NSTX

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Edge turbulence characteristics across the L-H transition in NSTX

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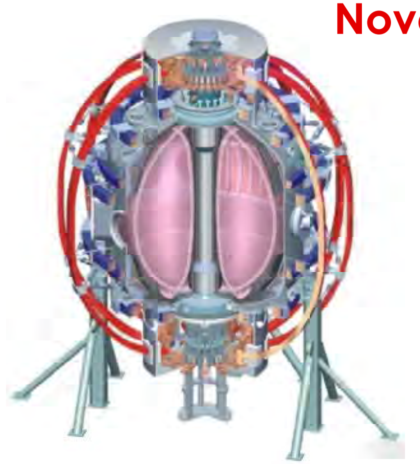

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Introduction and Overview

- **Edge parameters and their gradients important to L-H transition theories:**
  - Turbulence properties are inferred and rarely measured in experiments.
  - Obtaining simultaneous turbulence and profile information is usually difficult.
- **Possibility of measuring edge (and core) turbulence and profiles simultaneously on NSTX:**
  - New diagnostic (ultra-fast swept FMCW reflectometer) coupled with new analysis techniques.
  - Electron density profile measured across the L-H transition with a time resolution ($\leq$10 μs).
  - Possibility of estimating density turbulence levels and correlation lengths on a sub-millisecond time scale.
- **Preliminary application of methods to Ohmic H-mode discharges:**
  - Evidence of turbulence suppression coupled with density profile steepening at the barrier location.
  - Edge correlation length reduction prior to L-H transition.
- **Poloidal correlation measurements will be addressed in the future.**

Abstract

The fast evolution of turbulence and profiles are characterized across the L-H transition in NSTX. New millimeter-wave diagnostics are used to track the electron density profile and turbulence properties near the plasma edge. In NSTX, the rapid build-up of impurities in the edge following the L-H transition allows only a ≤10 ms window for reflectometry measurements across the transition barrier. The ultra-fast FMCW reflectometers (13-53 GHz) now have a <8.5μs sweep capability, which allows the system to be swept across the entire outboard plasma and therefore over the turbulence correlation length, faster than the decorrelation time. Substitution of the temporal correlation of the reflectometer signal for spatial correlation allows radial correlation length estimates in <0.5 ms. Fluctuation levels and mean/fluctuating flow velocities (zonal flows) are estimated with the poloidal correlation reflectometer. The connection between the local turbulence properties and ExB shear will be discussed.

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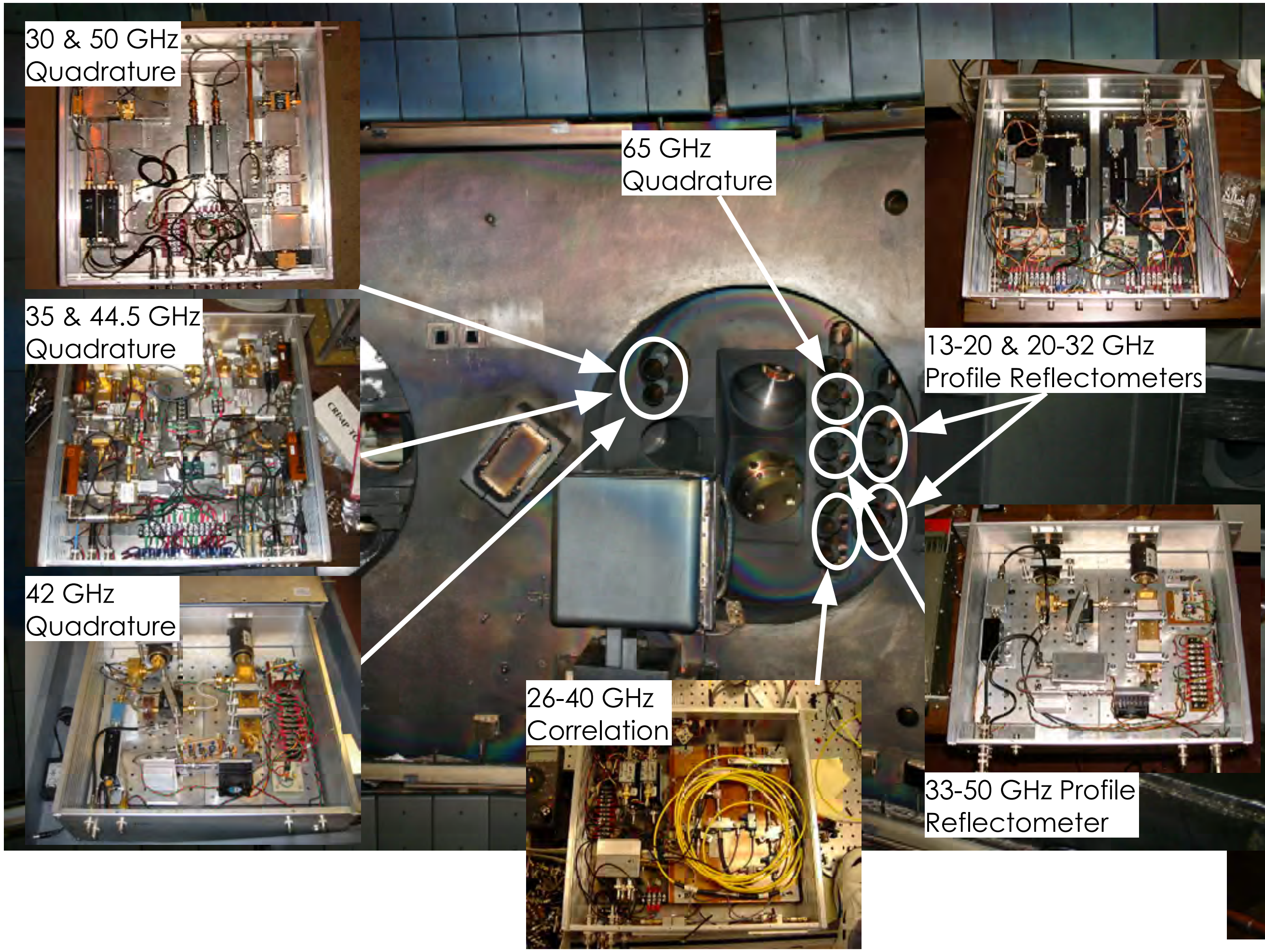
Millimeter-Wave Diagnostics for 2008 Campaign

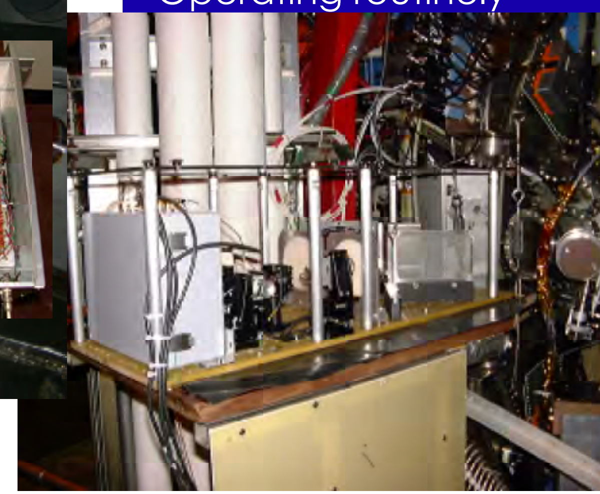


Bay J Reflectometers

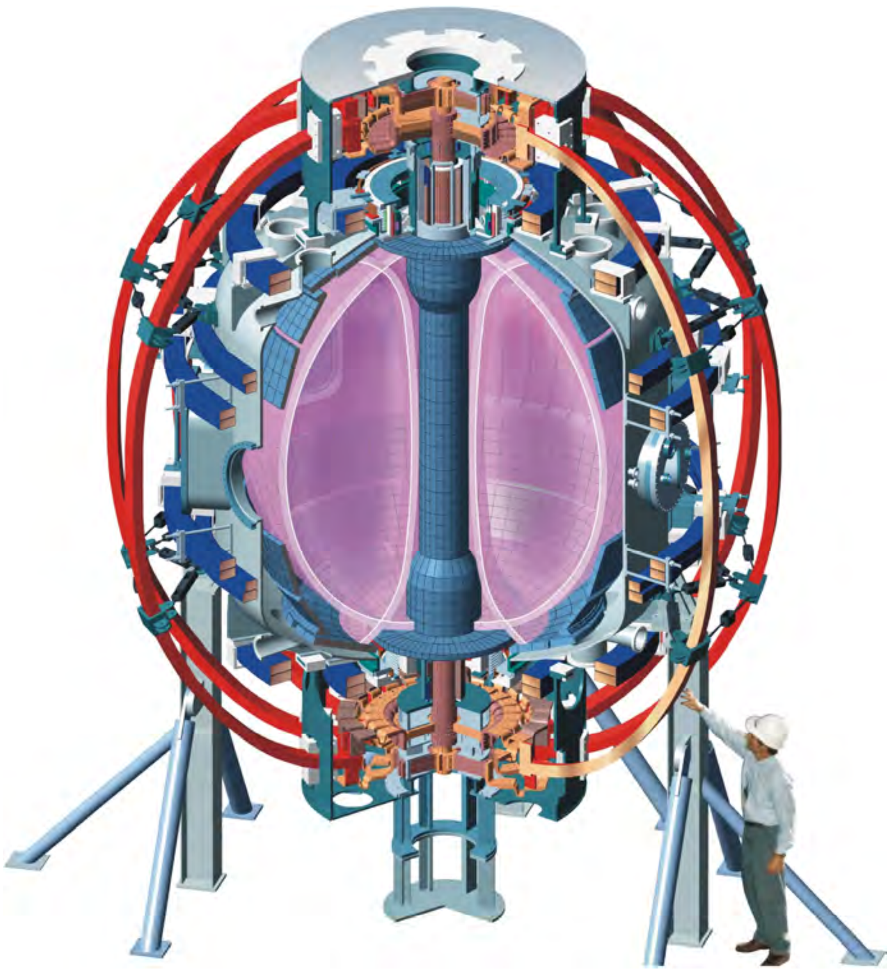
- Fluctuation levels
- Spectra
- Profiles

