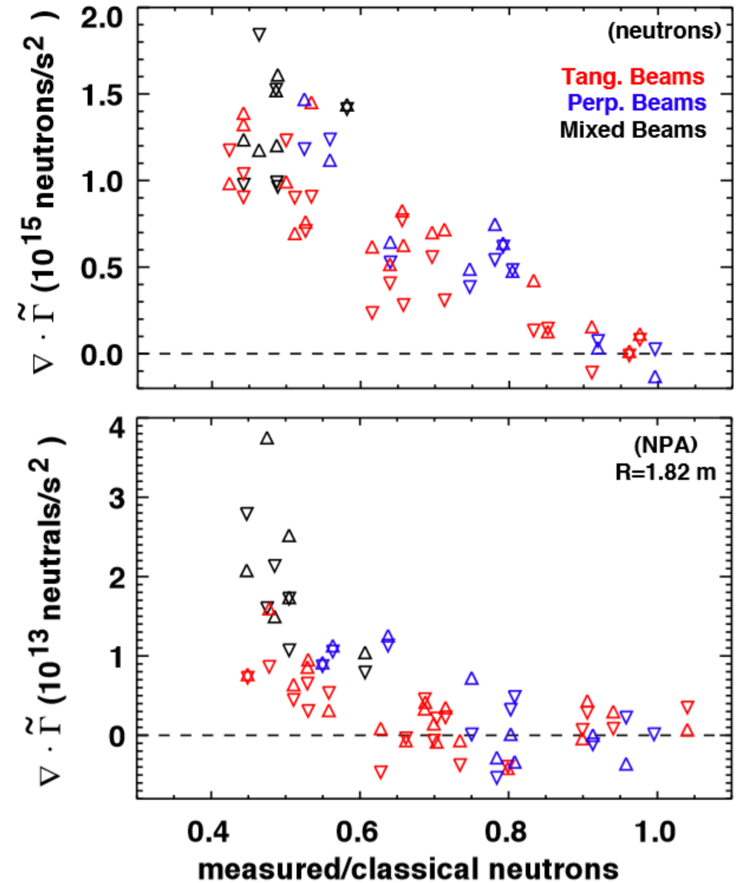
- **Intermittency describes the distribution of a data set**
  – In a time series, this can be thought of "wild" random behavior generated by non-Gaussian PDFs with fat tails [1]
- **One simple model of intermittent behavior is the sandpile, in which large avalanches redistribute the pile to avoid special gradients that exceed a threshold**
- **Concentrated avalanches can account for greater wall damage than time averaged losses**
  – Understanding and modelling these bursts can help protect future devices

[1] B. B. Mandelbrot, Fractals and Scaling in Finance

Fast Ion diagnostics on DIII-D show evidence of a critical gradient in the EP pressure gradient

- **FIDA, NPA, and neutron counting diagnostics all show critical gradient style onsets in transport of energetic particles [1]**
  - Each diagnostic has a separate threshold for transport as each is sensitive to a different area of phase space

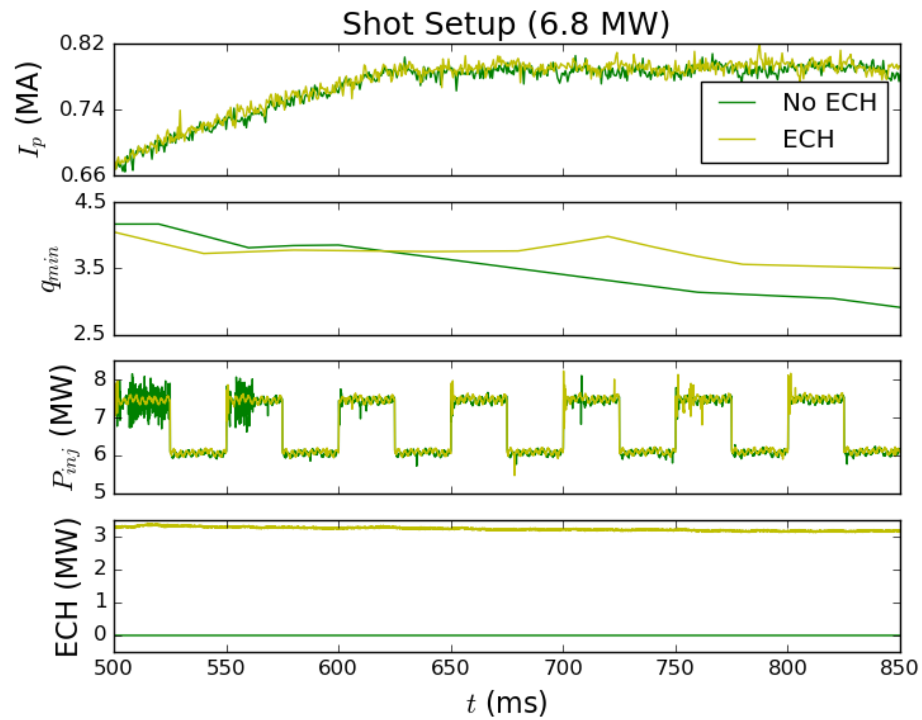




[1] C.S. Collins, W.W. Heidbrink, M.Podestà, et al., Nucl. Fusion 57, (2017)

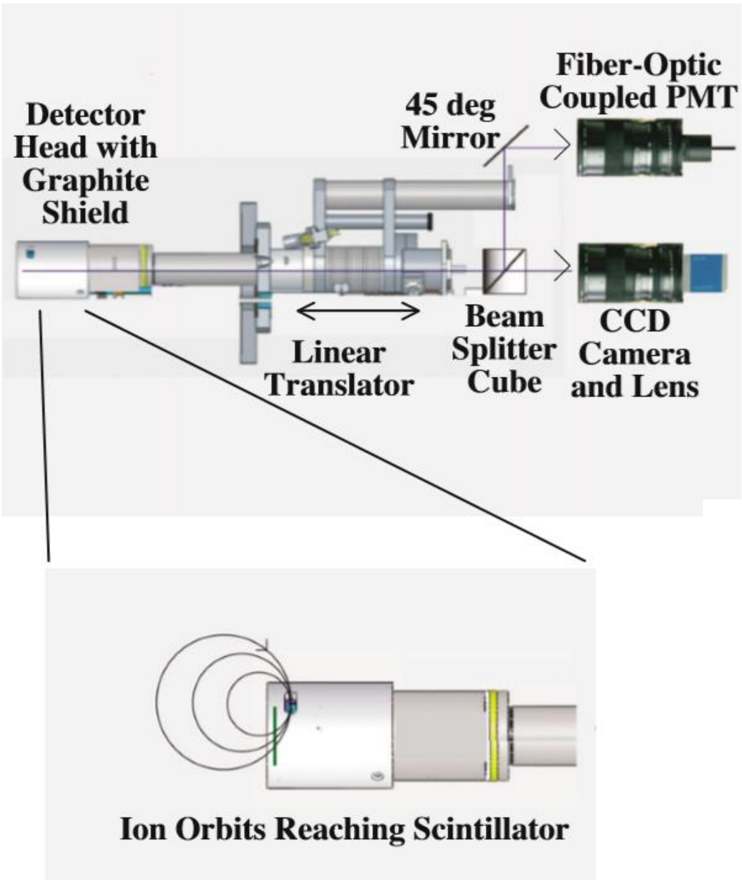
Shots in two experiments were designed to drive multiple AE modes

