Spatial structure of low-frequency plasma fluctuations in a laboratory dipole experiment

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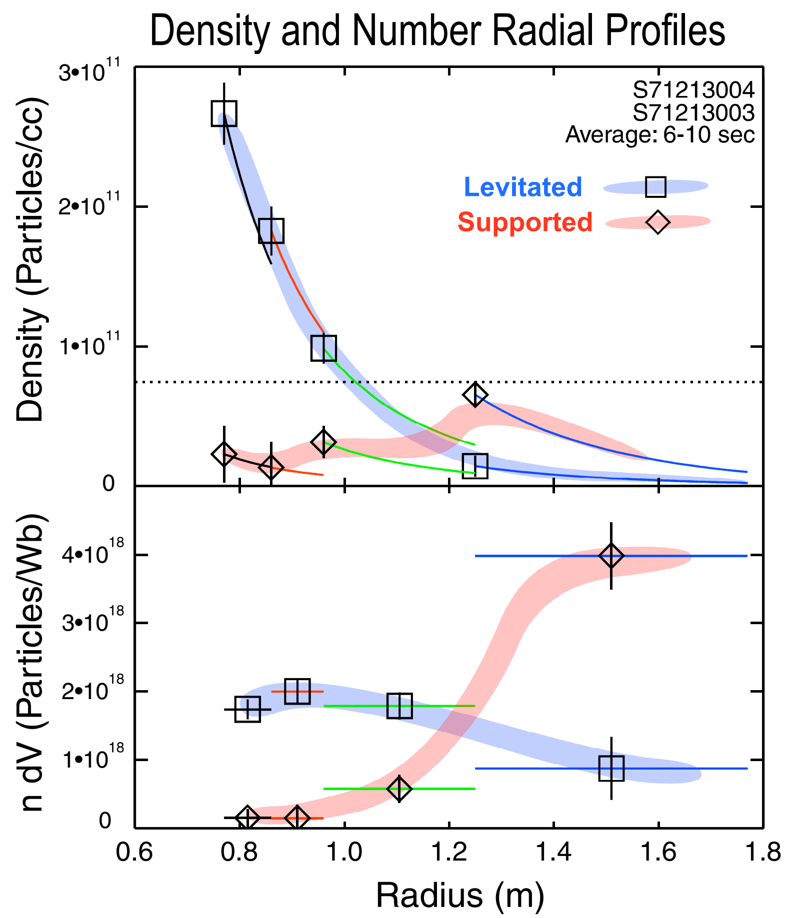
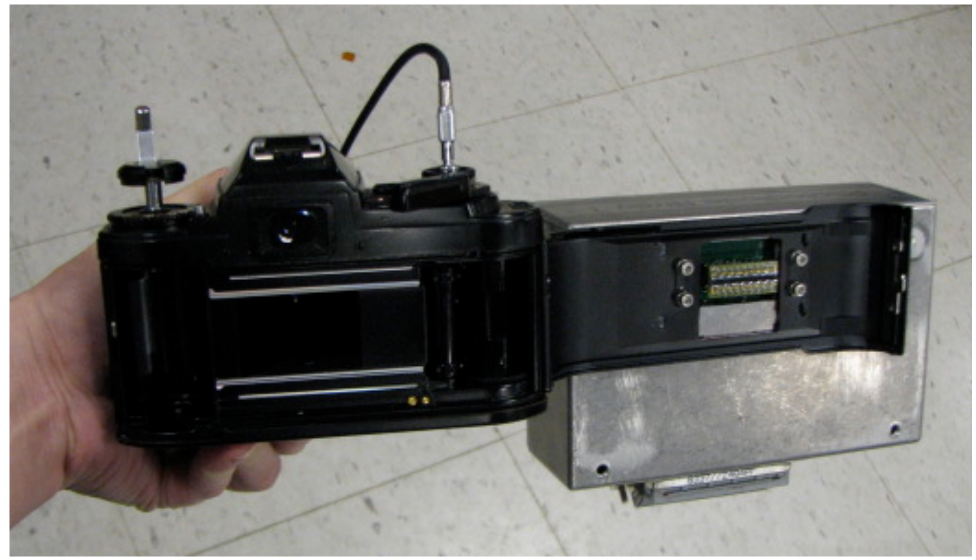
Introduction

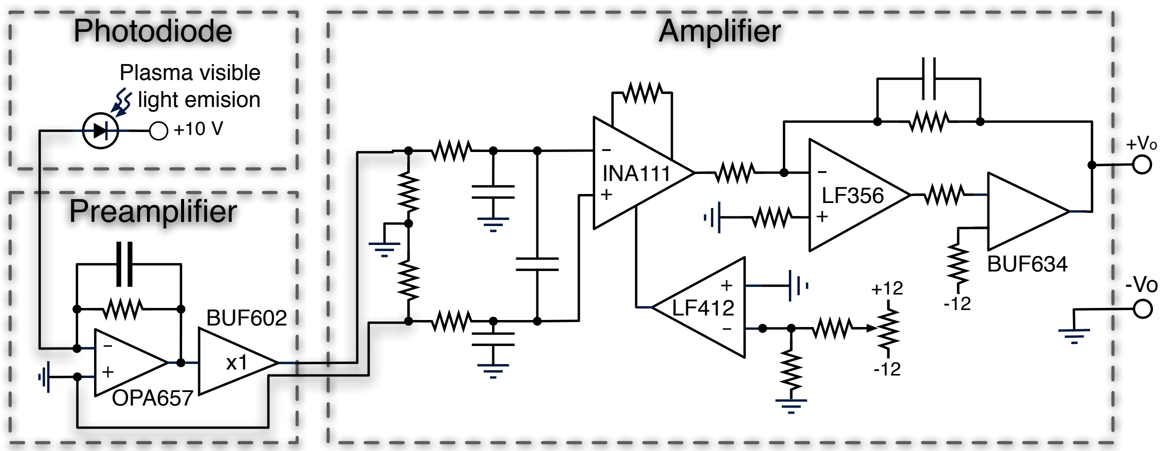
- Observation: Strongly peaked plasma density profiles during levitation.
- Hypothesis: Profiles are sustained by turbulent mixing.
- Goal: Evaluate the spatial structure of the low frequency density fluctuations



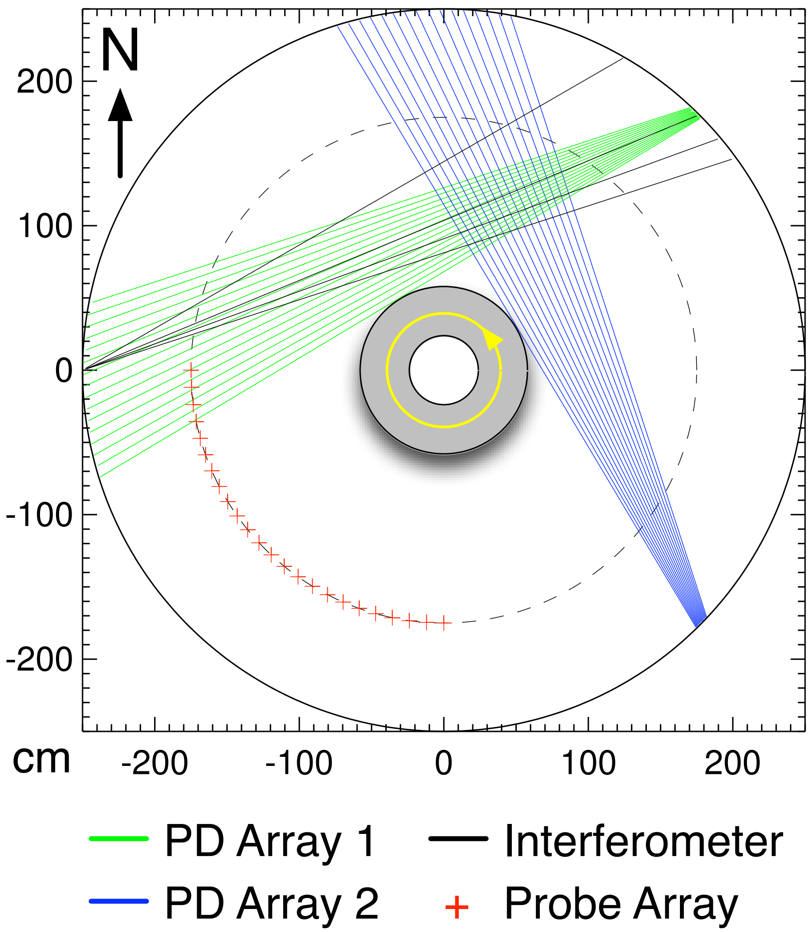
Photodiode Array Diagnostic

- 16-element photodiode array
- Built into an SLR camera body
- Detects visible light
- No filters are used
- Records the entire shot
- Good frequency response up to 5 kHz
- Signal is digitized at 50 kHz