Bay G Interferometer

- Radial line density
- Operating routinely

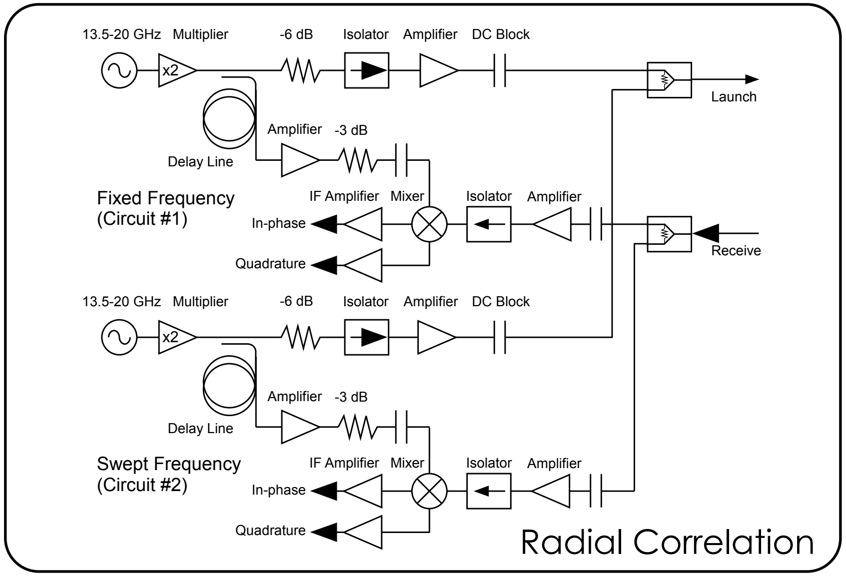


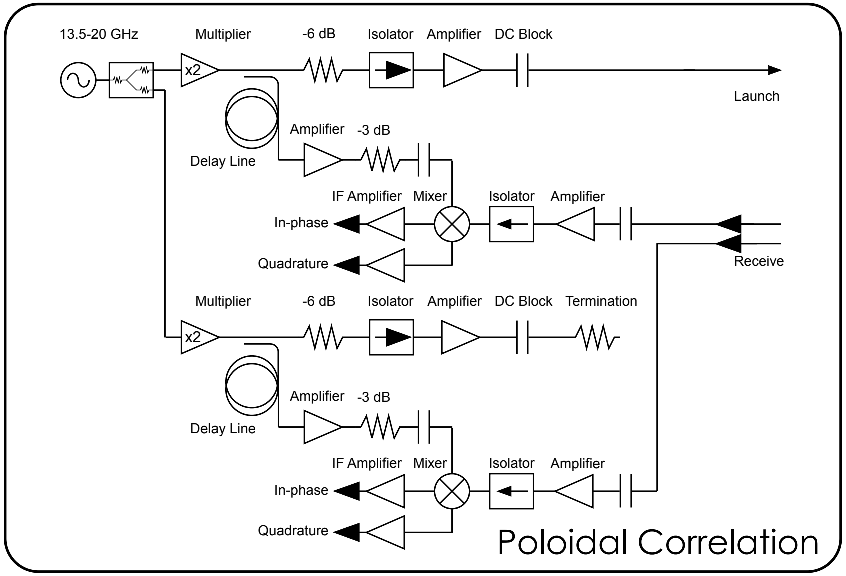
Machine Parameters

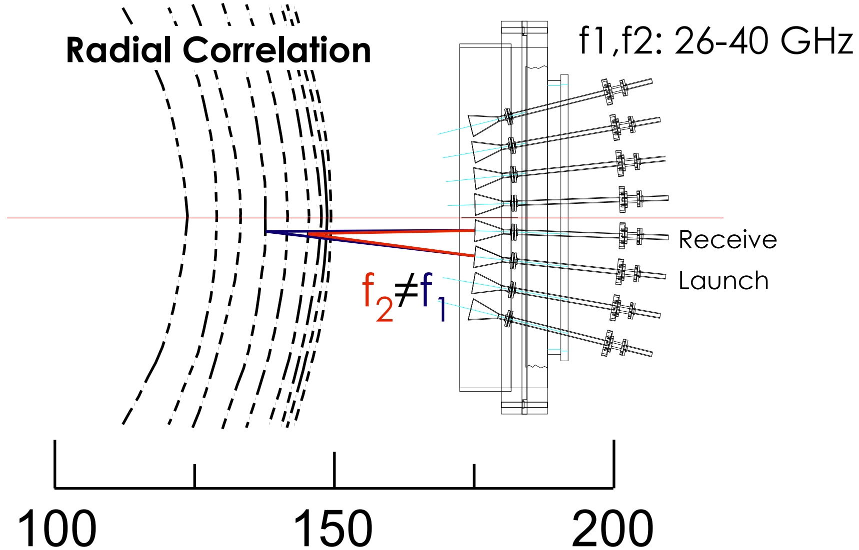


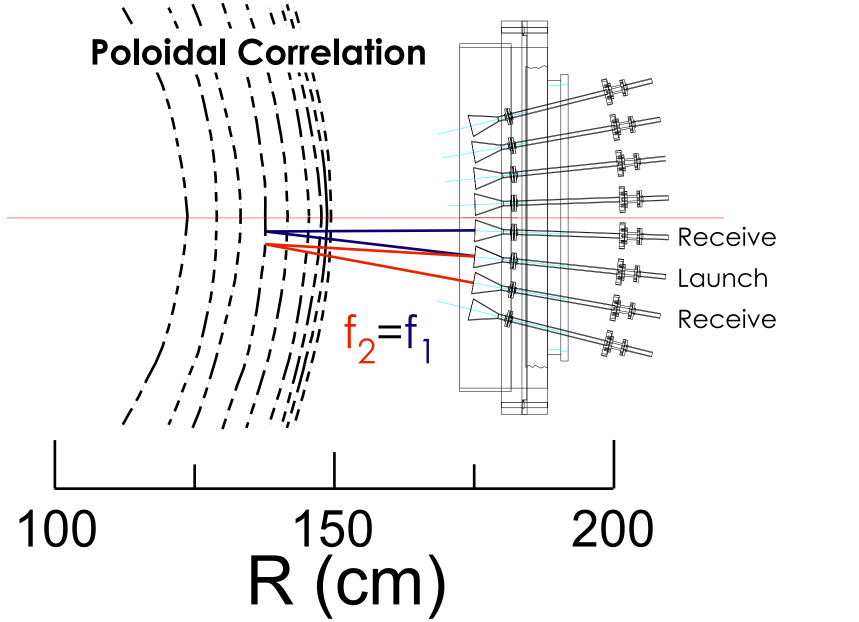
Aspect Ratio A	1.27
Elongation κ	2.5
Triangularity δ	0.8
Major Radius R_0	0.85 m
Plasma Current I_p	1.5 MA
Toroidal Field B_{T0}	0.6 T
Pulse Length	1.5 s
Auxiliary Heating	
NBI (100 kV)	7 MW
RF (30 MHz)	6 MW
Central Temperature	1-3 keV

Radial & Poloidal Correlation Reflectometers

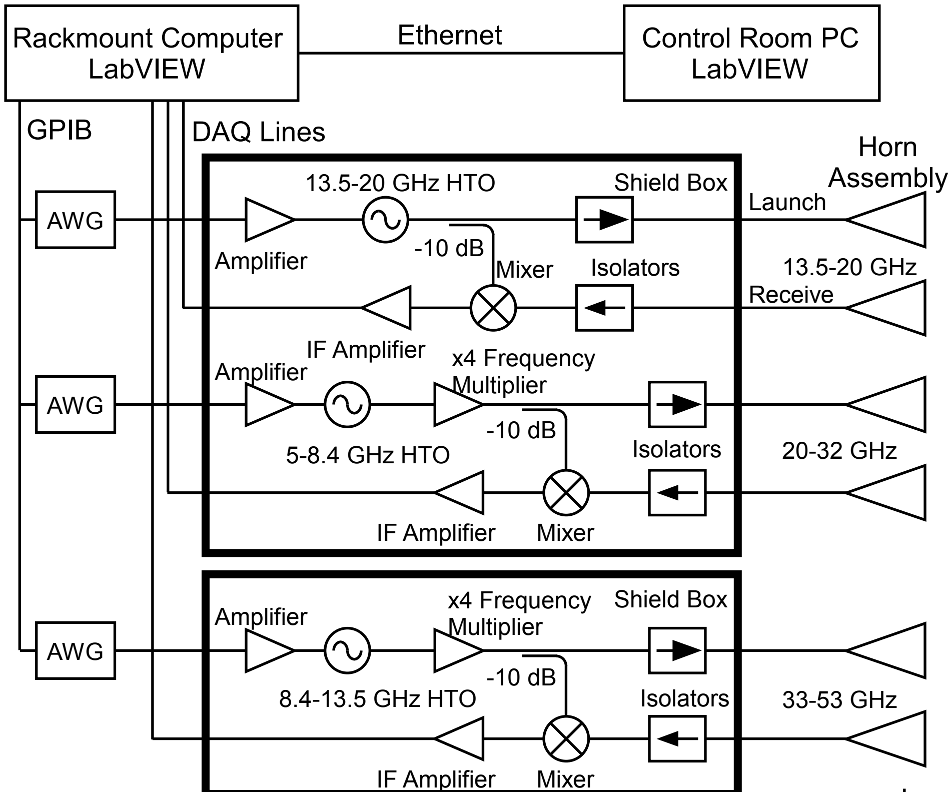


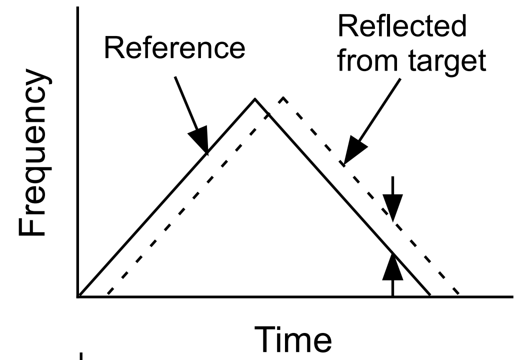


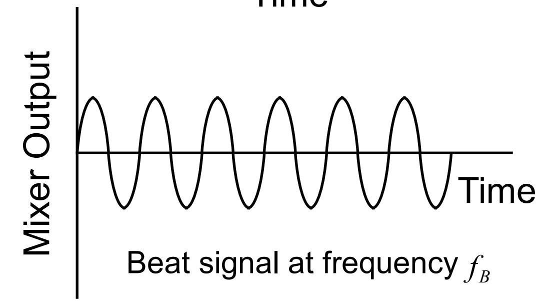


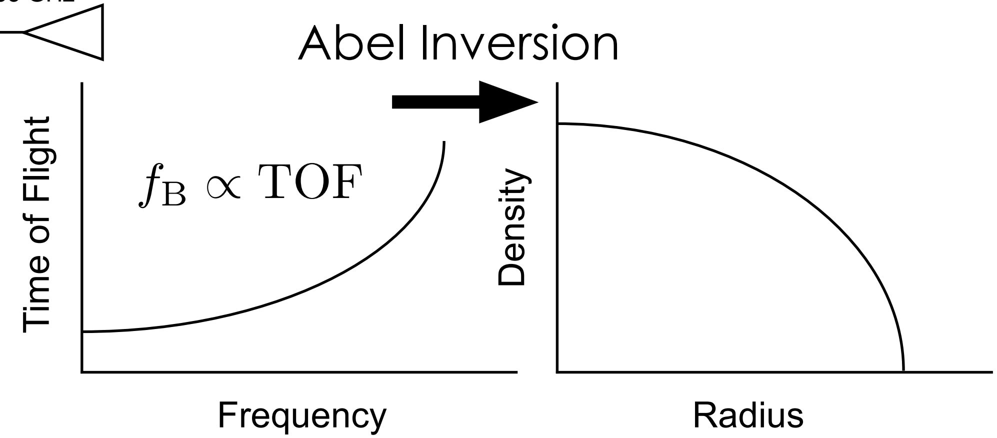


Upgraded FMCW Reflectometer (t_{sweep}<10 µs)