- **Low confinement (L-mode), inner wall limited, oval shaped plasmas with reversed shear safety factor q were observed at the end of the current ramp phase [1,2,3]**
  - The first experiment comprised of shots 159242-159260, and the second experiment included shots without ECH (163144-163157) and shots with ECH near $q_{\min}$ (163172-163181)
    - Shots 163151, 163152, and 163178 lost beams and are not included in this data set
- **Injected Neutral beam power was altered to change the drive of the AEs**
  - Magnetic field was unchanged between shots at 2T

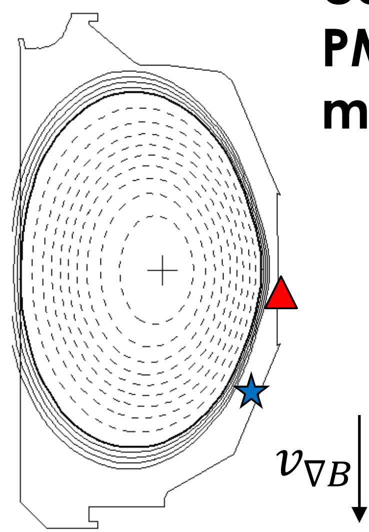


[1] C.S. Collins, W.W. Heidbrink, M.Podestà, et al., Nucl. Fusion 57, (2017)
[2] C.S. Collins, W.W. Heidbrink, M.E. Austin, et al., Phys. Rev. Lett. 116 (2016)
[3] W.W. Heidbrink, C.S. Collins, M. Podesta, et. Al., Phys Plasmas, 24, (2017)

Fast Ion Loss Detector (FILD) probes use magnetic field to separate losses according to phase space locations



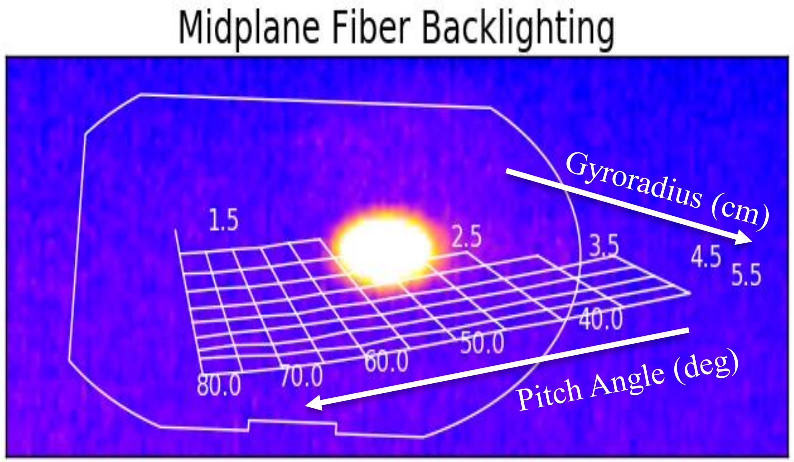
- FILD probes use an aperture as a pinhole detector to limit incoming ions to a small portion of a scintillator based on their gyroradius and pitch angle [1]
- Light from the scintillator is collected by a camera or PMTs via fiber optics for measurements

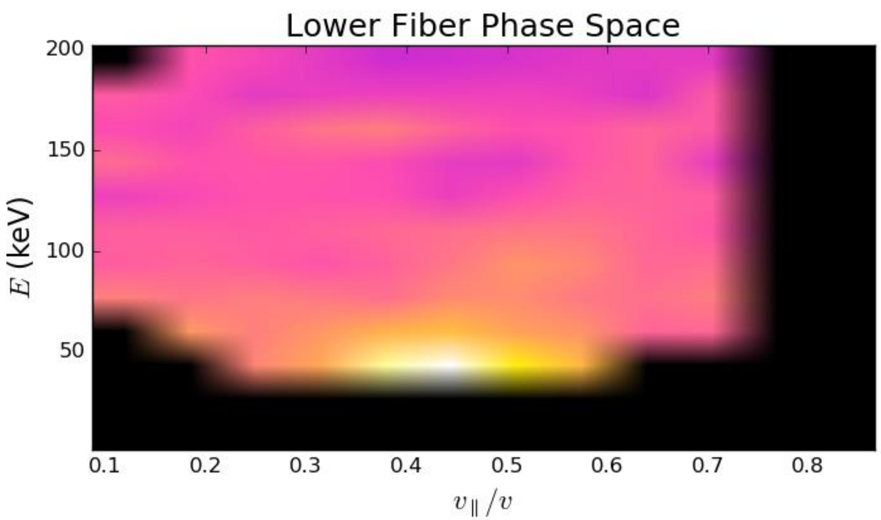


[1] R. K. Fisher, et al., Review of Scientific Instruments 81, 10D307 (2010)

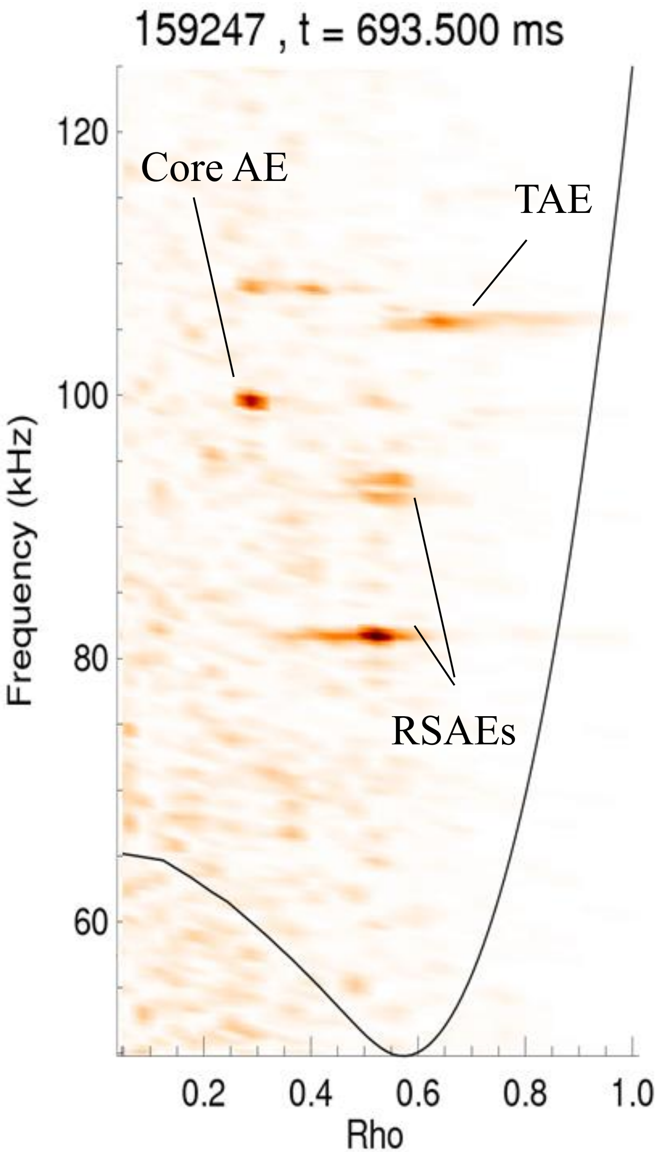
Each PMT views a different section of phase space