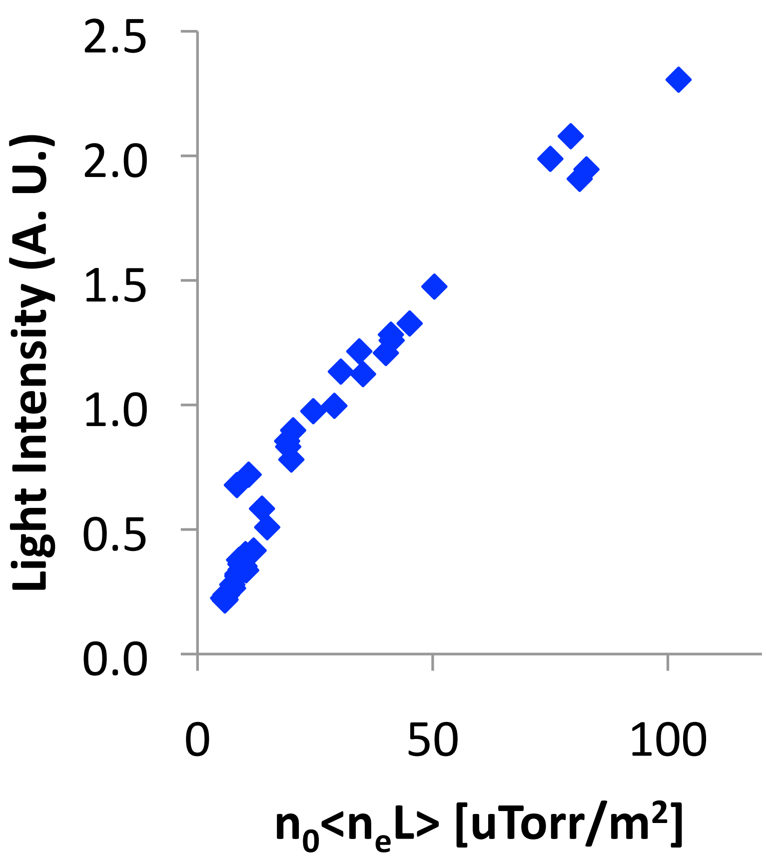


Diagnostic Views



- Top down view of the LDX vacuum chamber
- Diagnostics that measure plasma fluctuations include
  - Two 16-channel photodiode arrays viewing from different toroidal locations
  - 4-chord microwave interferometer
  - 24-element floating probe array
- Sony camera views from the same port as PD array 1

Visible Light Emission is Proportional to Plasma Density



- 15 kW of multi-frequency electron cyclotron heating
- Visible light and line-integrated plasma density are measured on chords with minimum radii of 77 cm
- Multivariable linear regression of the data gives

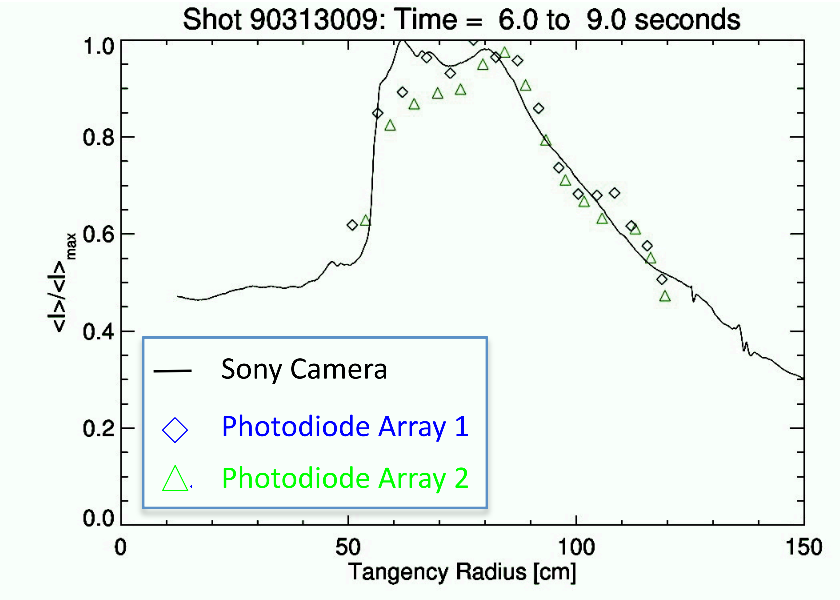
$$< I >= 1.9 \cdot n_0^{+0.2} < n_e L >^{+1.1} \phi^{-0.6}$$

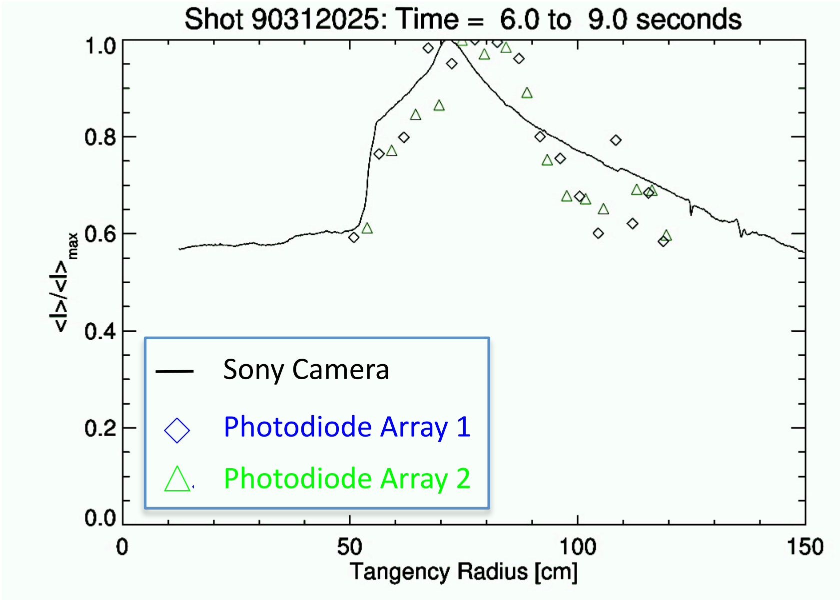
where ϕ is the diamagnetism

Light Intensity

Neither the n=0, nor the n=1 mode are observed in this shot. The data from the sony camera and the photodiode arrays agree well.

Both the n=0 and n=1 modes are observed during this shot. The sony camera data and the photodiode arrays do not agree as well.





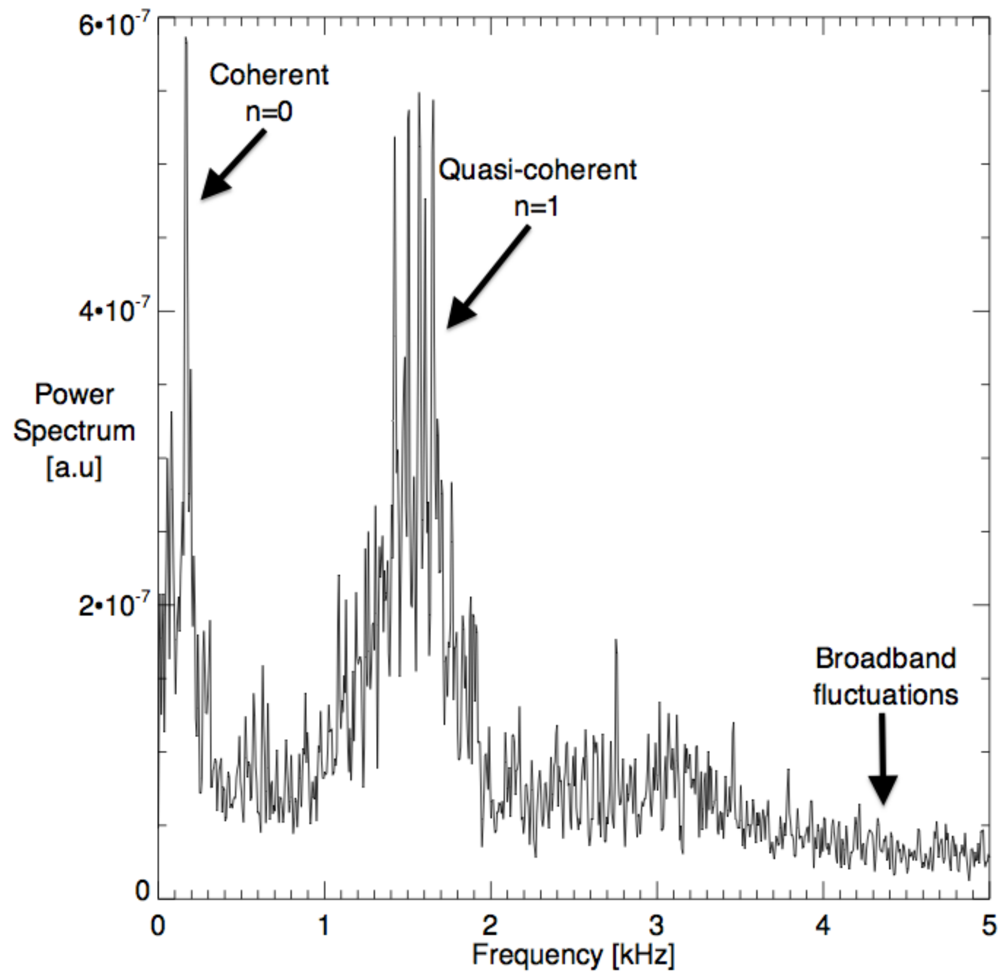
Scaled, time-averaged, chord-integrated visible light intensity from a Sony video camera, and each of the two photodiode arrays

Three Characteristic Fluctuations

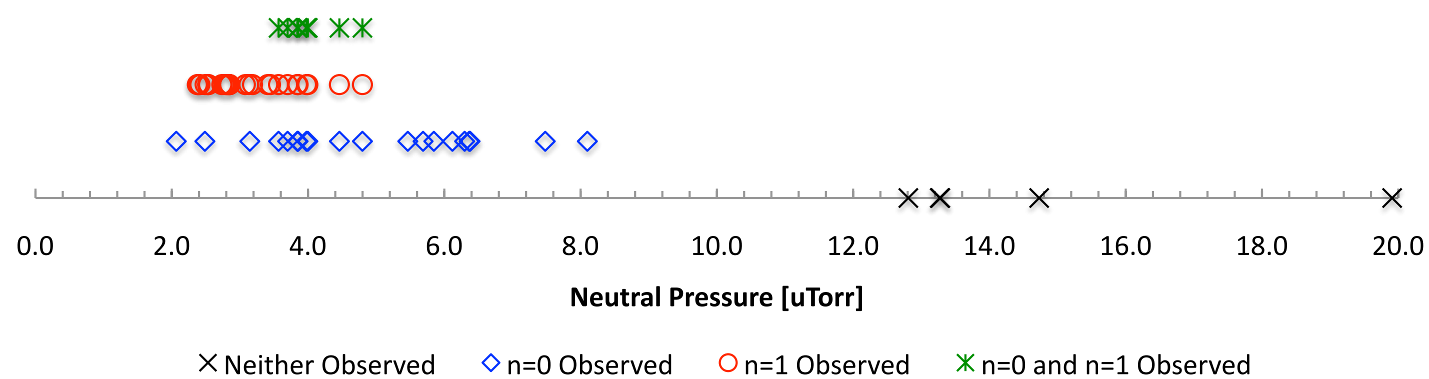
Time-averaged power spectrum of photodiode array 2 (100 cm) between t=7 and 8 seconds, during 15 kW heating power on shot 90312025 shows thee characteristic features:

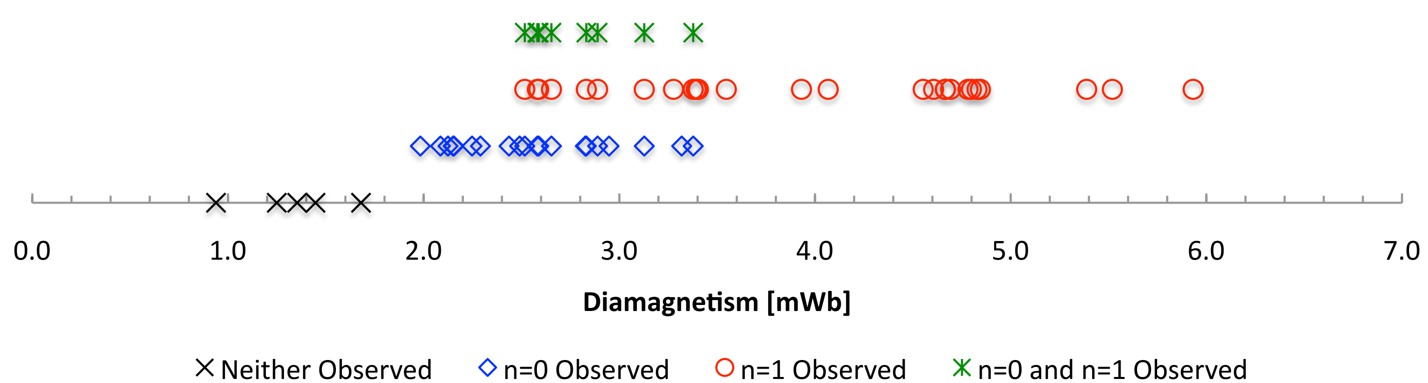
- n=0, coherent (ω/Δω ~ 100)
- n=1, quasi-coherent (ω/Δω ~ 5)
- broadband turbulent fluctuations

Although this shot has examples of each of the three type, they are not all present on all shots.



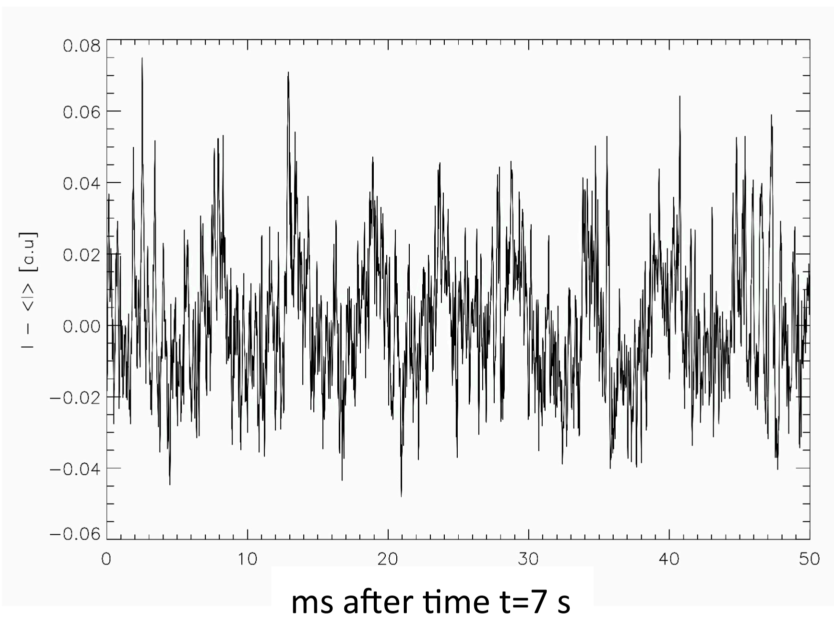
Diamagnetism is the Best Predictor of which Fluctuations will be Observed



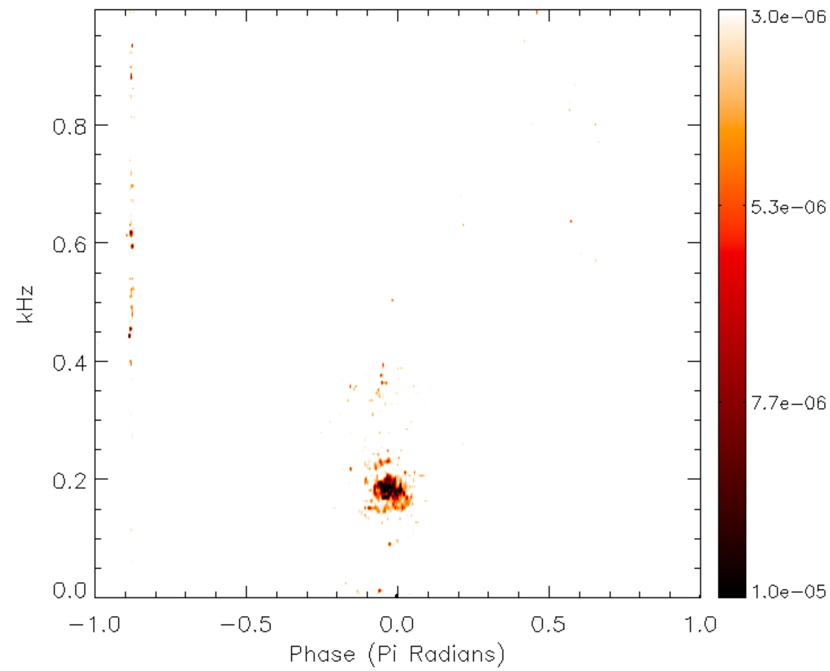


n=0 Mode

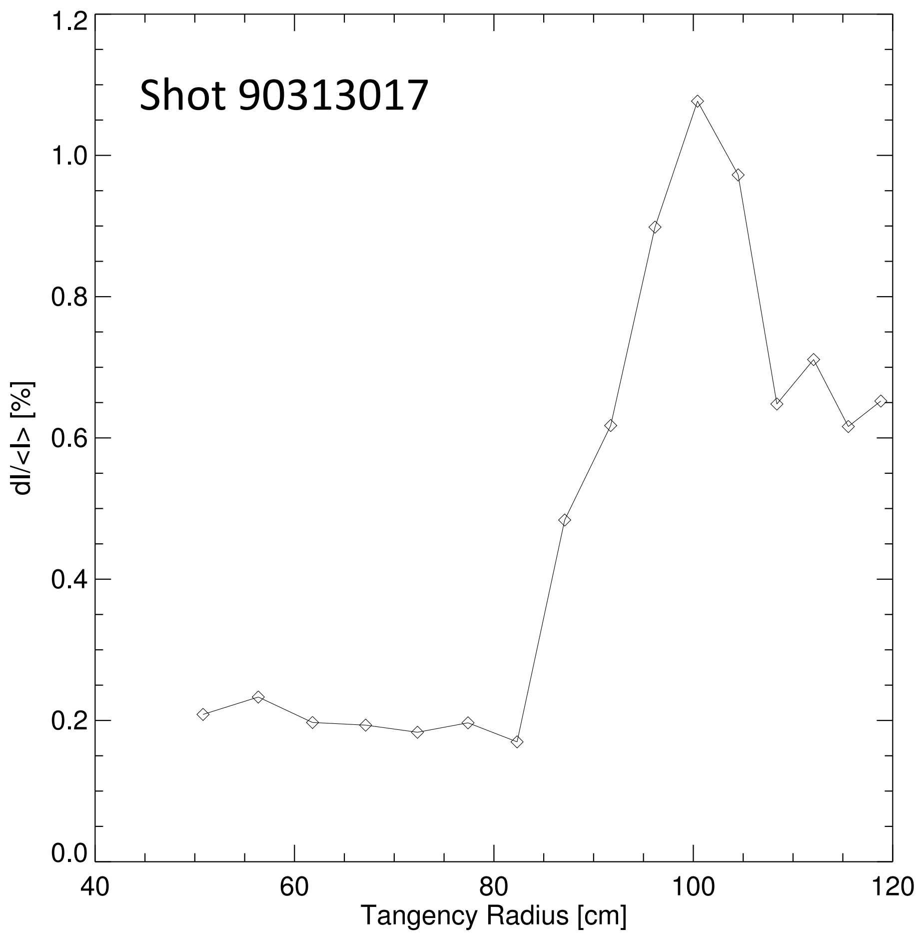
Time trace of the line-integrated visible light intensity measured by photodiode array 1 (100 cm) shows a strong fluctuation at 185 Hz. The mean of the signal has been subtracted.



Frequency spectrum of the time-averaged cross phase between photodiode array 1 (100 cm) and photodiode array 2 (102 cm). The 185 Hz oscillation is in phase indicating n=0.