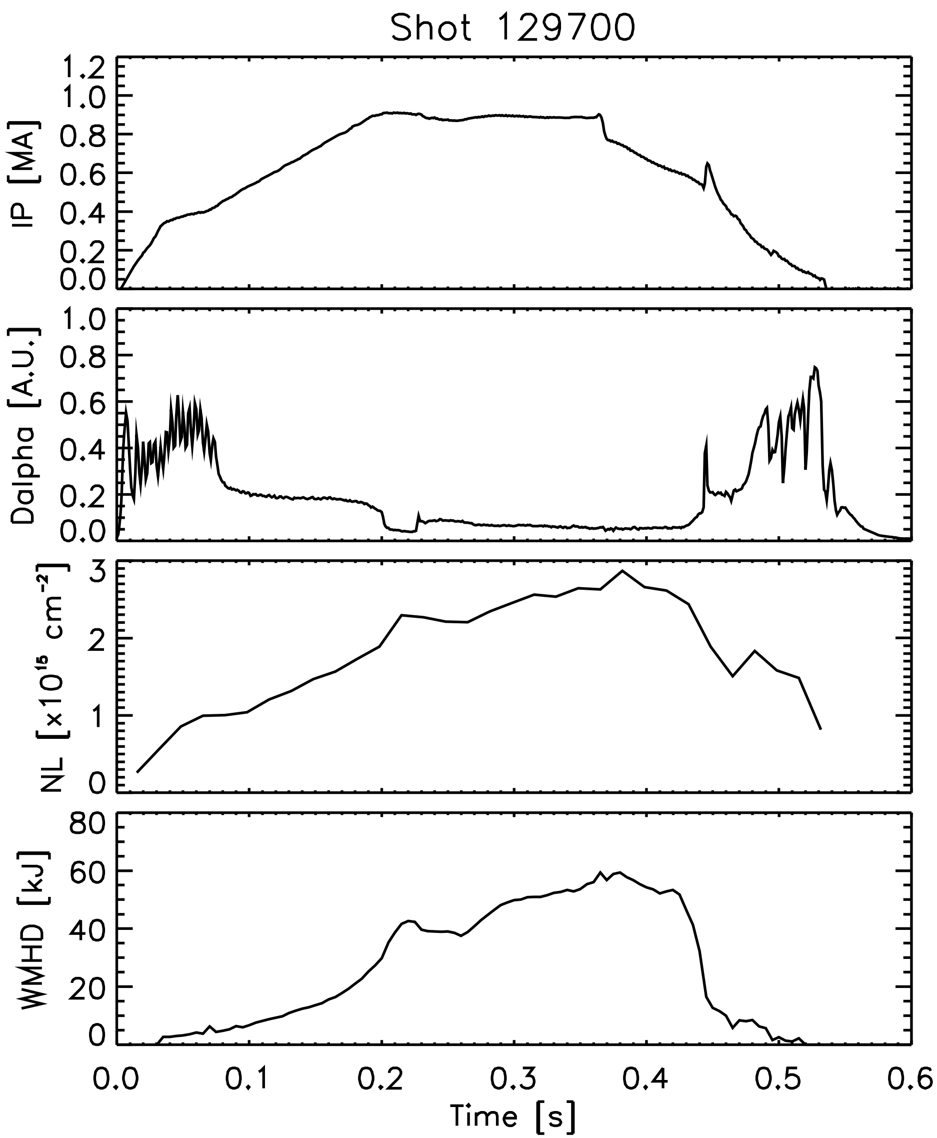
- 13-53 GHz coverage (2.1×10^{12} to 3.5×10^{13} cm^{-3}).
- Maximum repetition rate of 10 µs/sweep (9279 total profiles per shot).
- Using spline fit to Thomson edge profile below $n_e=9\times10^{11}$ cm^{-3}.

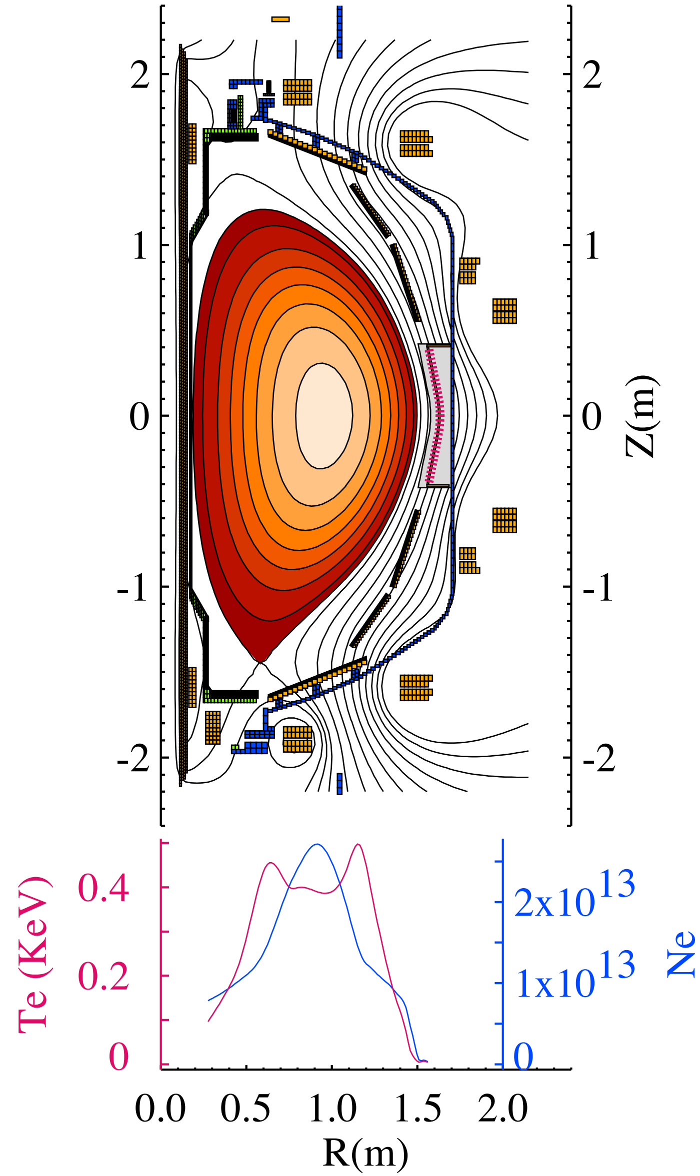
Ohmic H-Modes in NSTX

- **Characteristics of NSTX Ohmic discharges:**
  - Deuterium, I_p=900 kA, B_t=4.5 kG.
  - LSN diverted for ELM-free H-modes. Short H-mode phase (several tens of ms).
  - Typical edge density "ears" due to impurity (C) accumulation.
  - In L-mode phase, core density is peaked (3-4x10^{13} cm^{-3}).
    In H-mode phase, core density remains relatively unchanged.
  - This is in contrast to NB-heated H-modes which have density profiles that are flat before the L-H transition (unfavorable for reflectometry).
  - No coherent fast-particle induced MHD. Good target for measuring turbulence.
  - Some MHD: f<10 KHz, core-localized classical tearing mode. H-L back-transition when f~0 kHz.

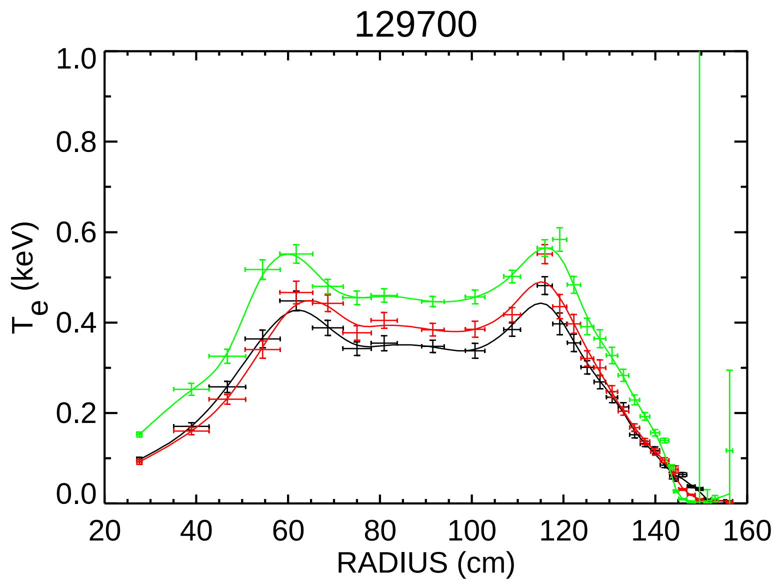
- **Difficulty due to the growth of edge density ears:**
  - Limits reflectometer accessibility to edge.
  - No core access ~10 ms after L-H transition.
  - True for all H-mode cases on NSTX except for ELMy H-modes.