- **Both poloidal probe positions see avalanching in these experiments**
- **Backlighting a FILD scintillator with fibers can be used to determine phase space sensitivity**
  - Fibers from each detector sensitive to low energies (~40keV) and moderate pitch angles (~55°) saw intermittent losses
  - A midplane fiber centered on ~140keV at ~70° detected losses similar to the other midplane fiber during the first experiment

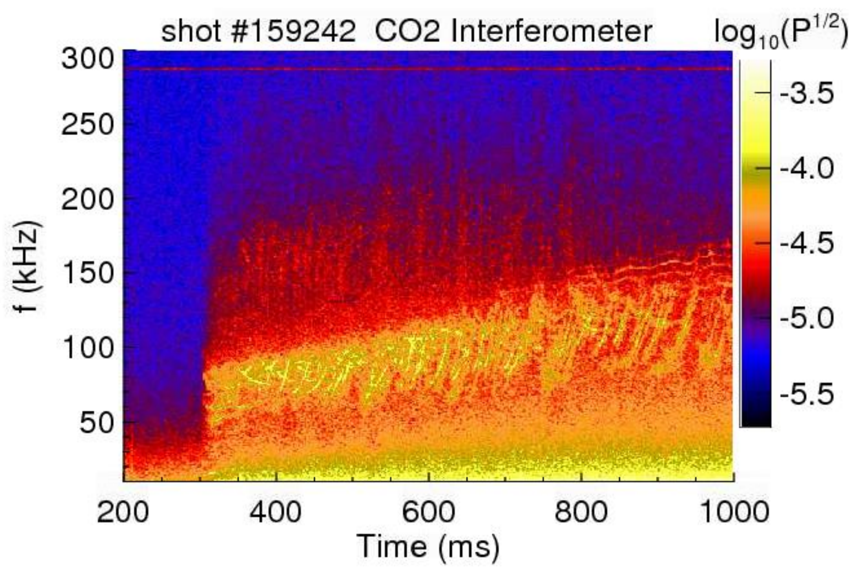




CO2 and ECE measurements identify AE activity in DIII-D

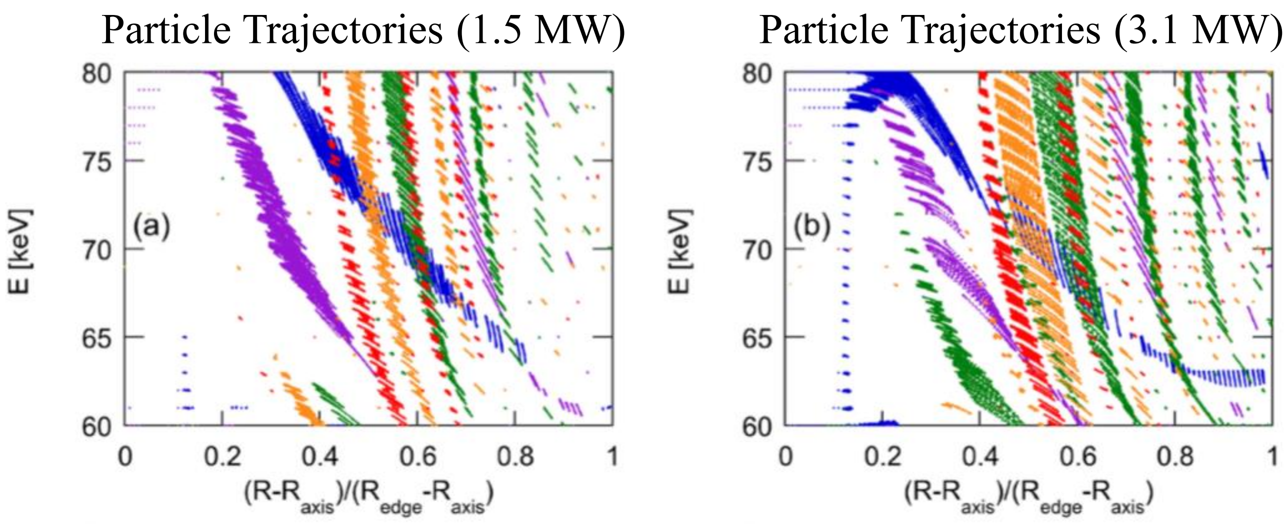


- **Types of AEs include reversed-shear Alfvén eigenmodes (RSAEs) and torroidicity-induced Alfvén eigenmodes (TAEs)**
  - RSAEs sweep in frequency, where TAEs maintain near constant frequencies



AE modes predicted to lead to avalanching when overlapping occurs

- **Intermittent transport due to the existence of multiple AEs has been predicted by models for some time [1]**
- **More recent MEGA simulations by Y. Todo [2] have found intermittent transport in the presence of TAEs and RSAEs**
  - Particle trajectories in the presence of a single TAE were followed to look at resonance overlapping