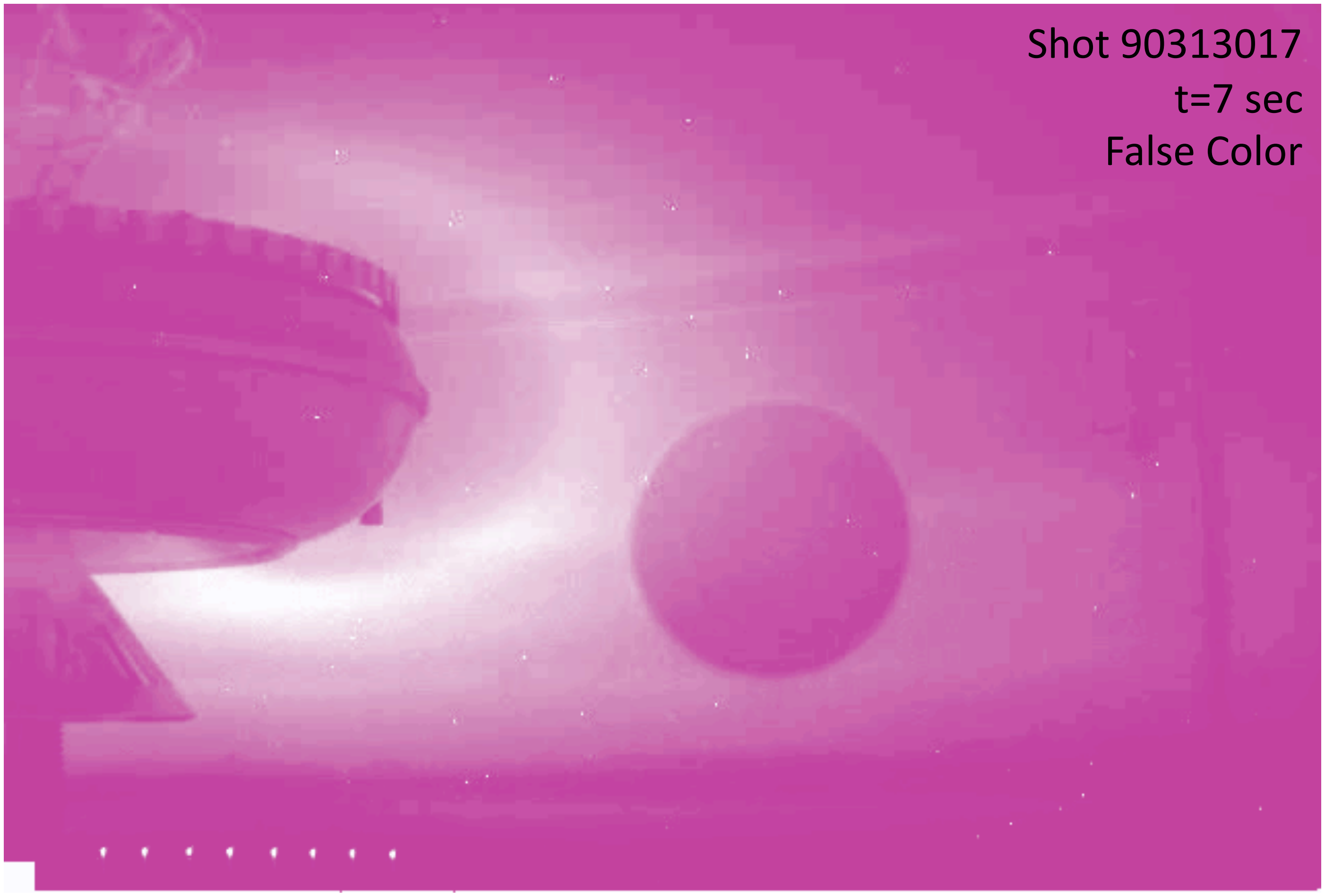


Radial Variation in Fluctuation Amplitude for n=0 Mode

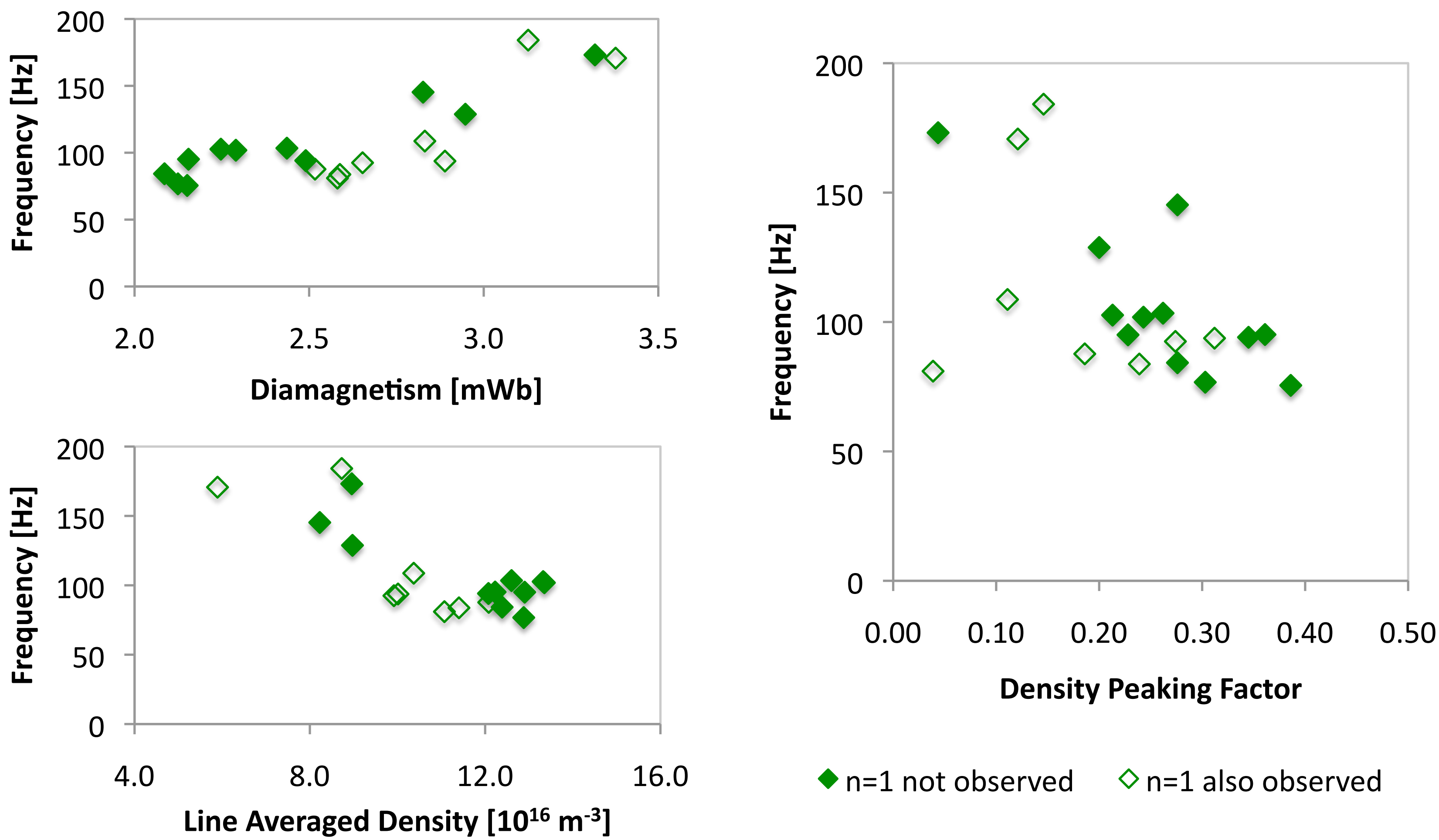


- Line integrated data
- Time averaged for the period 6s < t < 9s.
- Deuterium plasma with 15 kW multi-frequency ECRH
- Peaked near 100 cm channel,
- but visible light diagnostic may not be sensitive to density fluctuations in the plasma core.

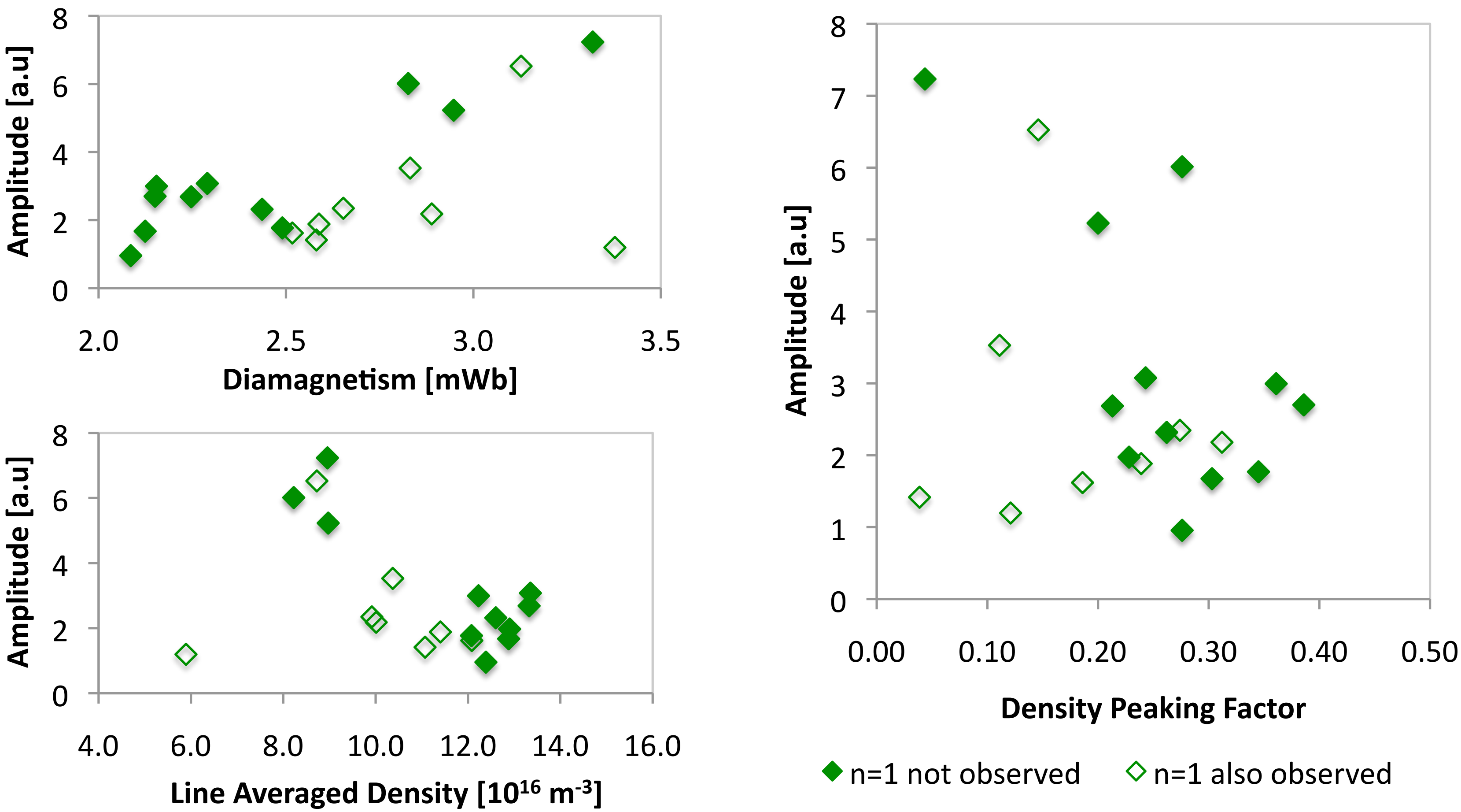
Still Image of Plasma
Shows Possible Ionization Edge