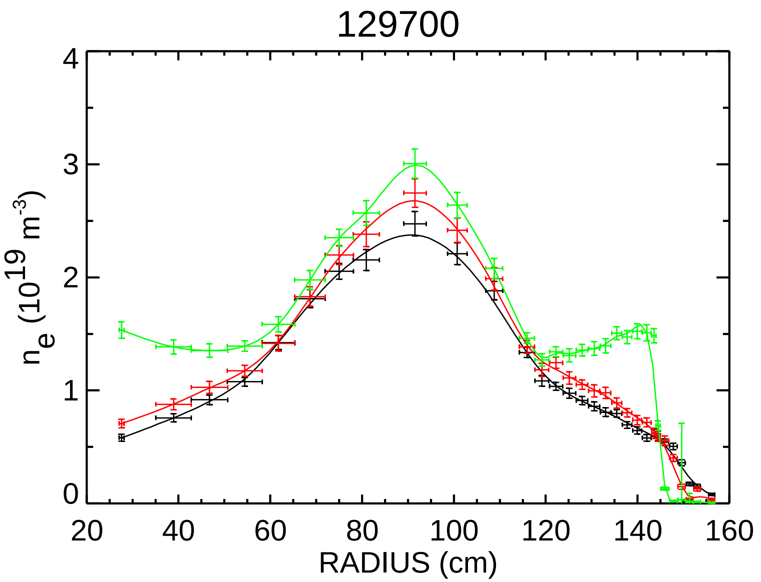
Ohmic Discharge Parameters

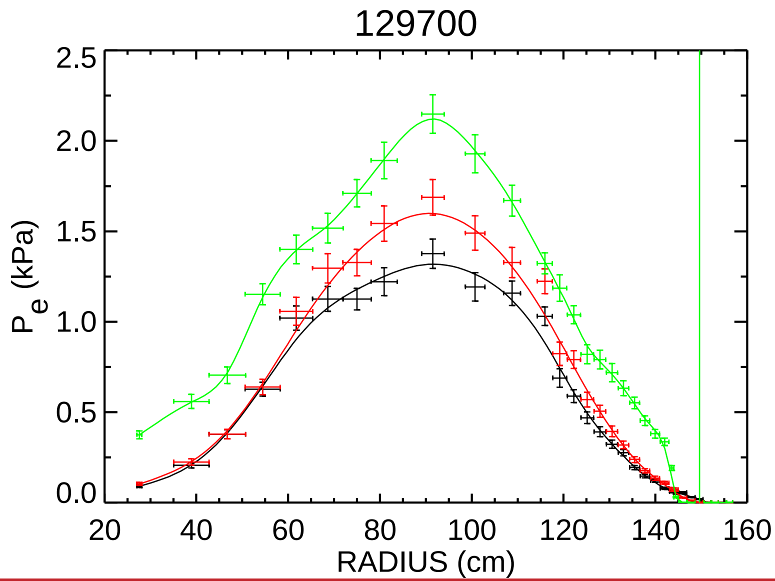


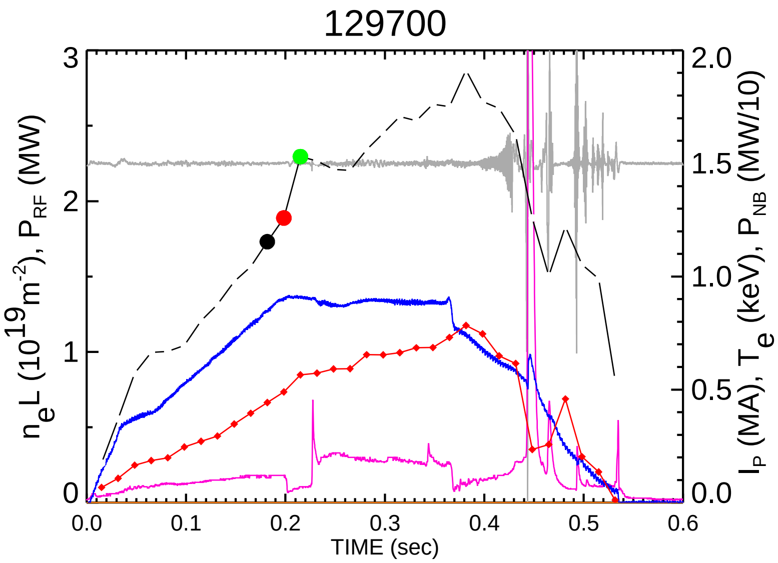


Ohmic Discharge Profiles





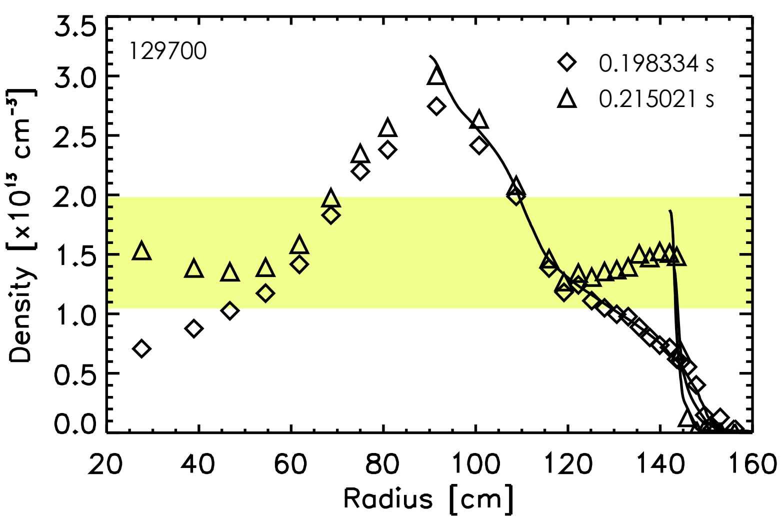




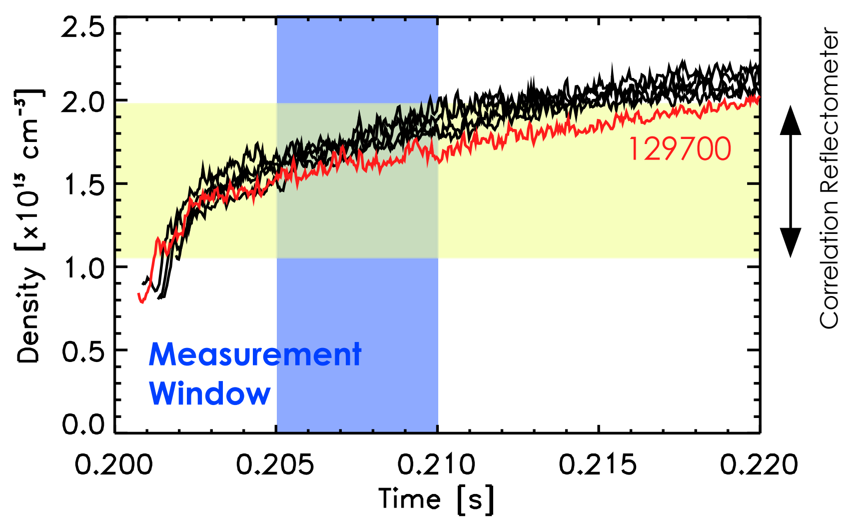
Objectives of Ohmic H-Mode Experiment

- **Goals:**
  - Characterize turbulence properties across the L-H transition.
  - Changes in the correlation length (requires plasma is stationary ~few ms). If edge is measurement is not possible -> infer from core.
  - Evolution of edge pedestal/ear (prevents core accessibility).
- **Old and new tools:**
  - Reflectometers (profile, fixed frequency, correlation).
  - Ultra-fast FMCW reflectometry for radial correlation measurements. Better radial coverage (0.2-3.5x10^{13} cm^{-3}) and time resolution (0.5 ms).