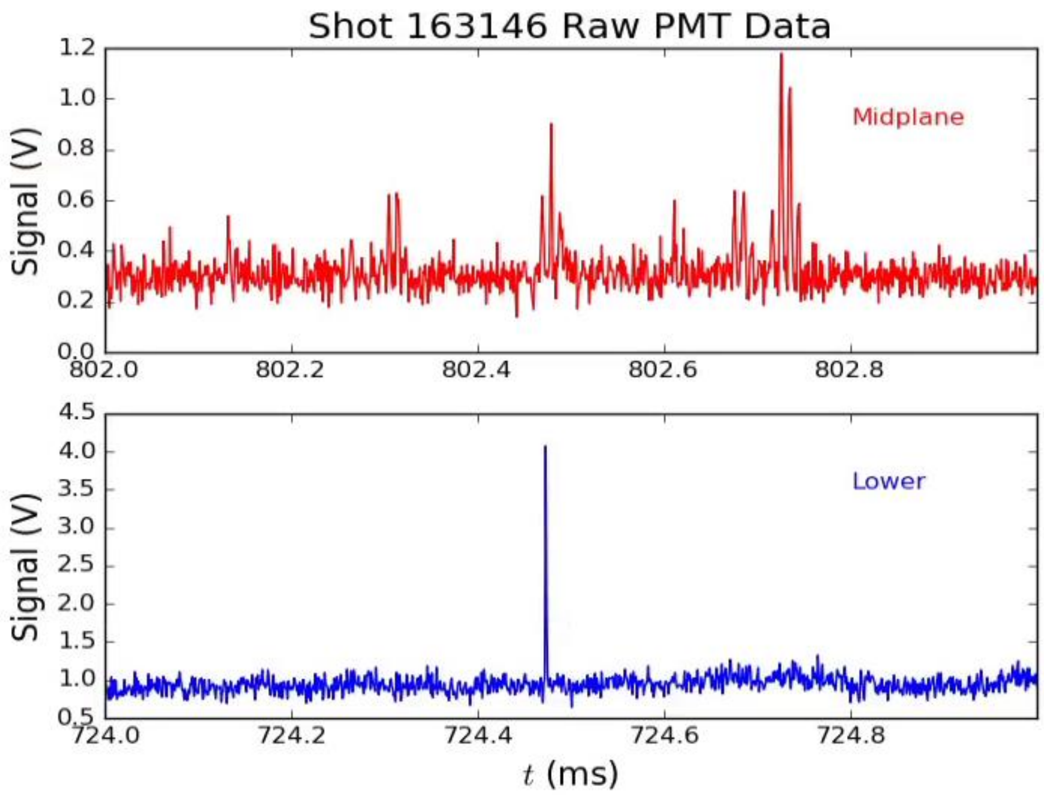


TAE eigenmodes are plotted as:
n=1 blue
n=2 purple
n=3 green
n=4 orange
n=5 red

[1] Berk H., Breizman B., Fitzpatrick J. and Wong H. 1995 Nucl. Fusion 35 1661
[2] Y. Todo et al 2016 Nucl. Fusion 56 112008

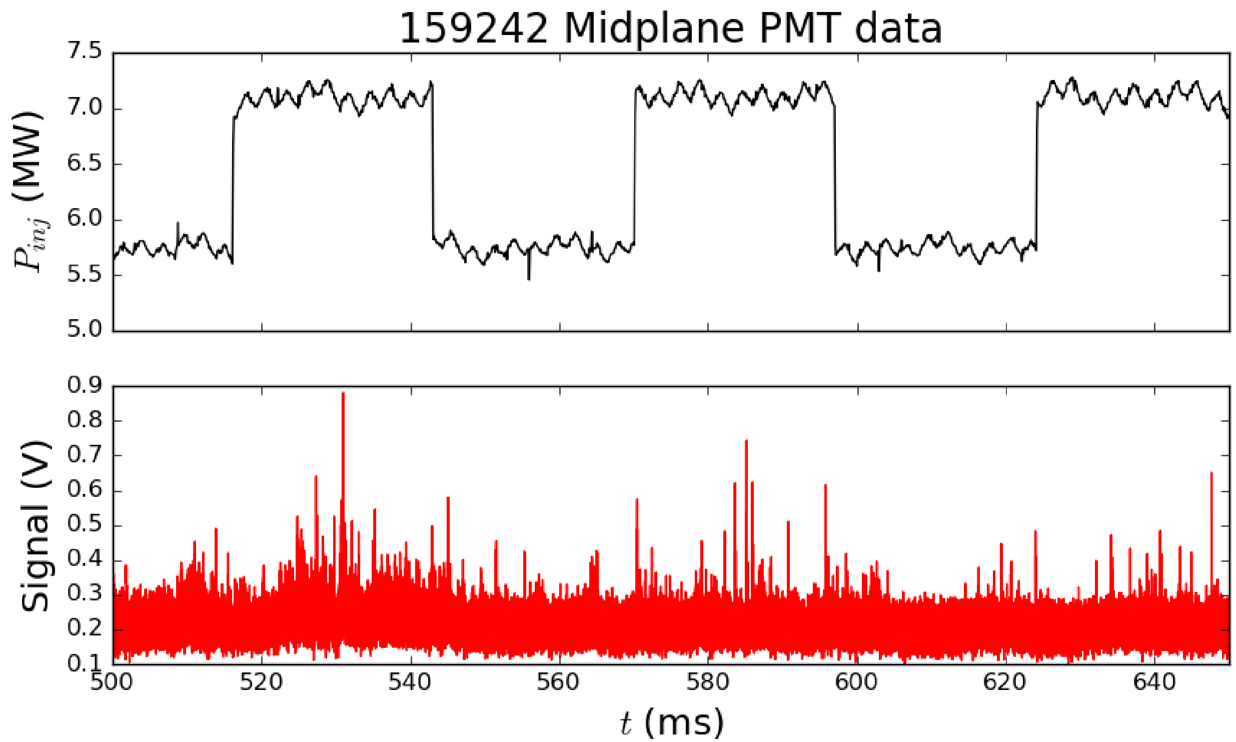
FILD probes measured two distinct types of avalanching

- **Losses at the midplane were characterized by groupings of 2-7 bursts in immediate succession**



- **The lower probe only showed solitary avalanches with long times in between them**
  - These avalanches are much larger in strength
- **Each probe observes losses at different times**
- **Transport observed in each probe is likely caused by two different mechanisms**

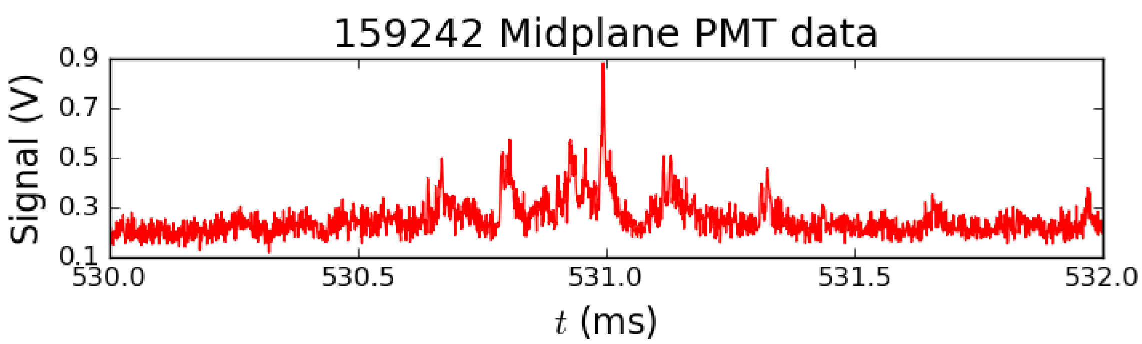
Midplane losses rise and fall with beam modulation

