Characterization of Magnetic Turbulence on the Pegasus-III Experiment

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Pegasus-III Experiment

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Pegasus-III: Non-Solenoidal Startup Testbed

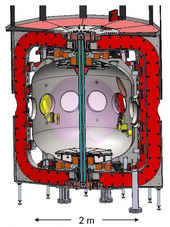
- Non-solenoidal startup is critical for scalability of spherical tokamaks

- Pegasus-III will test performance of non-solenoidal startup techniques
  - Local helicity injection, coaxial helicity injection, RF
  - All new coil sets allow for B_T up to 0.6 T

- Local Helicity Injection (LHI): promising non-solenoidal startup technique
  - Conservation of helicity (linkage of toroidal and poloidal flux) lets beams relax into axisymmetric tokamak-like plasma
    - T_e, I_p from LHI comparable to Ohmic startup [1]

-Magnetic turbulence associated with relaxation processes in toroidal devices, and prominent in LHI discharges

Pegasus-III



3-Axis Bdot Probe Measures $\tilde{B}$ During LHI

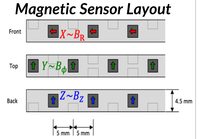
- Insertable magnetic probe designed to study turbulence on Pegasus [2]
  - Variable insertion depth: outside plasma edge to plasma core
  - Coil shape and graphite armor attenuates freq. response above ~1 MHz
  - 10 radially spaced triplets
  - Minimally perturbative to plasma
- Data better understood with spectral analysis
  - Power spectral density (PSD): frequency-domain analysis of power per wave number

$$P_{xy}(f) = \lim_{T\to\infty}\frac{2}{T}E[X_k^*(f,T)\cdot Y_k(f,T)]$$

- Coherence: relative power between two signals

$$\gamma_{xy}^2(f) = \frac{|Gxy(f)|^2}{G_{xx}(f)G_{yy}(f)}$$

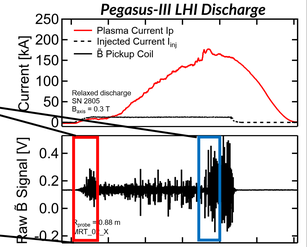
Magnetic Sensor Layout



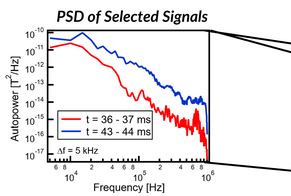
Example Sensor



Probe Data for Sample Pegasus-III LHI Discharge



PSD of Selected Signals

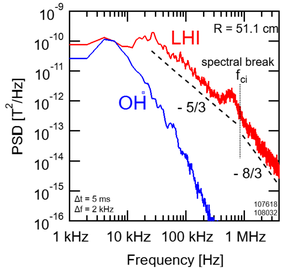


Magnetic Turbulence Observed During LHI

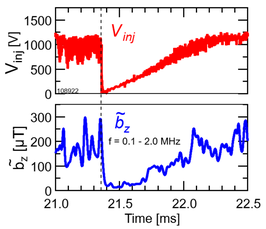
- Edge localized magnetic turbulence ubiquitously seen during LHI [3]
  - Significantly higher power in broadband magnetic turbulence for LHI plasmas compared to Ohmic
  - Power law behavior visible in PSD spectrum during LHI
    - Spectral index below f_{ci} consistent with Alfvénic fluctuations [10]

-Magnetic activity largely sourced from super-Alfvénic injected electrons [3]
  - Turbulence PSD ($\sim\tilde{B}^2$) drops to ohmic level when injectors turn off
  - Fluctuation amplitude scales with injector voltage, which is proportional to electron beam velocity

Magnetic Fluctuation PSD in Edge Is Higher for LHI vs. Ohmic Startup

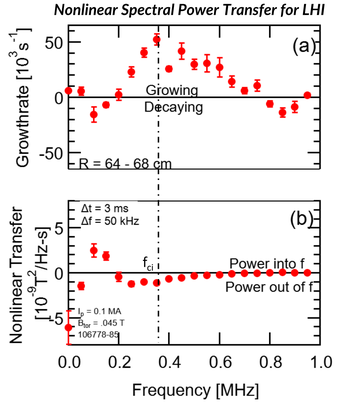


Magnetic Fluctuation Amplitude Scales With Injector Voltage



- Previous work suggests that source of broadband magnetic activity during LHI is instability in 100's of kHz range [3]

Estimates of Linear Growth Rate and Nonlinear Spectral Power Transfer for LHI



- Anomalous ion heating in edge region correlates with magnetic activity [4]

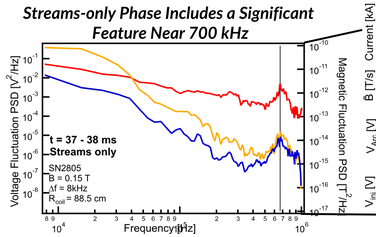
- Active beam instability is kinetic and causes EM fluctuations
  - Kinetic Alfvén wave instabilities seem promising [4][7]
  - Behavior of KAWs and other candidates determined by beam density, background plasma density, beam velocity, magnetic field [6] [7]

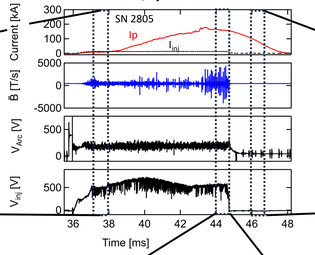
Initial Results Explore Spectral Features