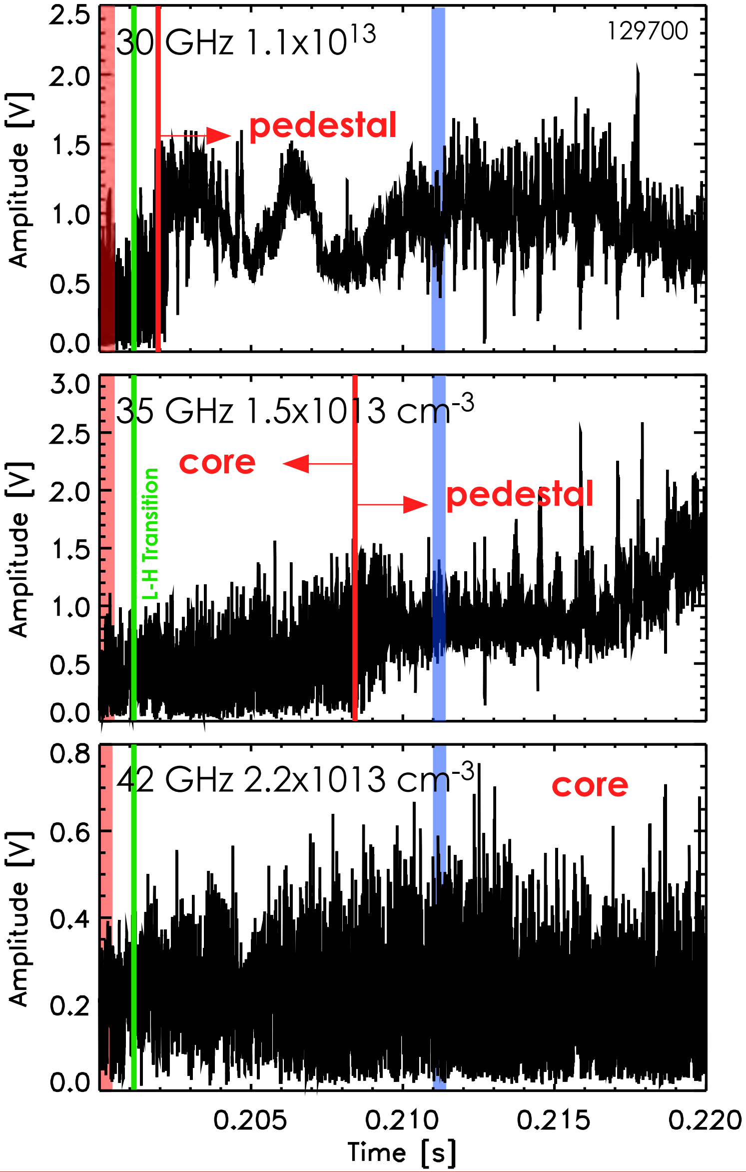
Electron Density Profile Evolution



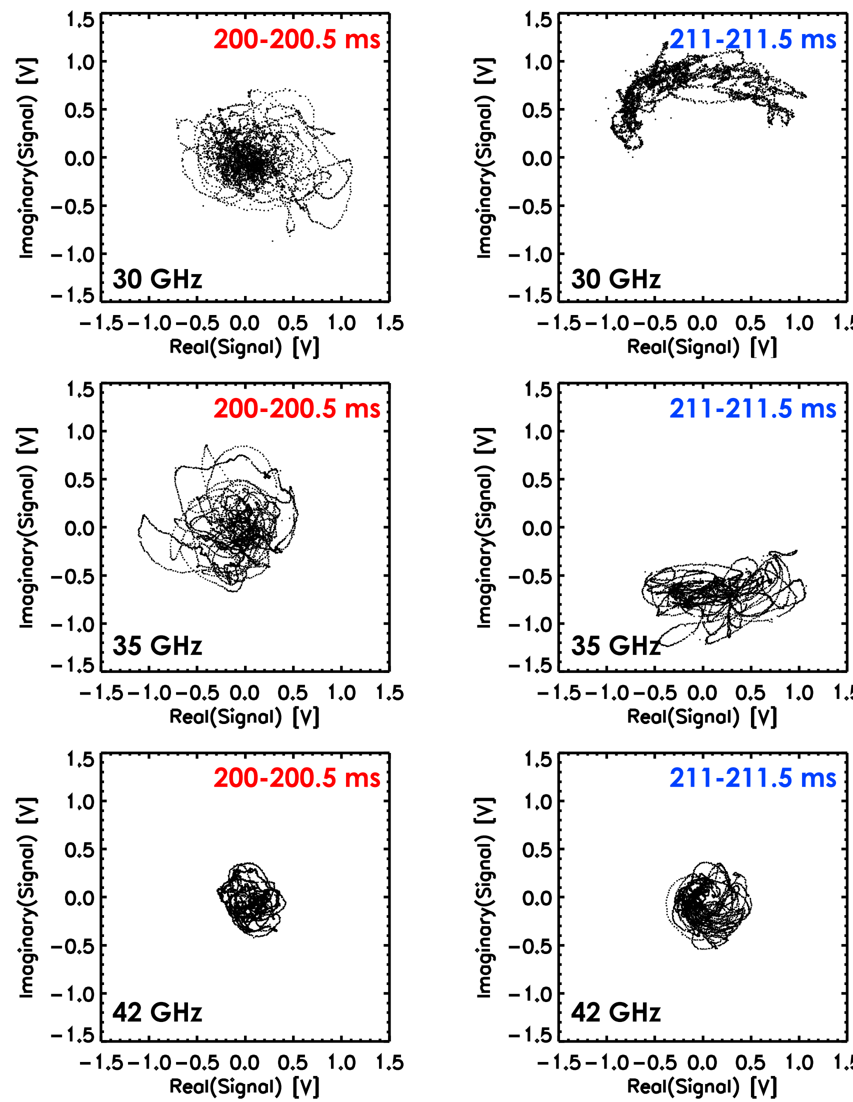
Pedestal Height from tanh fit



Reflectometer Signals in Core

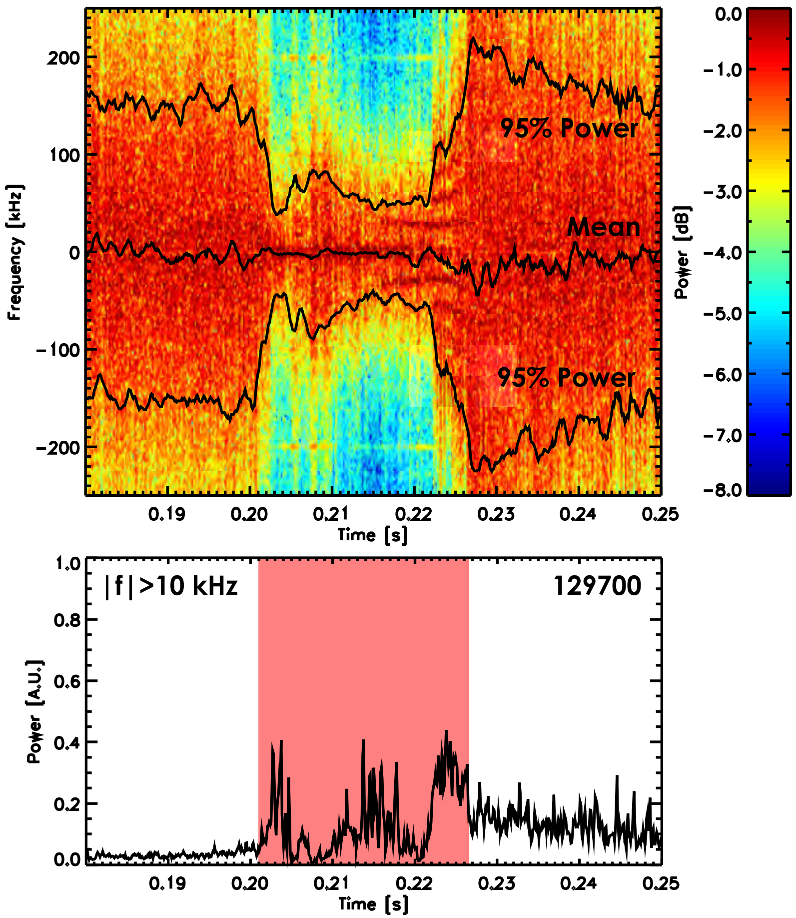


Complex Amplitude Before and After Transition

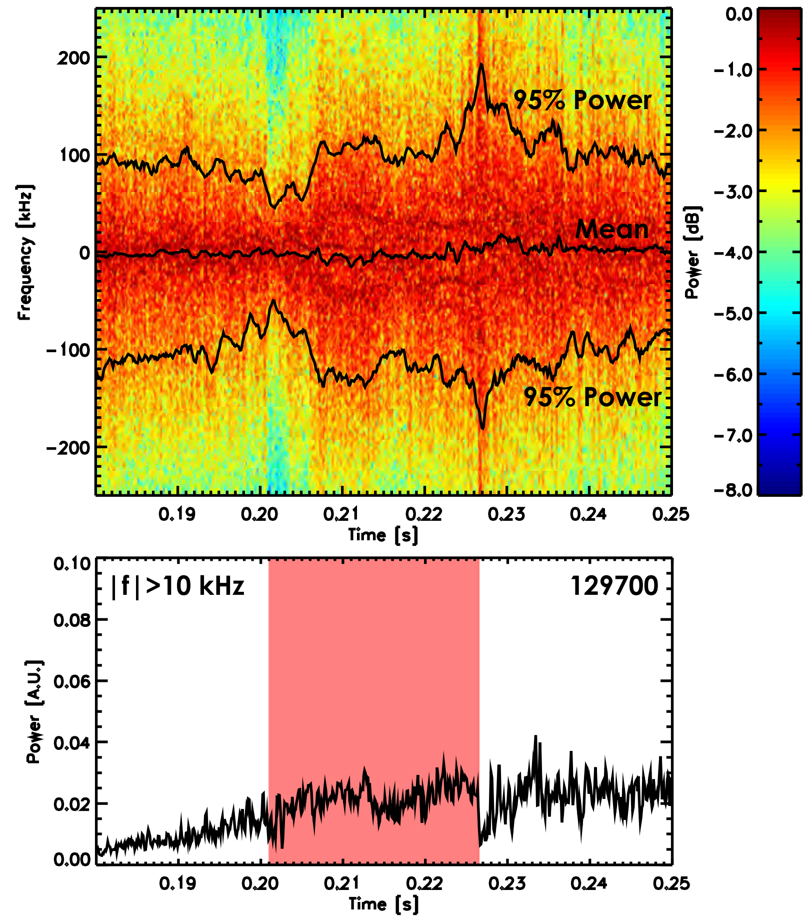


Complex Signal Amplitude & Spectra Across L-H Transition

Fixed-Frequency 30 GHz
Spectrogram of Complex Amplitude

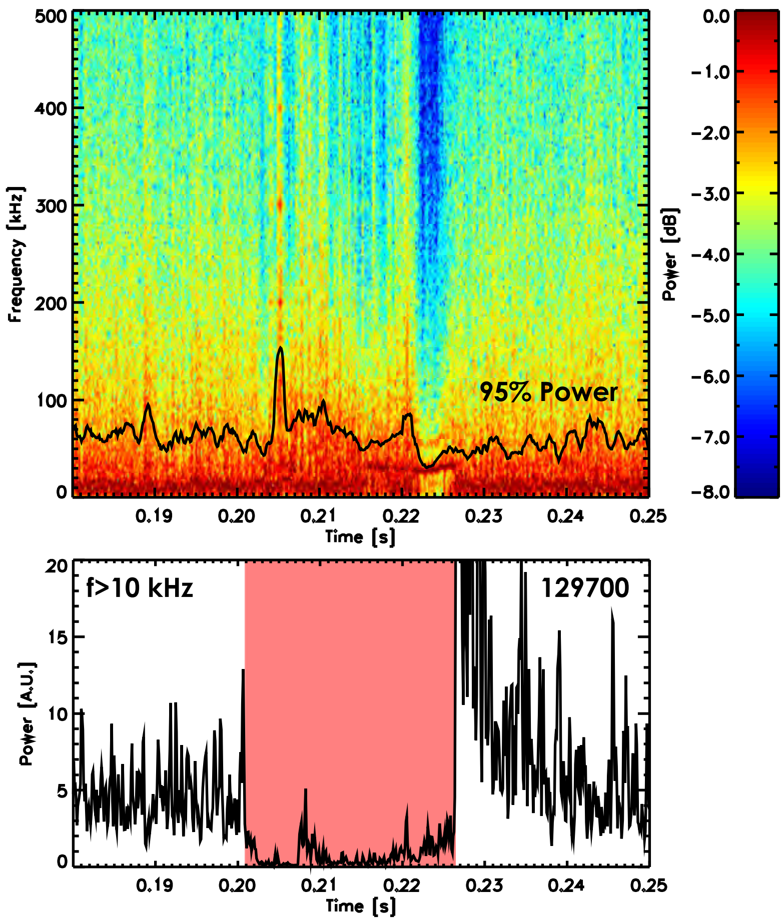


Fixed-Frequency 42 GHz
Spectrogram of Complex Amplitude

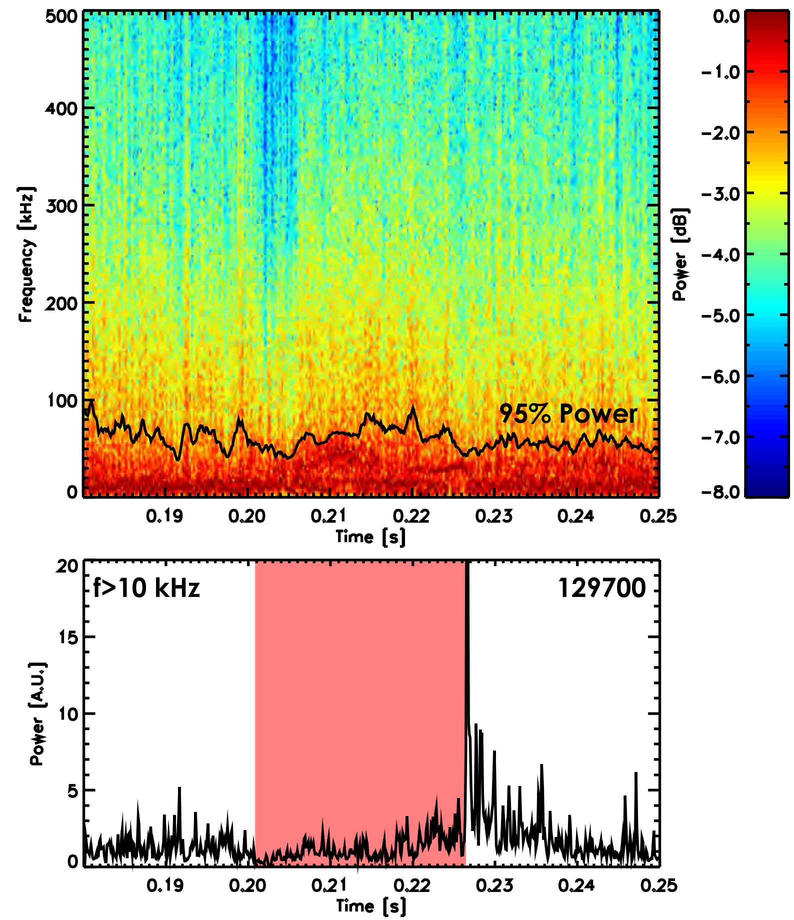


Phase Signal Amplitude & Spectra Across L-H Transition

Fixed-Frequency 30 GHz Spectrogram of Phase

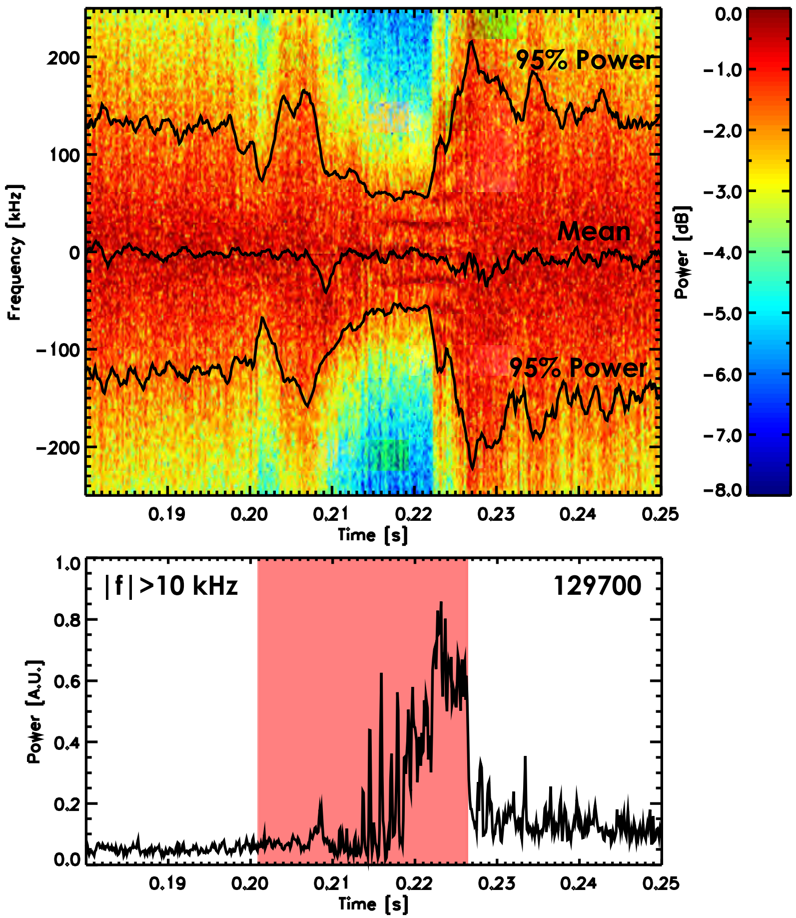


Fixed-Frequency 42 GHz Spectrogram of Phase

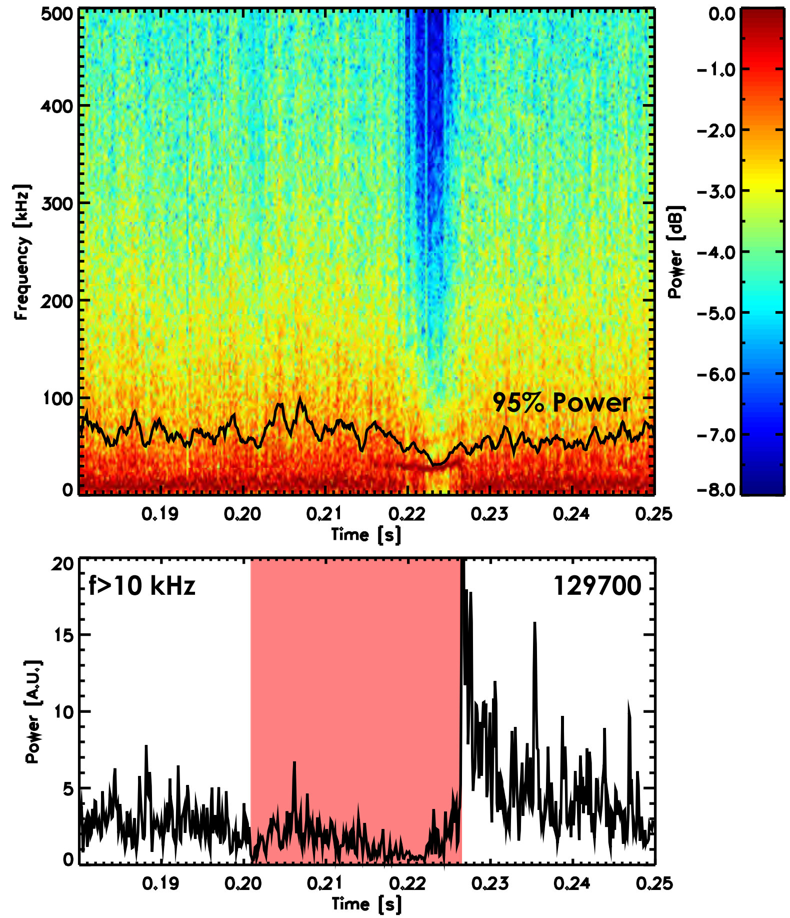


Evidence of Large Doppler Shift for 35 GHz Channel

Fixed-Frequency 35 GHz
Spectrogram of Complex Signal

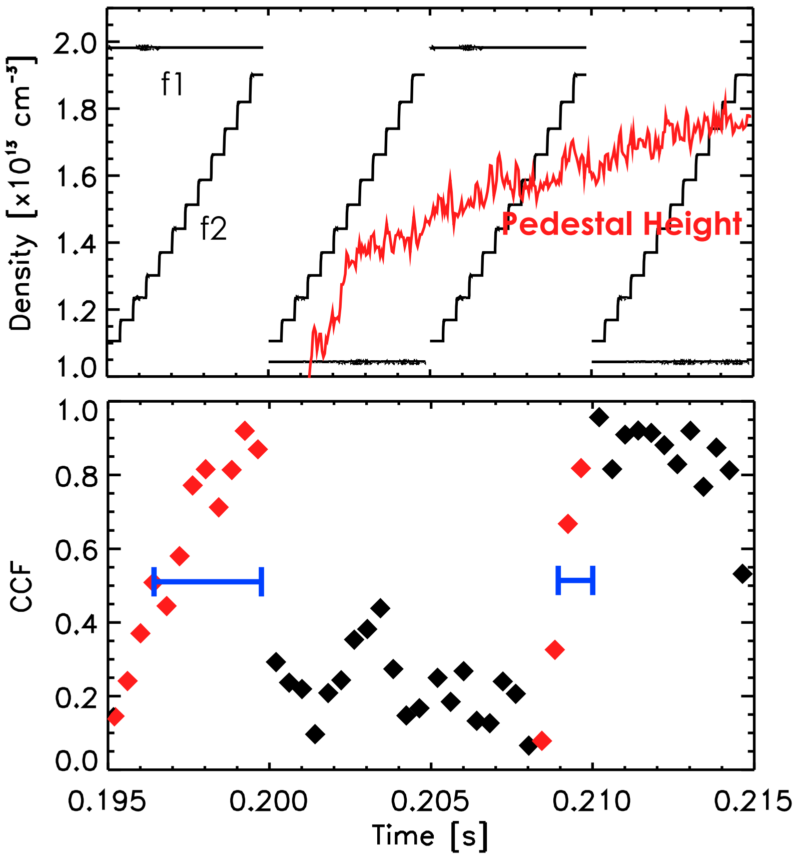


Fixed-Frequency 35 GHz
Spectrogram of Phase



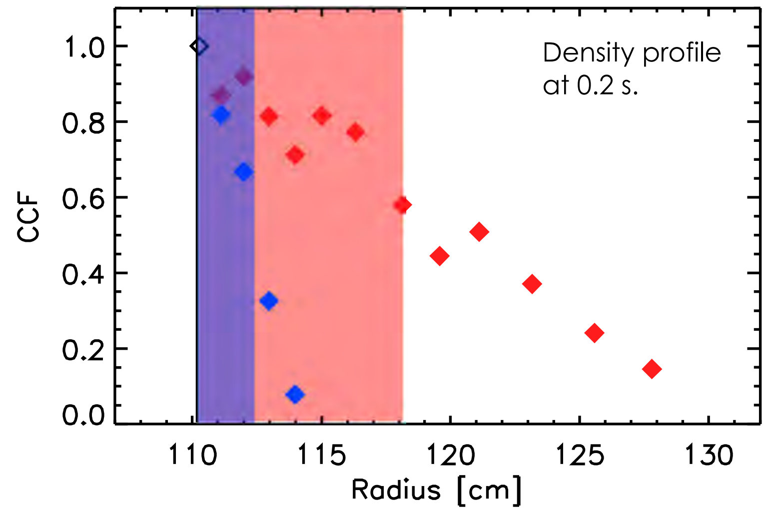
Core Radial Correlation Length at the L-H Transition

One channel of correlation reflectometer stepping in frequency (or density/radius).



CCF Width Decreases by a Factor of >3

CCF vs Major Radius



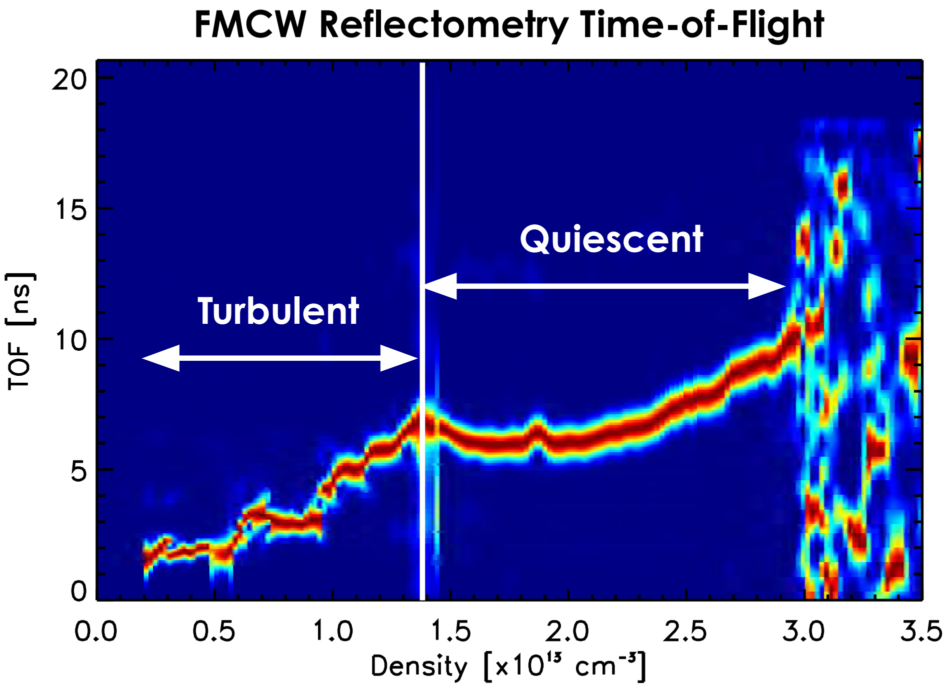