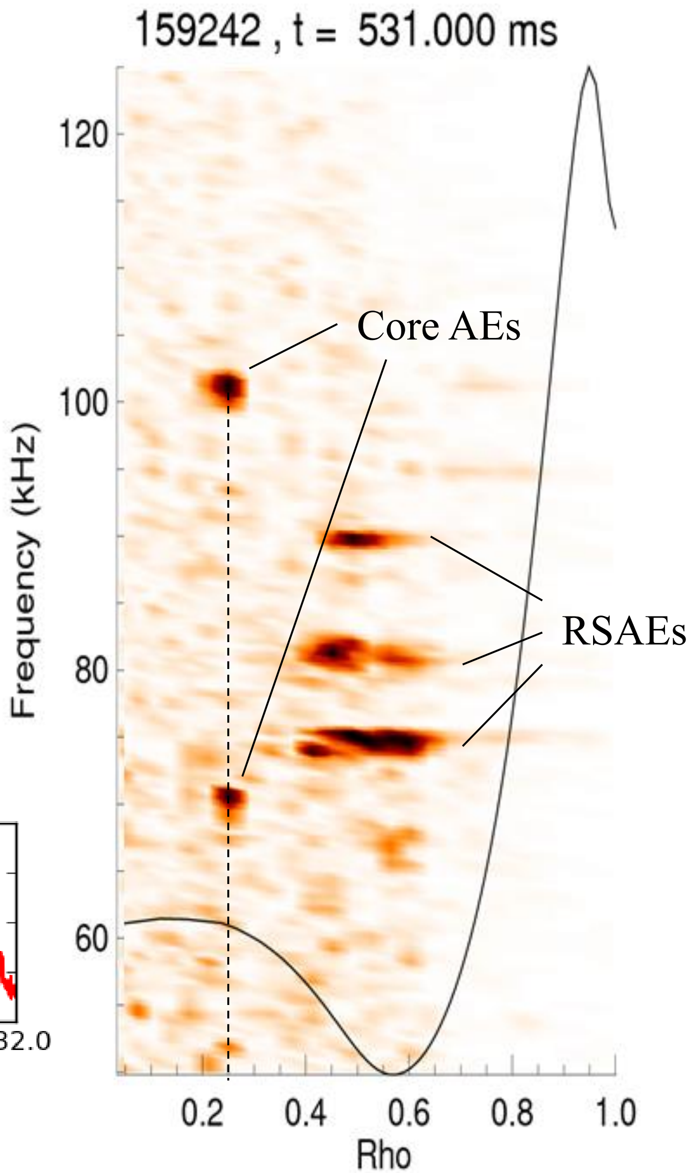


- **Avalanches at the midplane were observed to be largest and most frequent when modulated beams were active**
- **Intermittent activity is not modulated with the beams, but decays when the beams turn off**
  - Groups of avalanches can be seen before beams turn on, even after periods of quiet

AE modes follow pattern when midplane probe sees losses

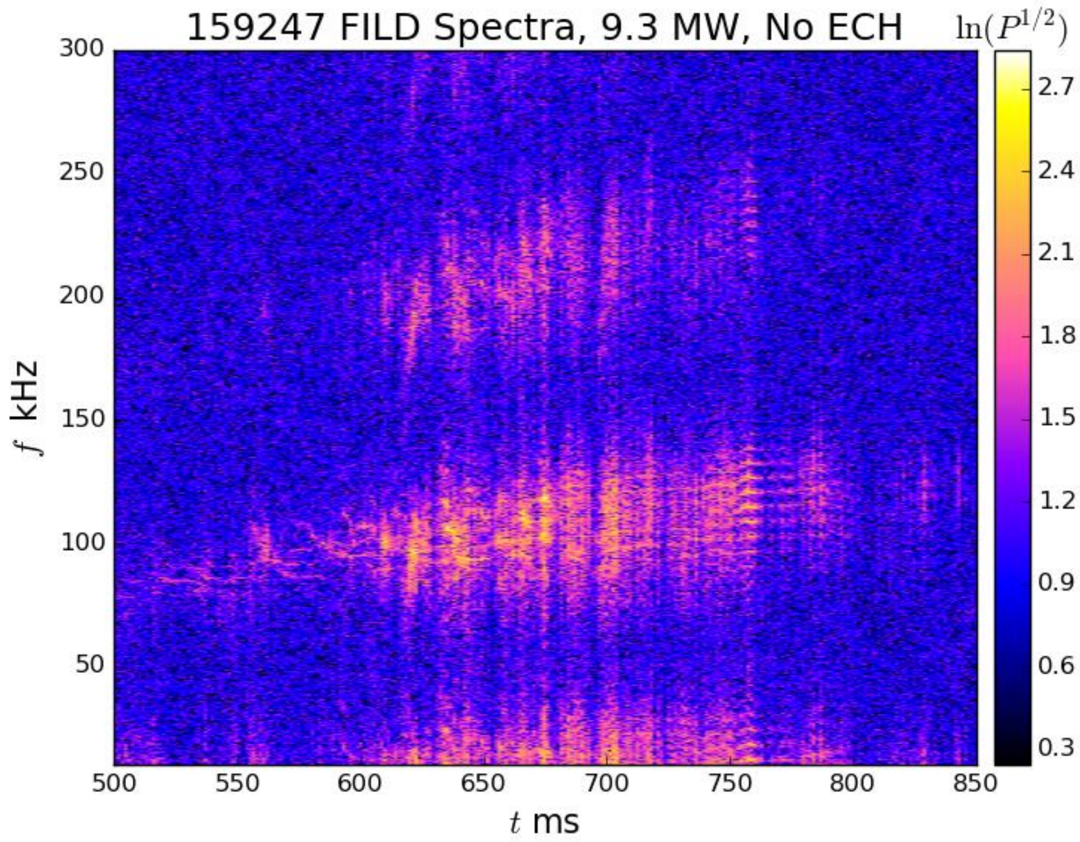
- **Midplane avalanching in the FILD probe usually occurs along with strong RSAEs near $q_{\min}$ and AEs in the core of the plasma**
  - While TAEs are sometimes present outside $q_{\min}$, this most commonly occurs alongside core modes, not in place of
  - Core modes around ~100 kHz are commonly stronger than lower frequency modes