Frequency of n=0 Mode Decreases with Increasing Plasma Density



Amplitude of n=0 Mode Decreases with Increasing Plasma Density

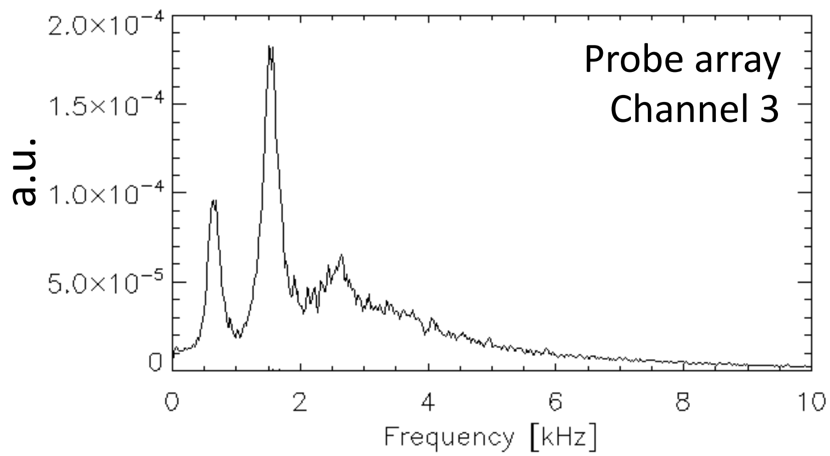


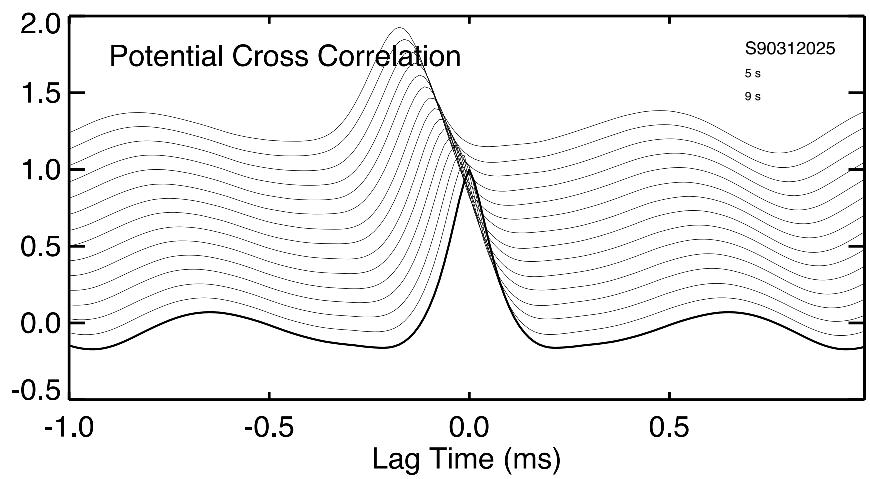
n=1

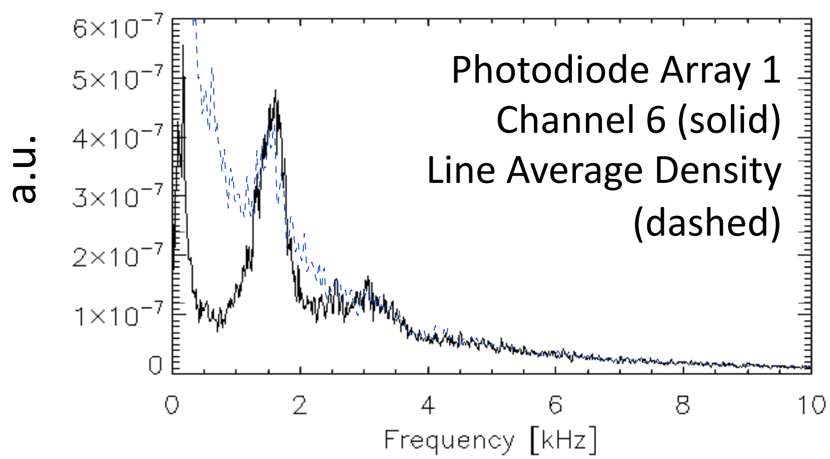
- Primarily n=1, although n=2 are sometimes visible.
- Visible light diagnostic is not really sensitive to higher order modes.
- Edge probes measure a real rotation of the plasma
- This rotation appears to be associated with the n=1 mode.
- Often, the same frequency is observed on both the probes and the chord integrated diagnostics
- But sometimes, there is radial variation in the n=1 mode frequency.