- Core turbulence correlation length decreases by ~3 in H-mode. (Assumption that core profile is the same).
- Reproduces measurements from 2005 but eliminates density ears as the reason for the short correlation.

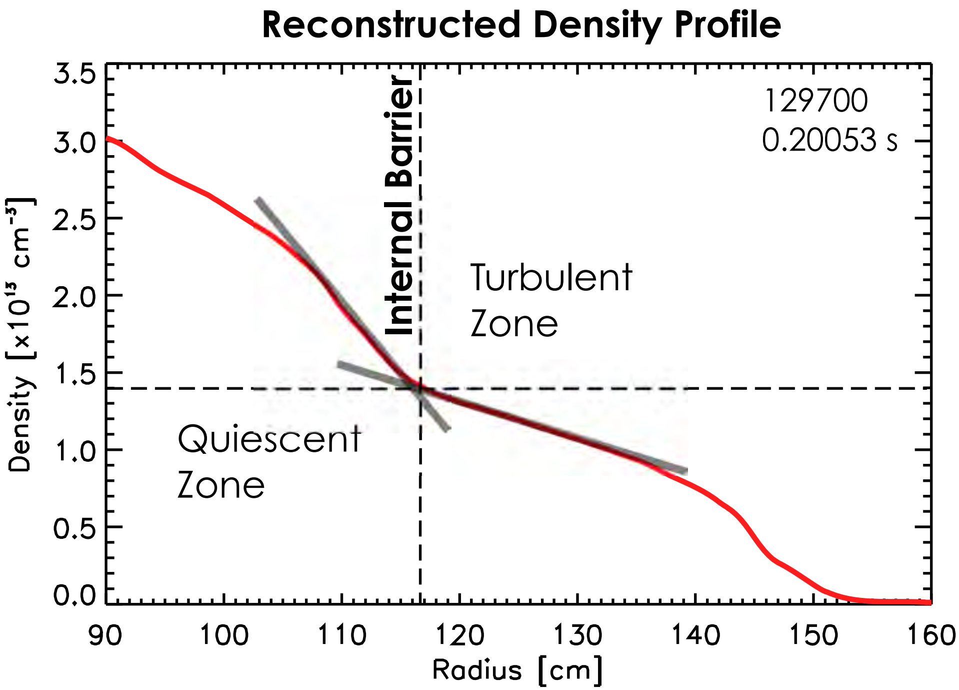
OK for core, but what about edge?

Two New Methods for Looking at Turbulence

- **Need a way to look at edge turbulence with good spatial and temporal resolution:**
  - Interested in fluctuation levels & correlation lengths.
- **Solution is to use the ultra-fast FMCW signal:**
  - (<10 μs) sweeps are fast enough that turbulence is frozen over relevant time or sweep distance.
  - Continuous coverage over nearly entire plasma. Number of frequency channels is "nearly infinite".
- **Method 1: Turbulence Level Estimate from Time-of-Flight**
  - Equivalent to pulsed-radar method.
  - Time-of-flight is extremely sensitive to local gradient near cutoff. (Conventional fixed-frequency signal analysis is sensitive to the equivalent path length).
  - Details of the theory are being developed.
  - **See movie** for examples.
- **Method 2: Quasi-Stationary FMCW Correlation Technique**
  - Method first used by Kurzan et al., PPCF **42** (2000).

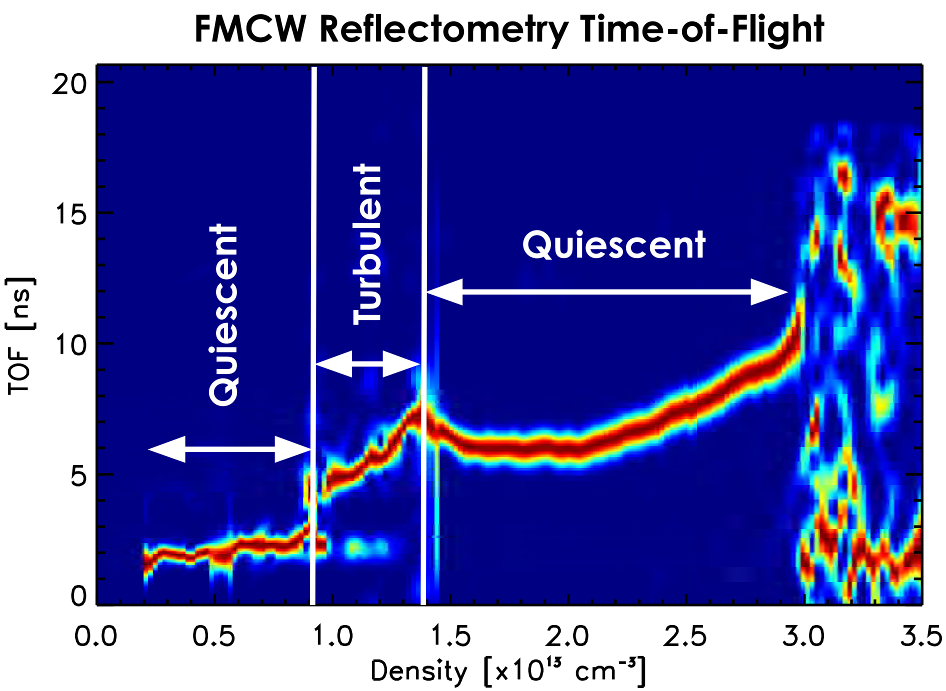
Qualitative Look at Turbulence Profile (Method 1)
Internal Barrier During L-Mode Phase