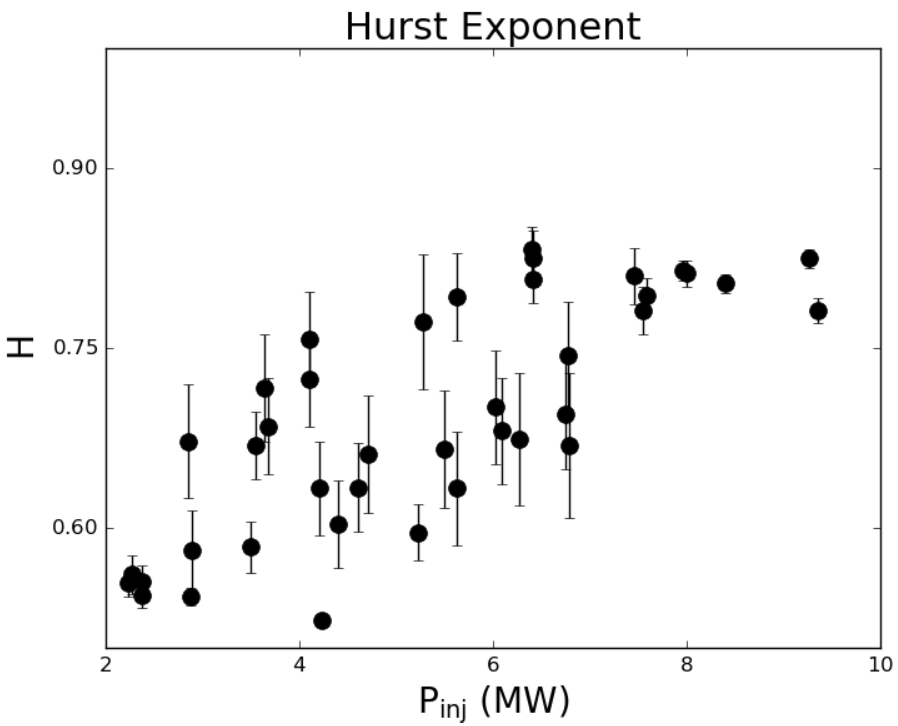
Fourier analysis shows midplane losses resemble TAE activity

- **Shots with high beam power have losses that follow similar frequency trends as the ~100 kHz AEs in the core**
  - Activity later in the shot (700ms – 800ms) shows several distinct frequencies in high power shots
- **This behavior seems to persist even with diminished RSAE activity**
  - The addition of ECH in the last set of shots did not appreciably effect midplane intermittency

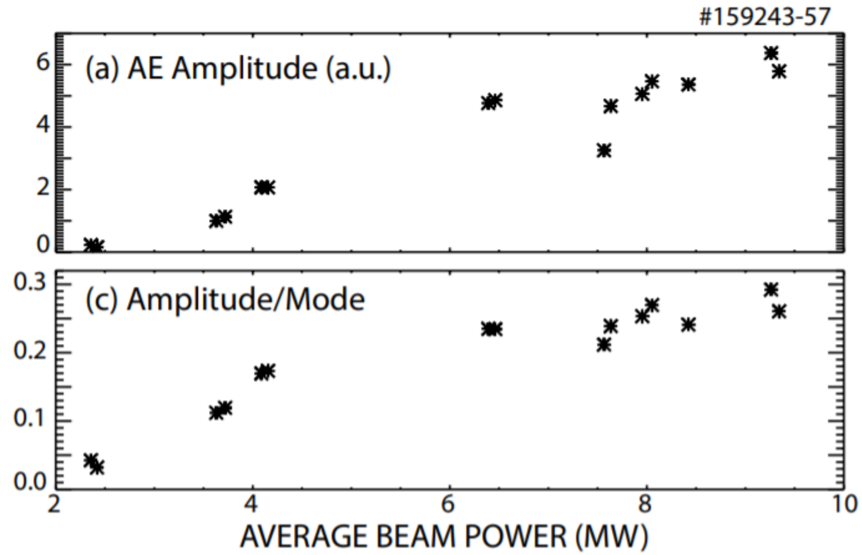


The Hurst parameter of midplane losses correlates with injected power

- **The Hurst parameter [1] describes the correlation between time steps in a series**
  - Larger Hurst exponents ($0.5 < H \leq 1$) correspond to higher correlations



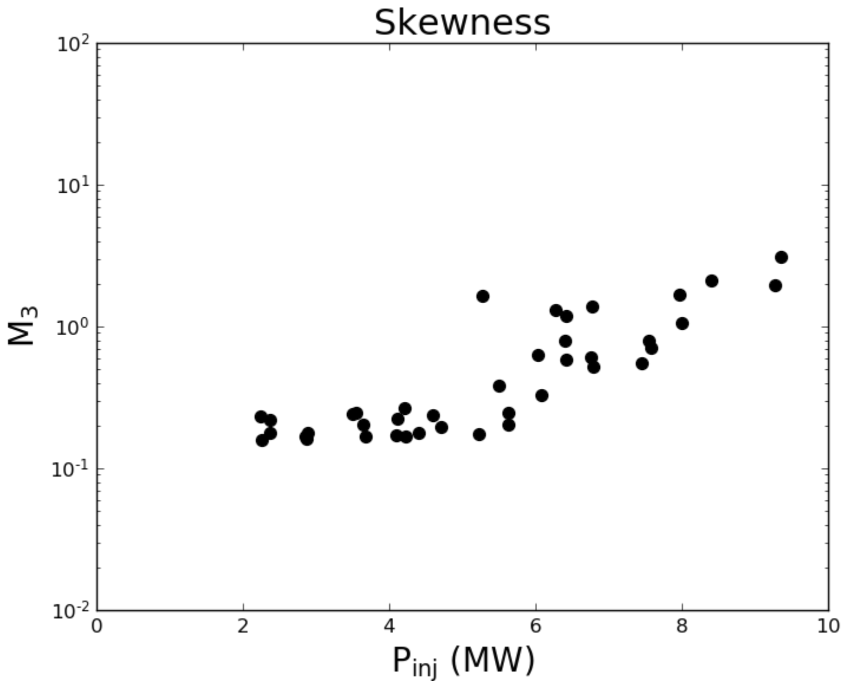
- **Loses from shots with more than approximately 6MW of NBI power (large AE amplitude [2]) show large increases in H**