Edge Electrostatic Probes also Measure this Fluctuation

Time-averaged Fluctuation Power



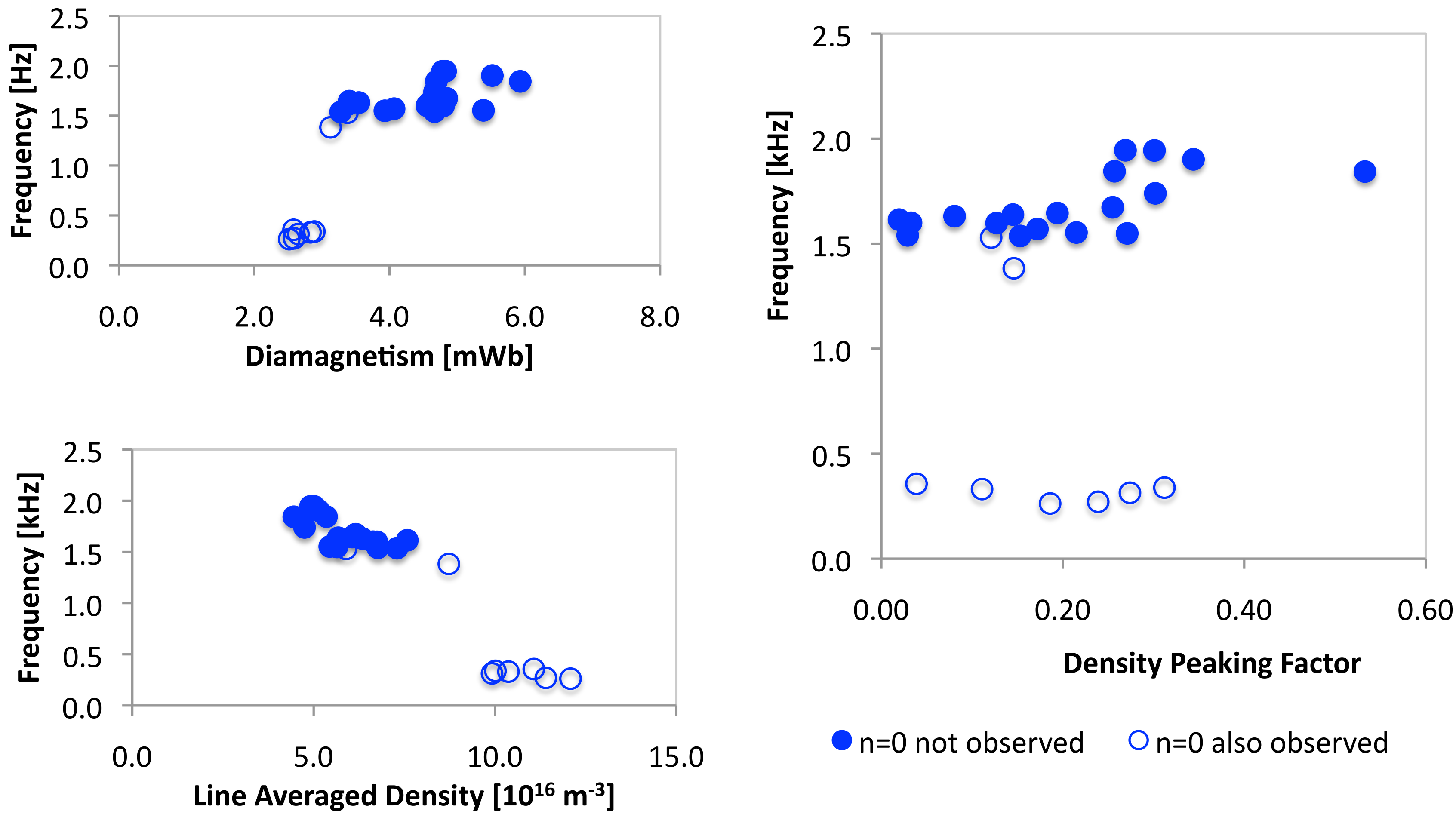




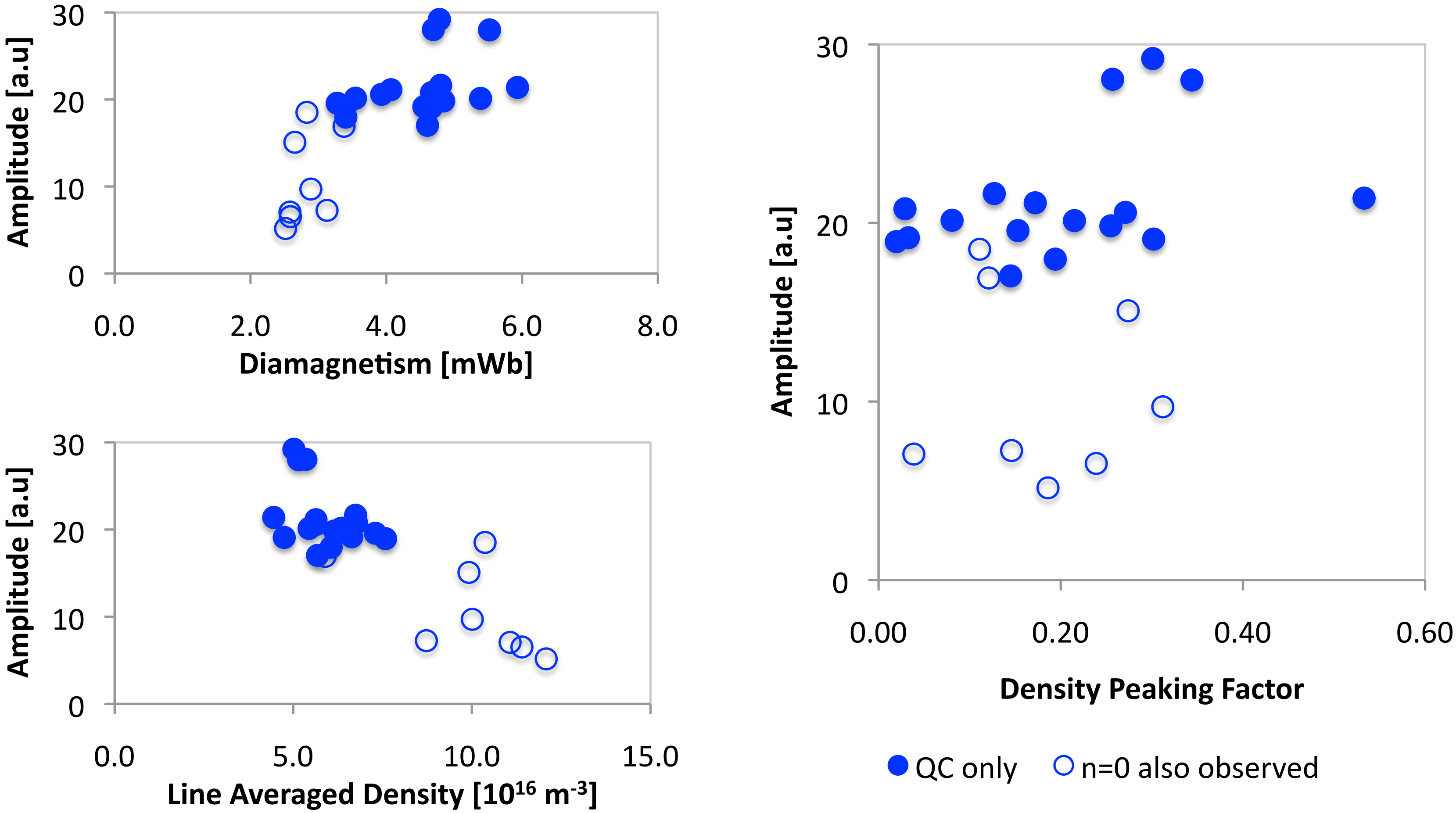
Cross-correlation of each of the floating probes in the probe array with the first probe in the array. Plasma rotation rate is 888 Hz.

See Adj. Poster by M. Mauel

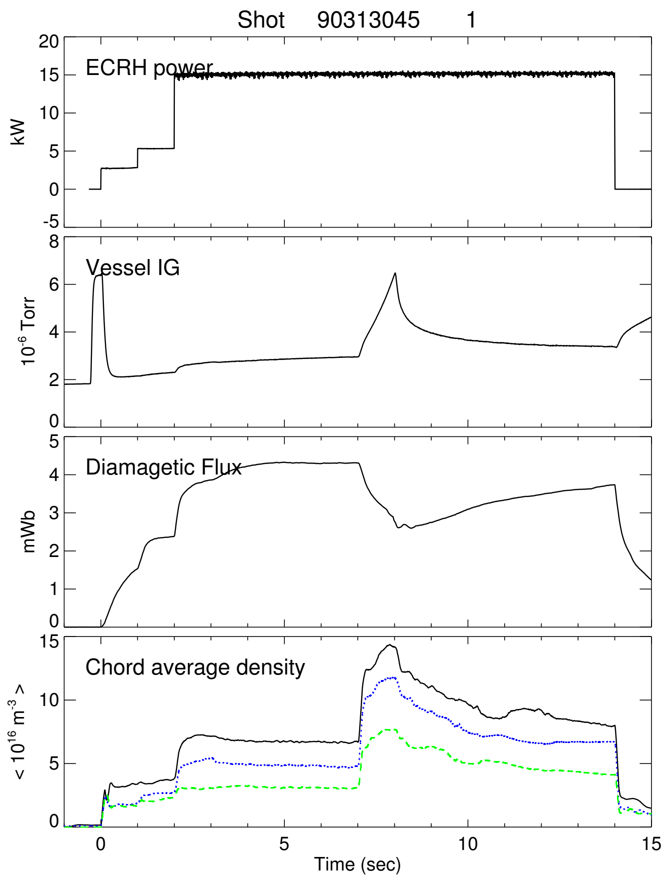
Frequency of n=1 Mode Decreases with Increasing Plasma Density

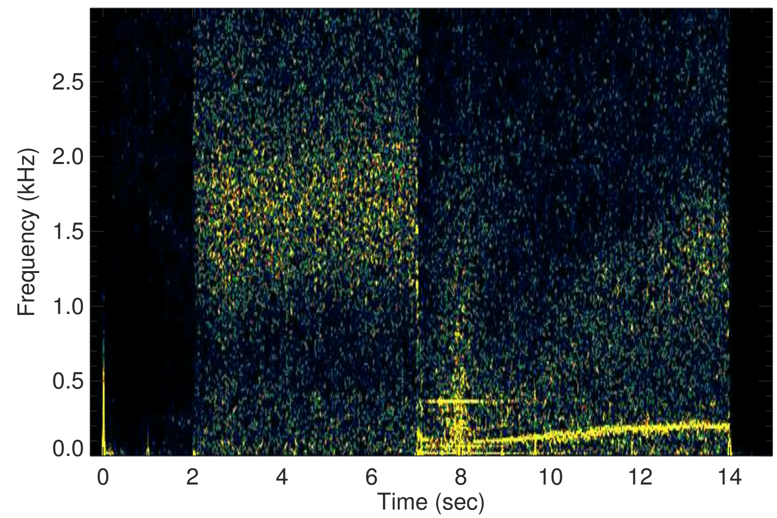


Amplitude of n=1 Mode Decreases with Increasing Plasma Density



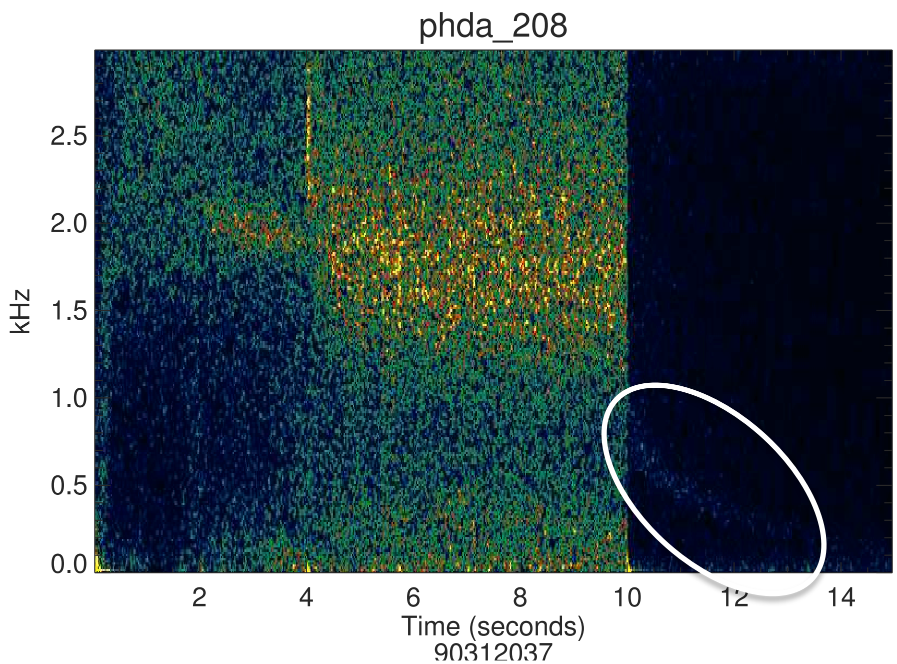
Gas Puff Experiment

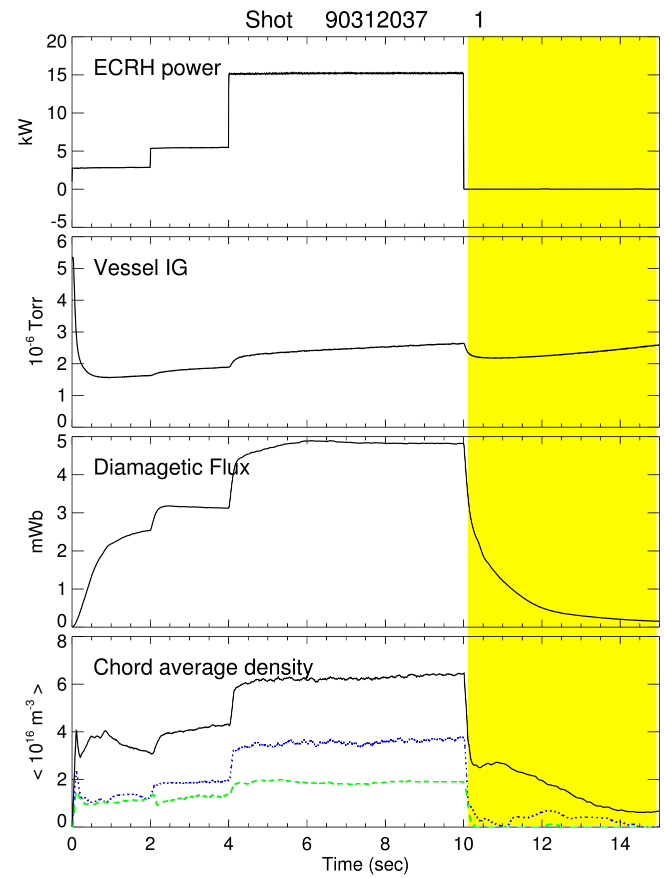




A large puff of gas is injected during times 7 s < t < 8 s. This causes the diamagnetism to drop and an n=0 mode appears. As the diamagnetism increases again after the gas puff, the n=1 mode begins to return.