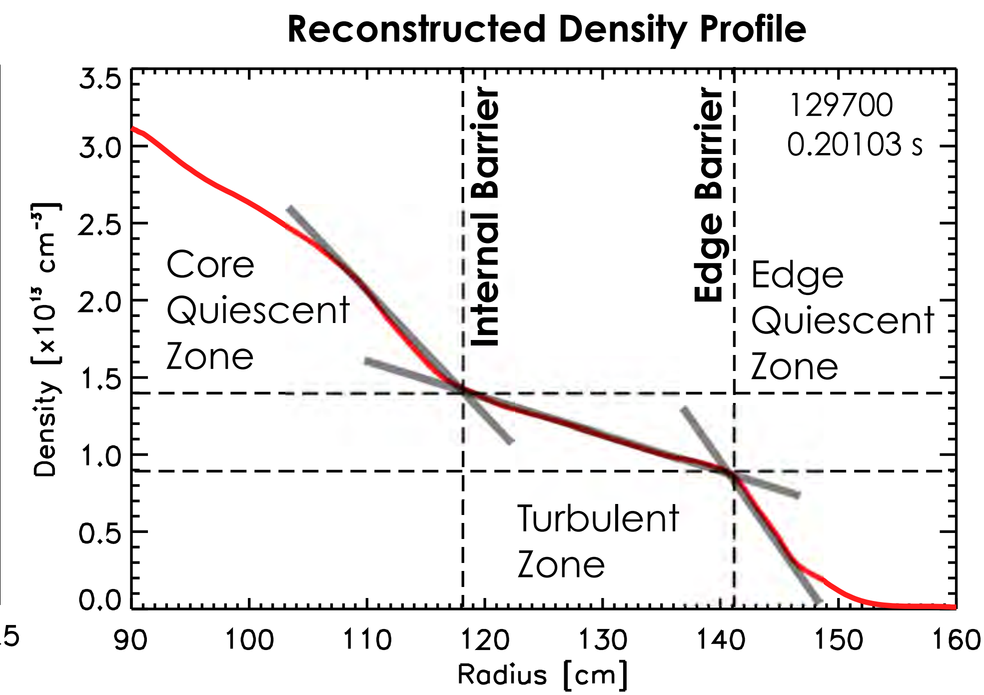




- **FMCW TOF shows internal barrier at ~$1.4\text{x}10^{13}$ cm^{-3} (~117 cm).**
  - Turbulent edge and quiescent core.
  - Density profile changes slope at barrier location.
  - MHD (island) interior to barrier. Not responsible for density flattening.

Qualitative Look at Turbulence Profile (Method 1) Additional Edge Barrier Forms at L-H Transition

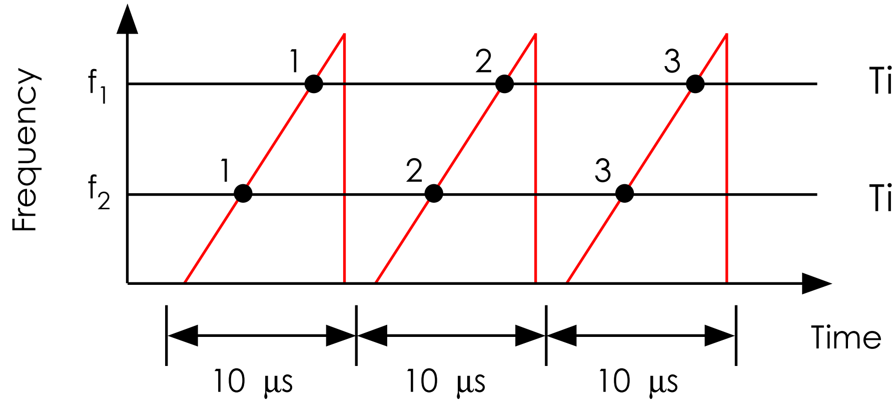




- **FMCW TOF at L-H transition.**
  - Edge density profile steepens.
  - Quiescent edge and core, with turbulent zone in-between.
  - Density profile changes slope at barrier locations.

Outline of Quasi-Simultaneous FMCW Correlation Technique (Method 2)

Step 1:

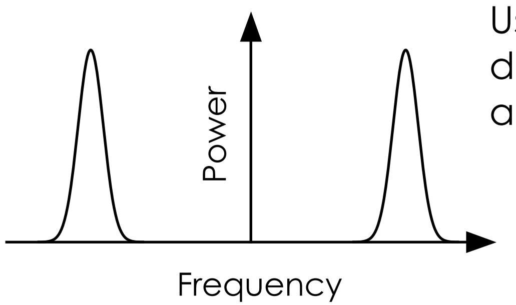


Time series for probe frequency f_1.

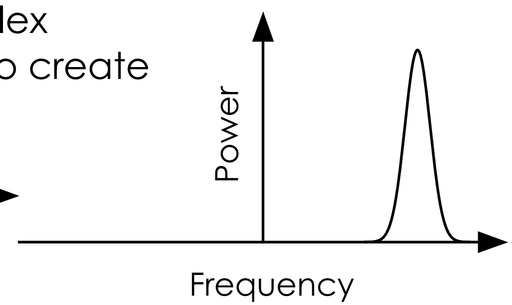
100 kHz equivalent sampling

Time series for probe frequency f_2.

Step 2:



Use CDM (complex demodulation) to create analytic signal.



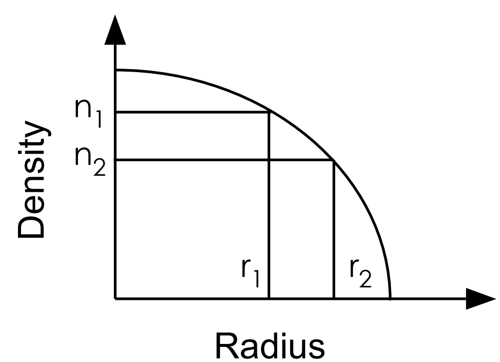
Real homodyne time series: $A(t)\sin(\phi(t))$.

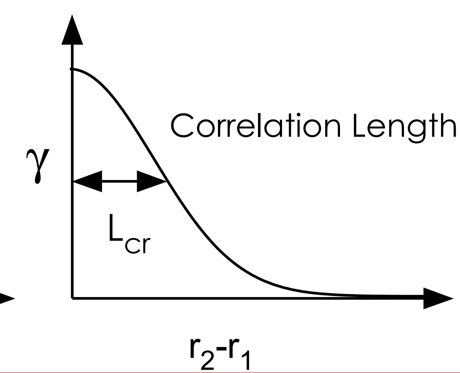
Complex amplitude $E(t)=A(t)\exp(i\phi(t))$.

Step 3:

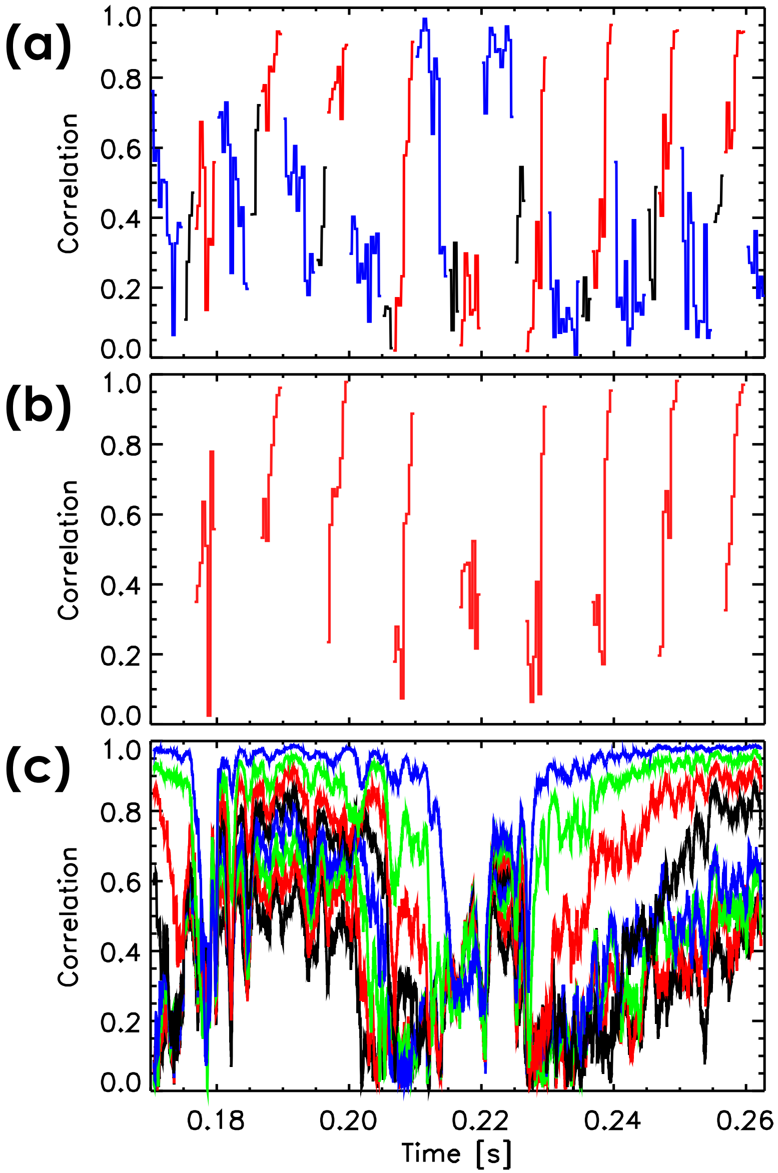
Normalized cross correlation:

$$\gamma = \frac{|\langle E_1 E_2^* \rangle|}{\sqrt{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle}}$$



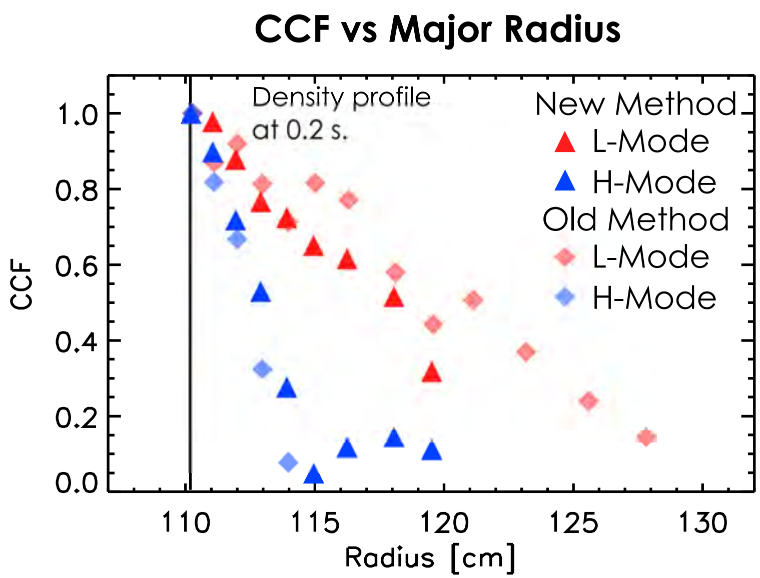


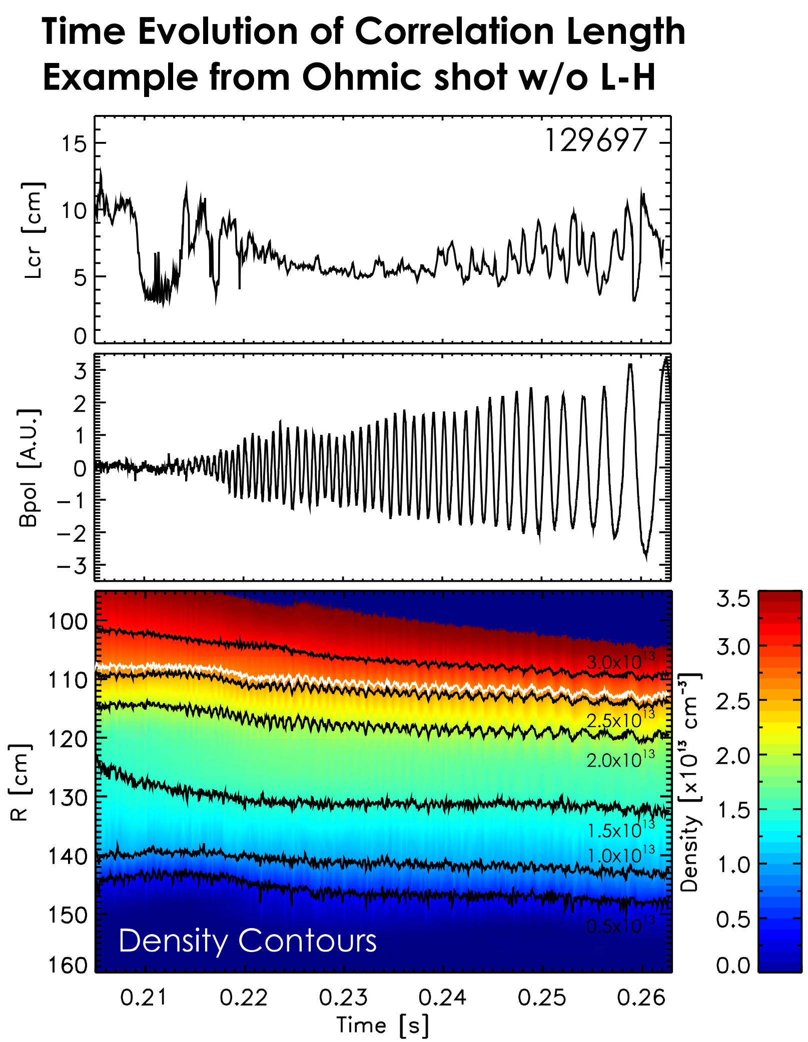
Radial Correlations Using Ultra-Fast Swept FMCW Good Agreement with Correlation Reflectometer