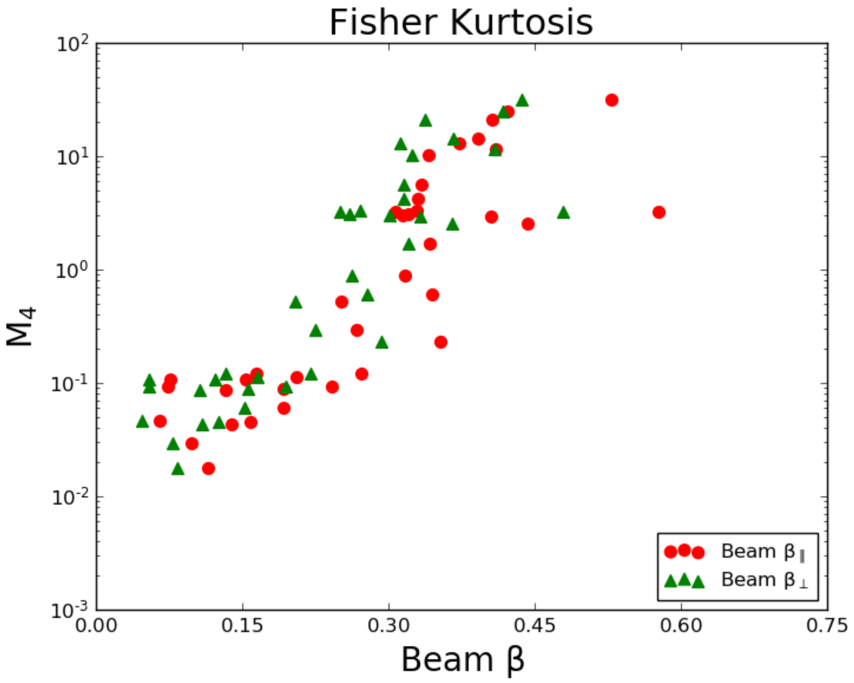


[1] Mandelbrot, B. B., and Wallis, J. R. (1968), Water Resour. Res., 4(5)
[2] W.W. Heidbrink, C.S. Collins, M. Podesta, et. Al., Phys Plasmas, 24, (2017)

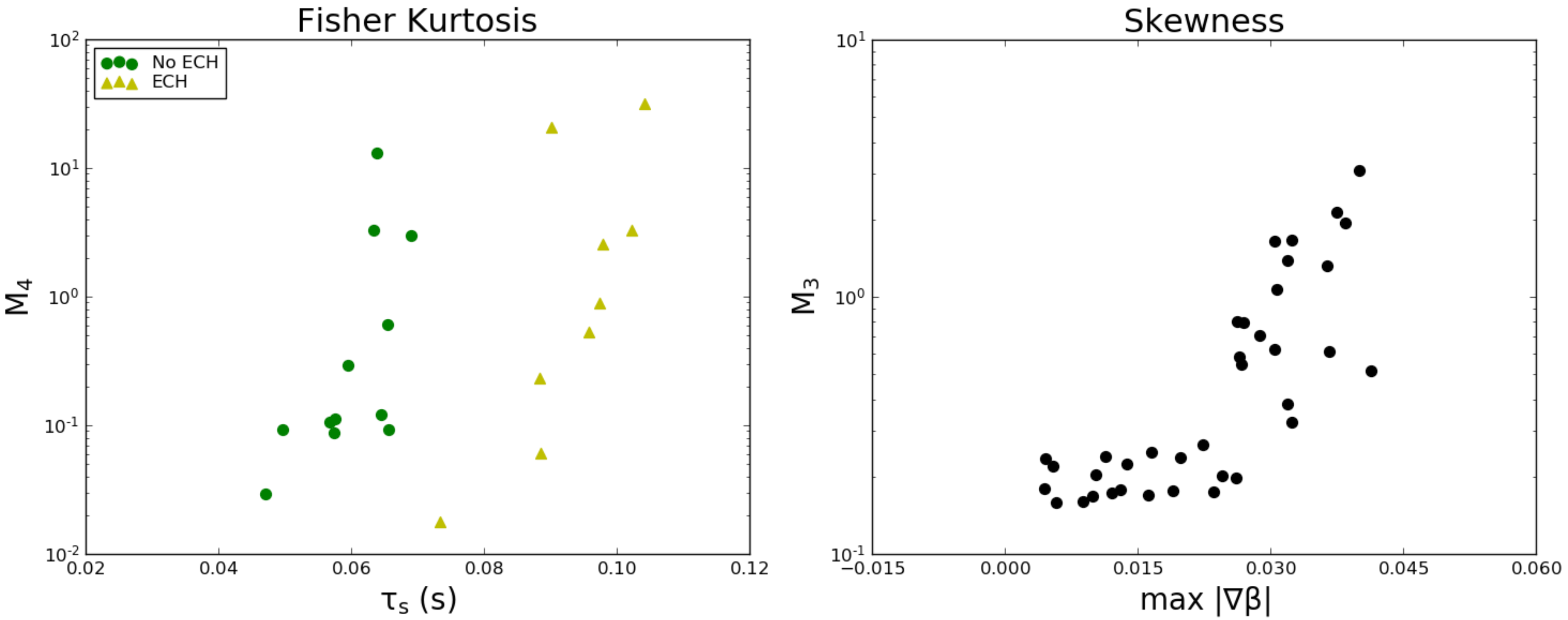
High order moments capture strength of avalanching behavior

- **Midplane probe measurements clearly show avalanching thresholds that likely correspond to critical gradient**
  - The threshold in injected power agrees with results for the Hurst exponent





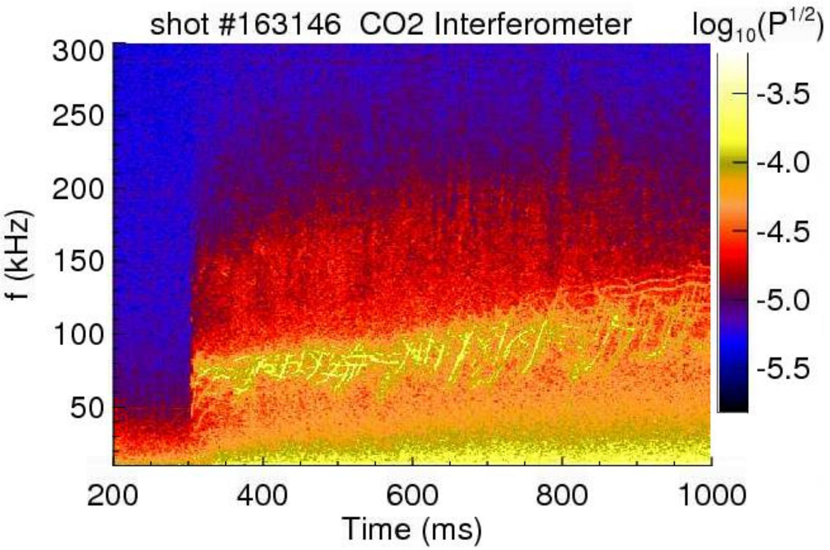
Avalanching behavior relates to calculated properties at q_{min}