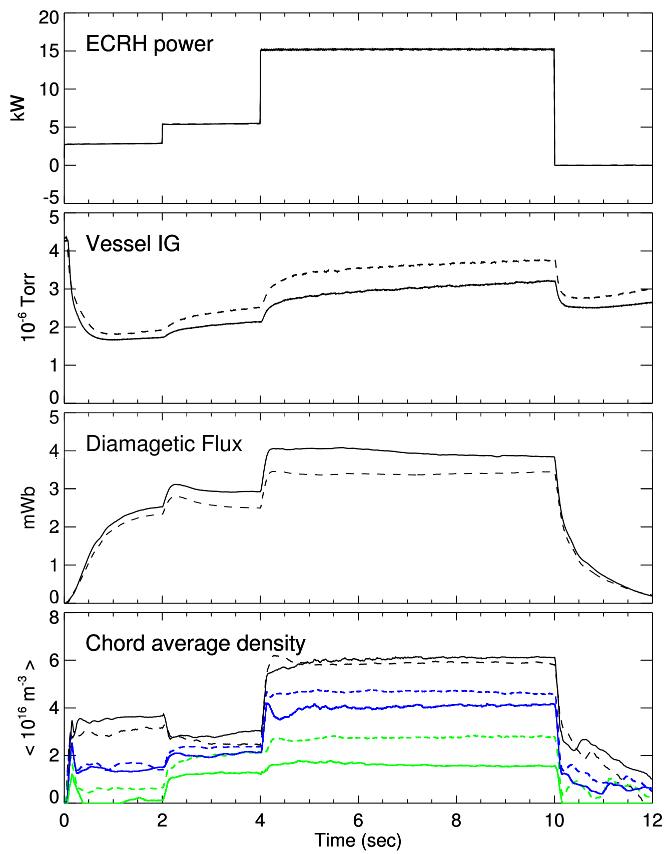
The n=1 Mode is Observed after the ECRH is Turned Off





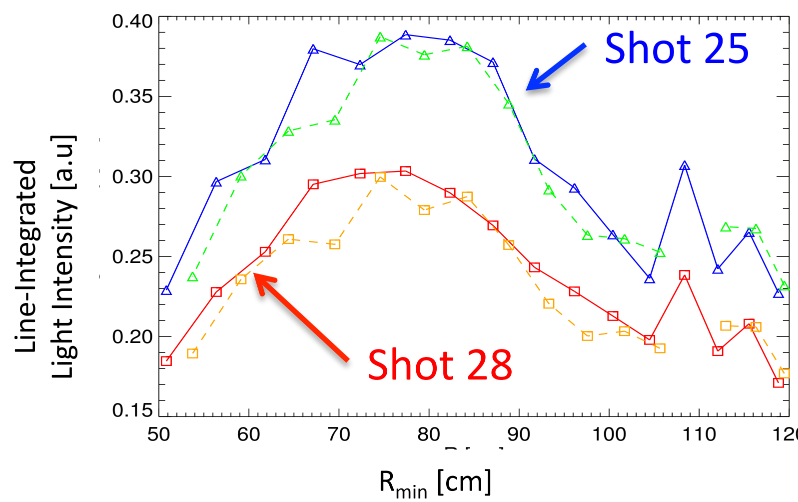
The n=1 mode frequency decreases during the afterglow as the diamagnetic flux decreases.

Compare Shots 90312025 and 90312028



Shots have identical RF heating and neutral fueling.

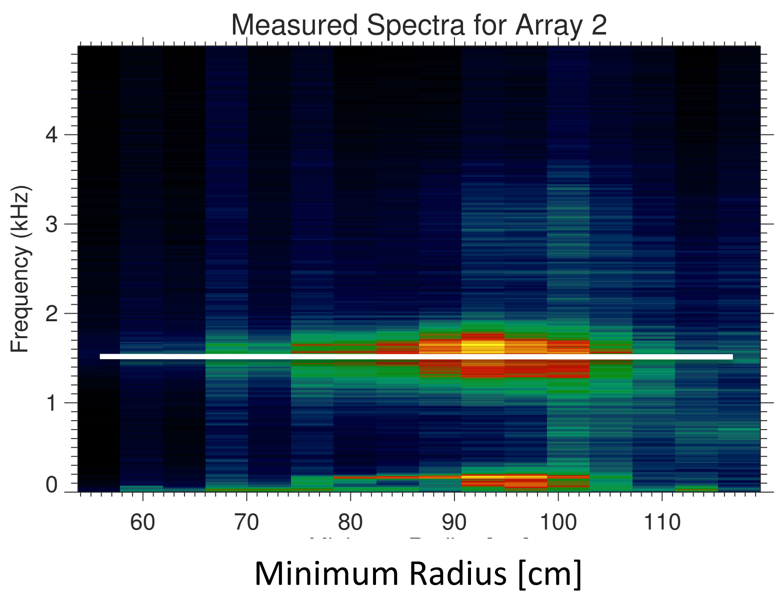
- Small differences in neutral pressure and diamagnetism
- Different density profiles
- Shot 28 has less visible light intensity

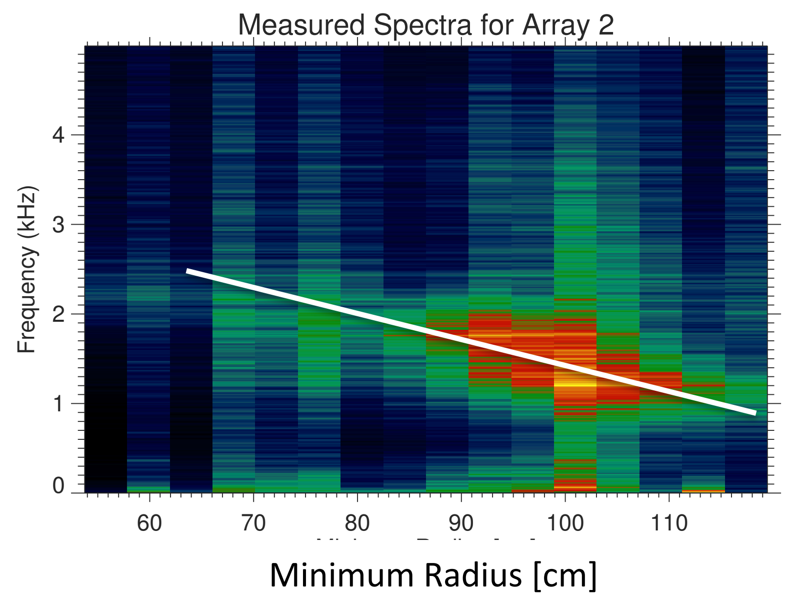


Radial Variation in the n=1 Frequency is Observed During Shot 90312028

Frequency of n=1 mode is about 1.5 kHz on each channel for shot 90312025.

Frequency of n=1 mode varies radially for shot 90312028.

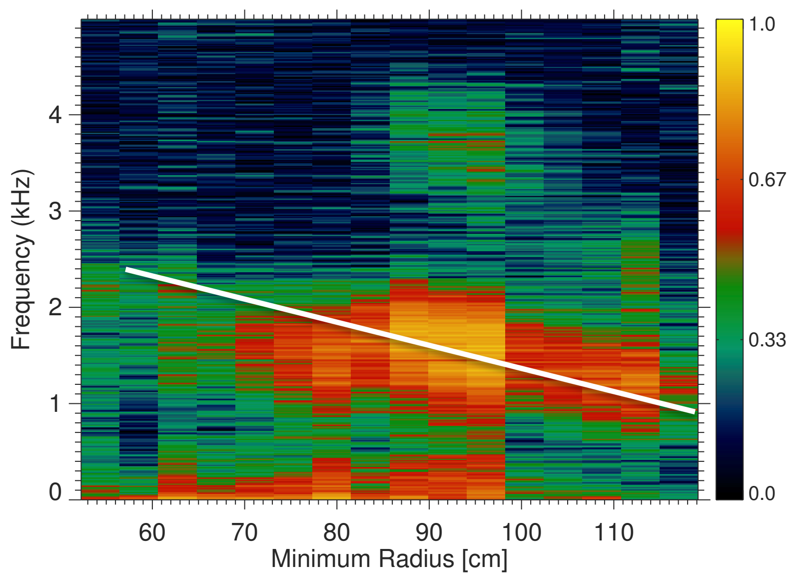




Color scale is the time-averaged, chord-integrated fluctuation power

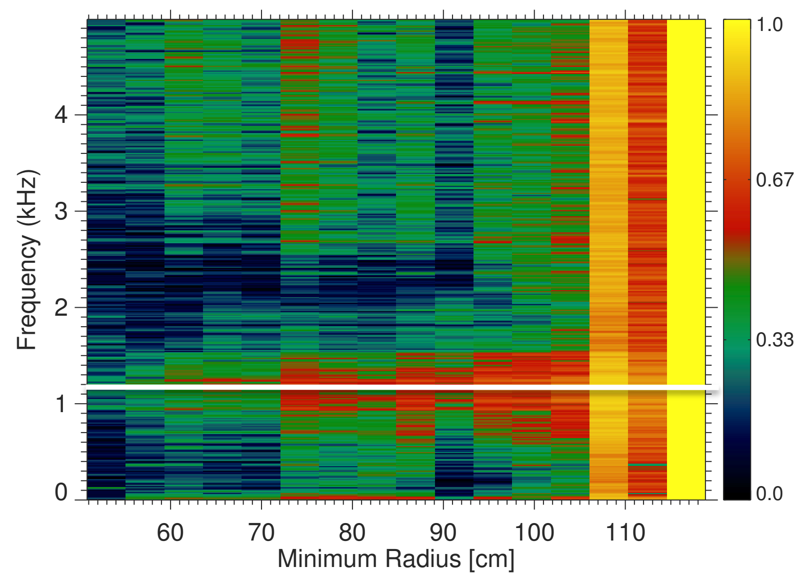
Cross-Correlations of the Photodiode Array Signals During Shot 90312028

Measured Cross-Correlation between Photodiode Array Channels Separated by 90° Toroidally



The n=1 mode is well correlated between the two arrays.