- Magnetic fluctuation measurements were taken with 3-axis Bdot probe during early LHI discharges at 0.3 T
  - Supplemental diagnostics measured arc and injector voltage fluctuations

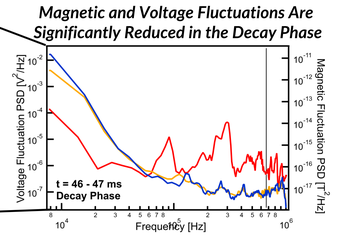
Magnetic Activity Varies at Different Phases of Ip Evolution

Streams-only Phase Includes a Significant Feature Near 700 kHz

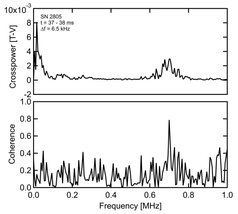




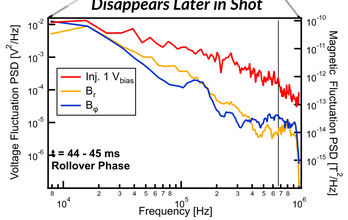
Magnetic and Voltage Fluctuations Are Significantly Reduced in the Decay Phase



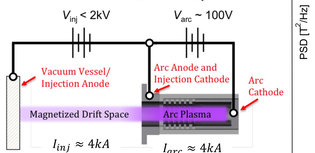
Crosspower, Coherence Between $\tilde{B}$ & V_{inj} Peak at 700 kHz in the Streams-only Phase



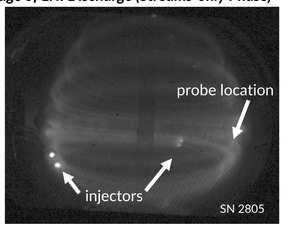
~700 kHz Feature in B, V Spectra Disappears Later in Shot



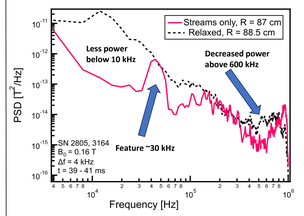
Each LHI Injector Has Distinct V_{arc} and V_{inj}



Fast Phantom Camera Image of Probe in Edge of LHI Discharge (Streams-only Phase)



Relaxed and Streams-only Discharges Exhibit Different Spectral Features



- 700 kHz visible in streams-only phase (pre-relaxation) correlated with voltage fluctuations in injectors
  - Feature visible in injector voltage, arc voltage at early time
  - Feature disappears from both voltage and magnetic fluctuations
  - Arcs-only discharge analysis shows that feature disappears partway through discharge even when streams aren't present

- High frequency content comparable between relaxed and streams-only spectra
- Low frequency content much lower amplitude in streams-only
- 30 kHz feature associated with n=1 line-tied kink mode

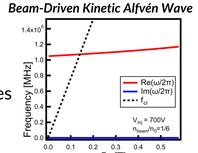
Future Work To Further Explore Instabilities

- Understanding scaling of instability key to projecting LHI behavior at higher field (ex: ST pilot plant)

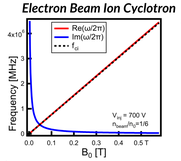
Example: Instability Scaling with Magnetic Field

- Scans in B_0, V_{inj}, n_b/n_0 can be used to identify characteristic scalings for candidate instabilities

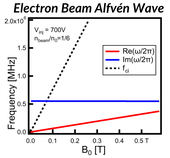
Beam-Driven Kinetic Alfvén Wave



Electron Beam Ion Cyclotron



Electron Beam Alfvén Wave



- New probe: study toroidal variation in $\tilde{B}$ to 5 MHz (~max f_{ci})
  - Toroidally spaced probes can measure $\tilde{B}$ evolution along stream, assess $k_{||}$ structure to test for KAWs
  - Situate magnetic fluctuation sensor near injector to study arc instability

Summary

- Magnetic turbulence work on Pegasus-III ongoing in new LHI campaign

- $\tilde{B}$ turbulence in LHI sourced from kinetic beam instability producing EM fluctuations and ion heating

- New work shows evolution of $\tilde{B}$ spectrum with relaxation, including ~700 kHz feature from V_{inj} fluctuations

- Near-term investigation: instability ID and toroidal variation $\tilde{B}$ spectra for more complete picture of turbulence during LHI on Pegasus-III

References: [1] Bongard *et al.*, Nucl. Fusion **59**, 076003 (2019); [2] Richner *et al*, Rev. Sci. Instr. **89**, 10J103 (2018); [3] Richner *et al.*, Phys. Rev. Let. **128** , 105001 (2022); [4] M. G. Burke *et al.*, Nucl. Fusion **57**, 076010 (2017);[5] Sovinec + O'Bryan; [6] Hasegawa, *Plasma Instabilities and Nonlinear Effects*. Berlin, Heidelberg: Springer-Verlag, 1975. [7] Chen *et al.*, Astr. Journal **793**, 13 (2014); [8] G.M. Bodner *et al.*, Phys. Plasmas **28**, 102504 (2021); [9] Chaston et al., Phys. Rev. Lett. **100**, 175003 (2008).

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