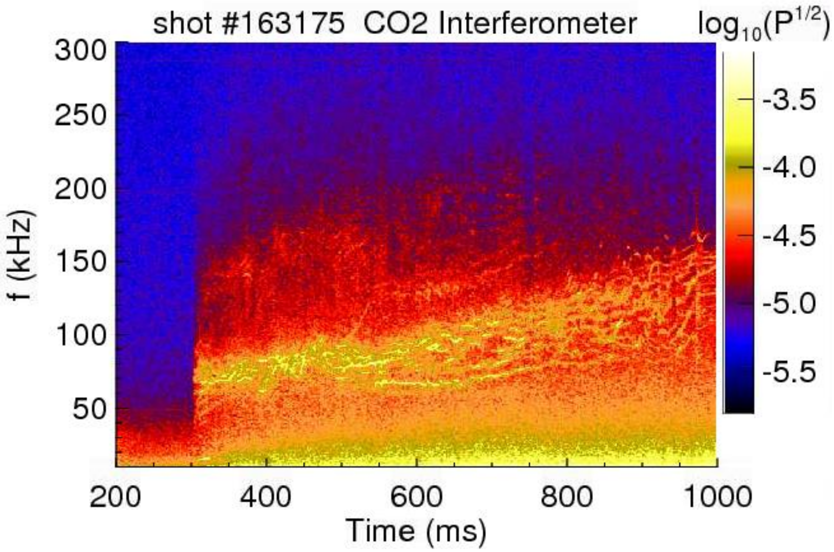


- **Classical TRANSP runs were made to make more detailed comparisons of shots**
- **Increases in electron density and slowing down time near q_{min} both correlate with increased avalanching**
- **Larger gradients in beam β also increase intermittency**

The addition of ECH drastically reduces RSAE activity

- **Even for shots with similar levels of injected beam power, the AE spectrum with ECH is dominated by TAEs**
  - This change in AE activity is due to the local electron temperature gradient increasing the RSAE frequency up to the TAE frequency [1]
  - Core TAEs remain present, but TAEs outside of $q_{\min}$ seem to become more common

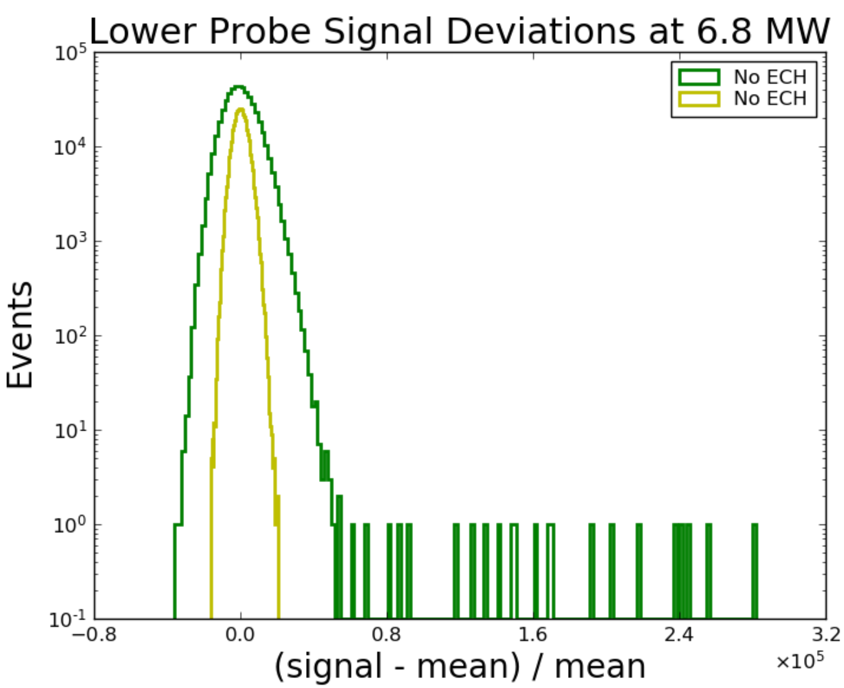


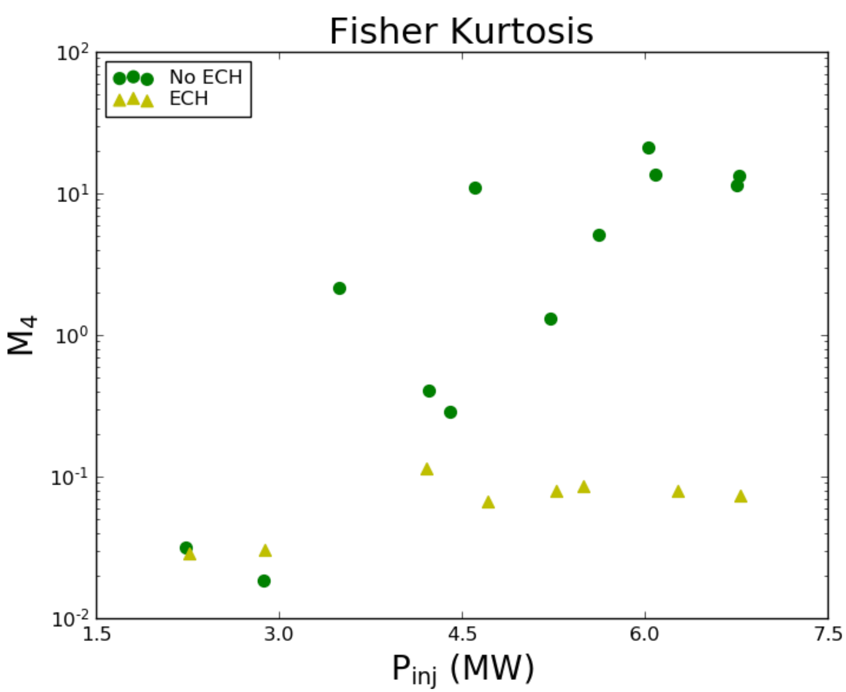


[1] M.A. Van Zeeland, W.W. Heidbrink, S.E. Sharapov, et al., Nucl. Fusion 56, (2016)

ECH suppresses avalanching in lower probe measurements

- **While the midplane probe still sees intermittent avalanching with ECH, bursts in the lower probe disappear almost entirely**
- **Orbit tracking finds the trapped/passing boundary shifts with ECH, potentially outside the sensitive region for the fiber**
  - It is also possible that the decrease in RSAE activity prevents losses from occurring at all





Summary and Future Work

- **Fast Ion Loss Detectors on DIII-D show intermittent behavior and avalanching that supports a critical gradient model**
  - Analysis suggests a threshold in beam power around 4-5 MW
- **Midplane probe losses seem to be strongly connected to AE activity in the core**
  - Resilience to RSAE amplitude reduction and spectra suggest this is an essential part of this transport
- **Avalanching in the lower probe disappeared with the addition of ECH power near $q_{\min}$**
  - Research into how ECH affects these changes may lead to methods of controlling some AE induced losses
- **More information may be obtained by acquiring fluctuation data for other EP diagnostics**
  - DIII-D working on upgrades to FIDA and INPA for these measurements

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