Measured Cross-Correlation between the Outermost Photodiode Array Channel and Each Channel with the Same Toroidal Location



The 1 kHz fluctuation at the edge of the plasma is observed by most of the radially separated channels.

Synthetic Diagnostic

- We are interested in local information, but the data is chord integrated
- Inversions are not always appropriate for fluctuation data.
- Build a synthetic diagnostic that uses a model of the plasma fluctuations to see which models are consistent with the data
- Synthetic diagnostic uses the calibrated viewing chords for the photodiode array diagnostic
- Accepts 1, 2, or 3-dimensional models

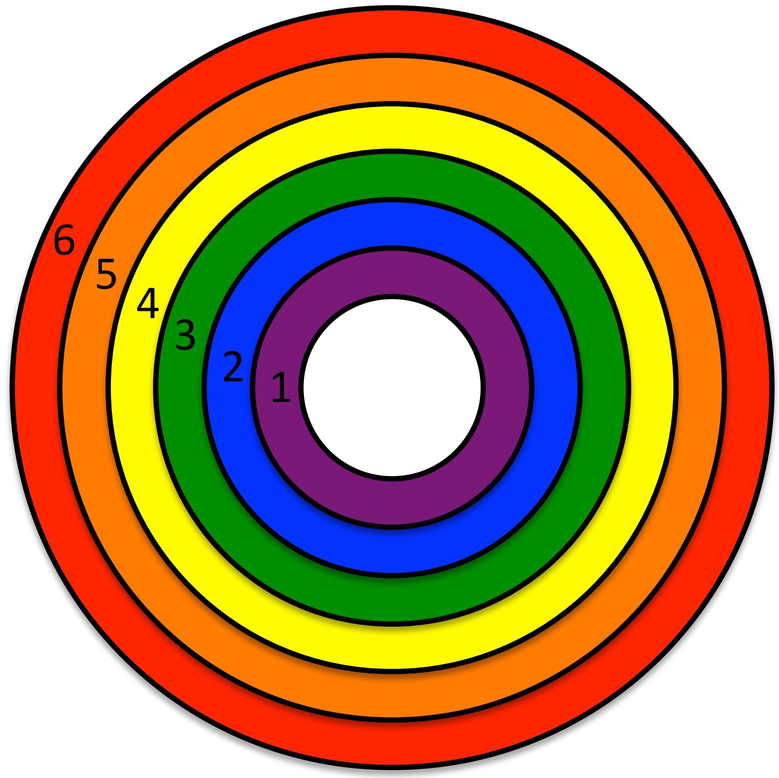
Fluctuation Model

- Split the plasma into six sections of either equal radial extent, or equal magnetic flux
- Define an amplitude A_k, frequency ω_k, and mode number n_k
- Fluctuation within the region is

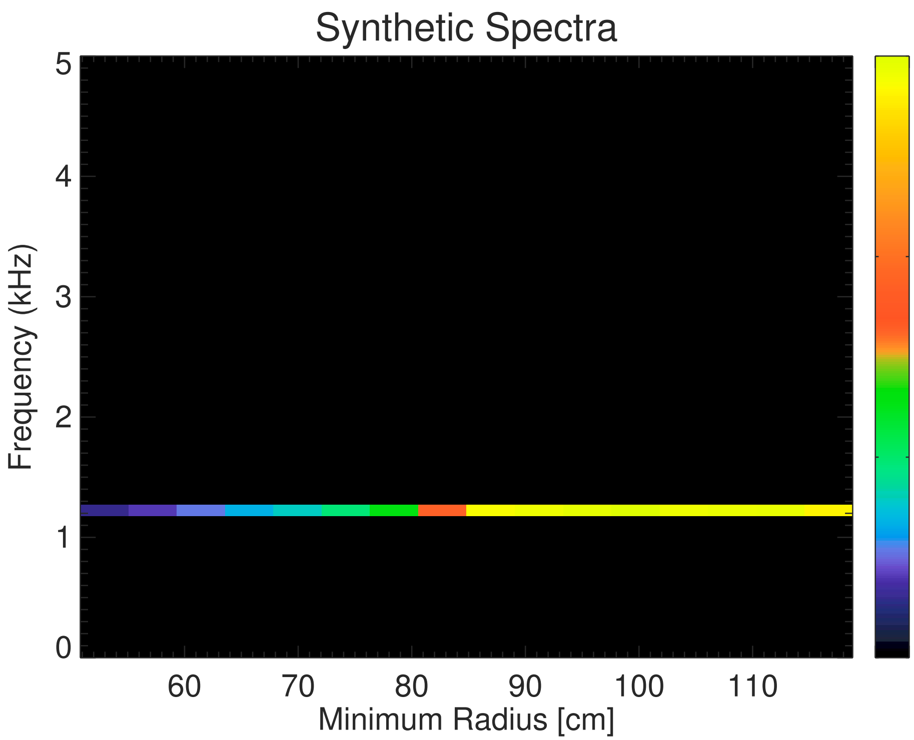
$$\tilde{f}_k(t,\theta) = A_k \sin\left(\omega_k t - n_k \theta\right)$$

- And total fluctuation is the sum of the fluctuations from all six regions

$$\tilde{I}(t,\theta) = \sum_{k=0}^{6} \tilde{f}_k(t,\theta)$$



Synthetic Diagnostic Results (1)

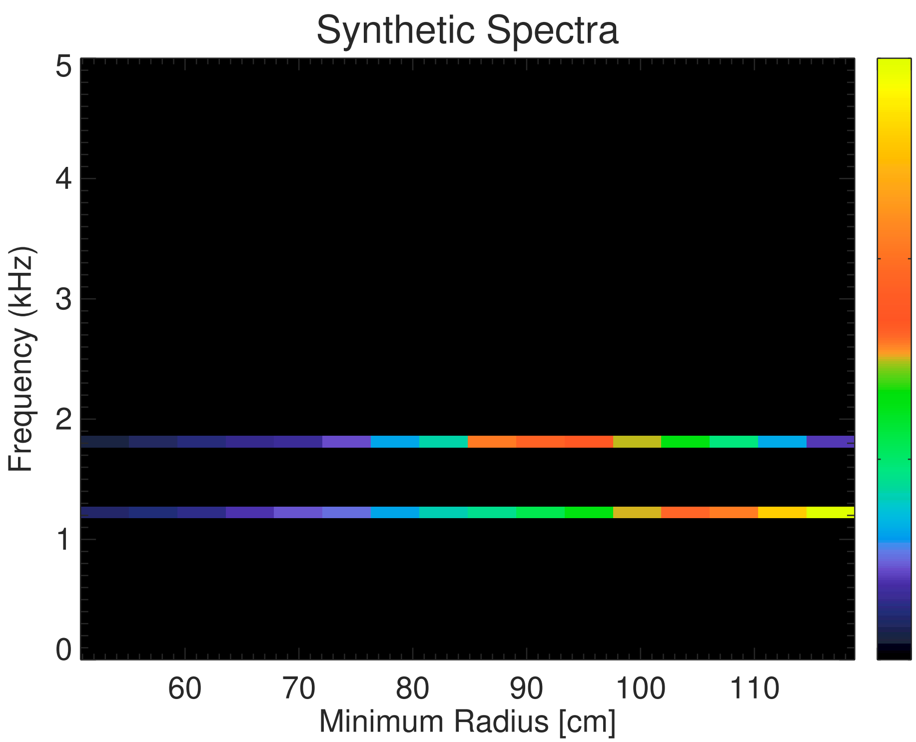


Model Parameters

k	A_k	ω_k	n_k	r_{min}	r_{max}
1	0	-	-	60	92
2	1	1200	1	92	123
3	1	1200	1	123	155
4	1	1200	1	155	187
5	0	-	-	187	218
6	0	-	-	218	250

An n=1 mode with a single frequency is consistent with the fluctuation spectrum observed in shot 90312025.

Synthetic Diagnostic Results (2)



Model Parameters

k	A_k	ω_k	n_k	r_{min}	r_{max}
1	0	-	-	60	92
2	1	1800	1	92	123
3	1	1200	1	123	155
4	1	1200	1	155	187
5	0	-	-	187	218
6	0	-	-	218	250

Two n=1 modes with constant amplitude and varied frequency are consistent with the fluctuation spectrum observed in shot 90312028.

Summary

- Three types of low-frequency fluctuations are observed
  - Broadband turbulence
  - n=0 mode that corresponds to a global fluctuation of the plasma
  - n=1 mode that is closely related to the rotation of the plasma
- The different types of fluctuations are observed under different plasma conditions
- Low frequency fluctuations are observed on every channel of the photodiode arrays.
- Determining the structure of the fluctuations is not straightforward.
- More work is needed to fully understand the dynamics of the plasma.