- **(a) Radial cross-correlations from conventional correlation reflectometer.**
  - f1=40.0, f2=39.2, 38.3, 37.5, 36.6, 35.8, 34.9, 34.1, 33.2, 32.4, 31.5, 30.7, 29.8 GHz
  - f1=29.0, f2=39.2, 38.3, 37.5, 36.6, 35.8, 34.9, 34.1, 33.2, 32.4, 31.5, 30.7, 29.8 GHz
- **(b) Radial cross-correlations from FMCW reflectometer.**
  - f1=40.0, f2=39.2, 38.3, 37.5, 36.6, 35.8, 34.9, 34.1, 33.2 GHz
  - Identical analysis as correlation reflectometer data (comparison).
- **(c) Radial cross-correlations from FMCW reflectometer.**
  - f1=40.0, f2=39.2, 38.3, 37.5, 36.6, 35.8, 34.9, 34.1, 33.2, 32.4, 31.5, 30.7, 29.8 GHz

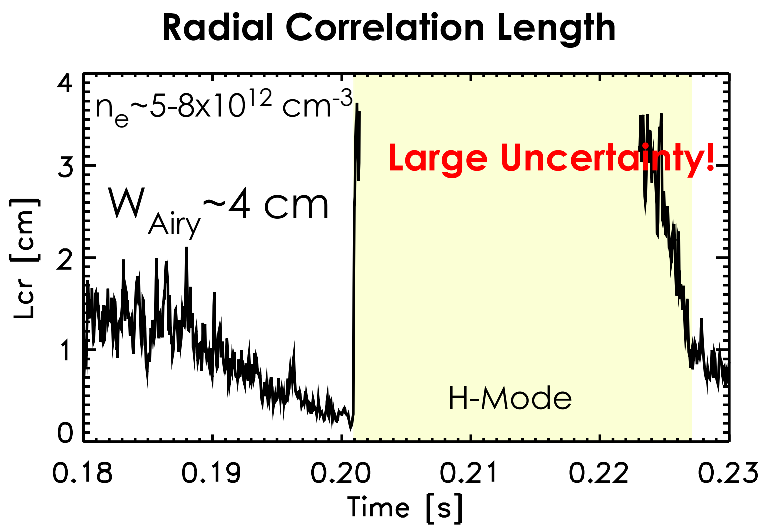
Core Radial Correlation Length Comparisons (Conventional vs New)

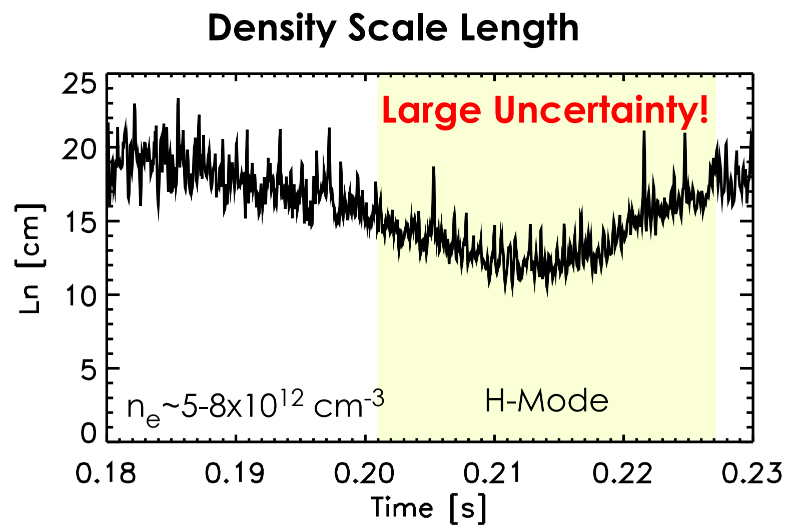




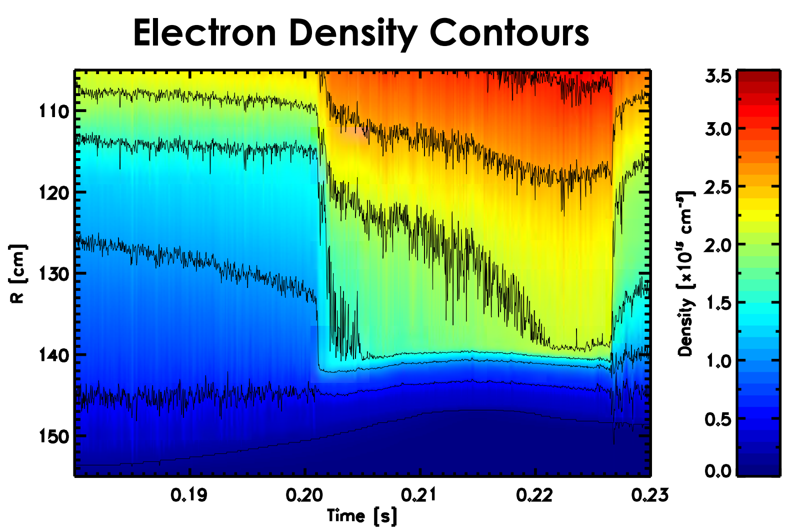
- **Conventional and new techniques agree extremely well.**
- **Slight discrepancy for L-mode case:**
  - Turbulence may be evolving over sweep time.
  - Problem if correlation length is too long or turbulence decorrelation time is too short.

First Look at Edge Correlation Lengths





- **General trends:**
  - Edge density steepening, L_{cr} decreasing near L-H transition.
- **Uncertainties:**
  - Edge profile reconstruction, especially during H-mode.
  - This issue will be addressed with the addition of an edge X-mode channel (sweep from zero density).

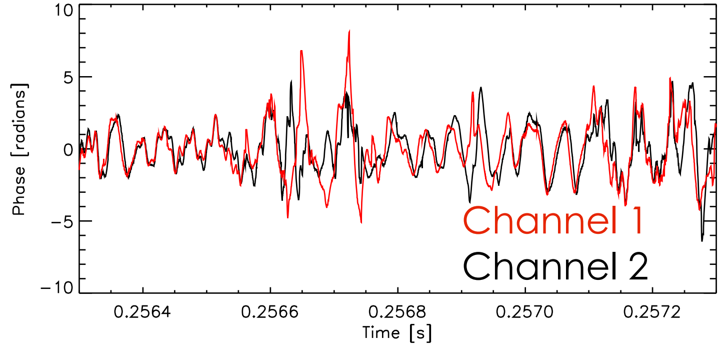


Summary and Future Work

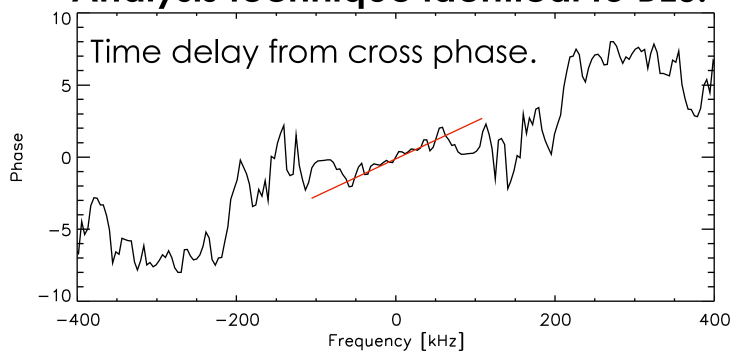
- **Summary**
  - Two new techniques with the promise of better time resolution and spatial coverage were used for measuring edge and core turbulence characteristics.
  - Profile and turbulence evolution across the L-H transition in Ohmic H-modes investigated.
  - Evidence of internal barrier formation in L-mode phase. Edge barrier appears at L-H transition, with turbulent zone in-between
  - While some preliminary numbers on radial correlation lengths have been indicated, it should be pointed out that all analysis presented thus far is highly qualitative.
  - Full-wave codes used on various turbulence models are necessary for any quantitative estimates.
- **Additional Future Work**
  - Application of these techniques to study core plasmas in NSTX.
  - Possible to apply these techniques to existing reflectometer data on DIII-D for ST/conventional-A tokamak comparison?
  - Poloidal correlation reflectometer to investigate the connection between shear flows and turbulence in the ST.

Future Work Will Involve Velocity Measurements Using the Poloidal Correlation Reflectometer

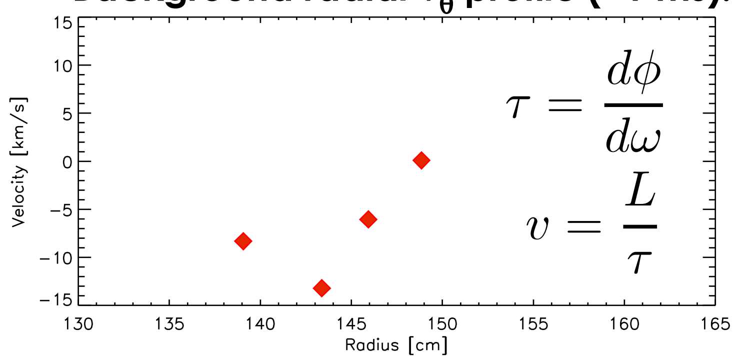
NSTX example: H-mode shot 124645.



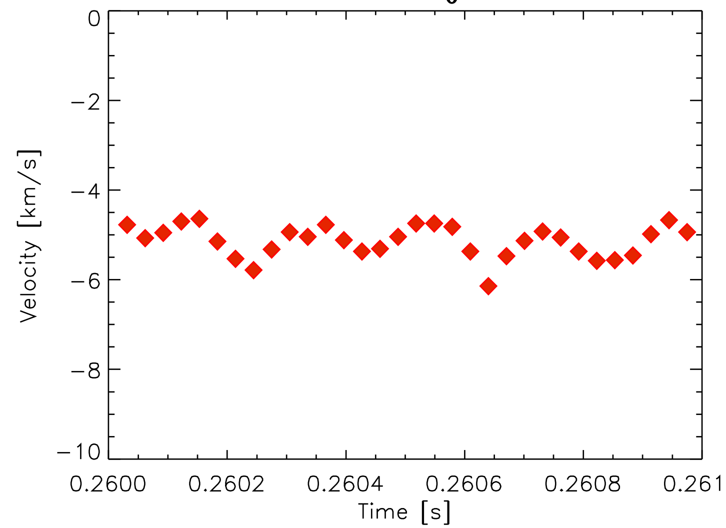
Analysis technique identical to BES.



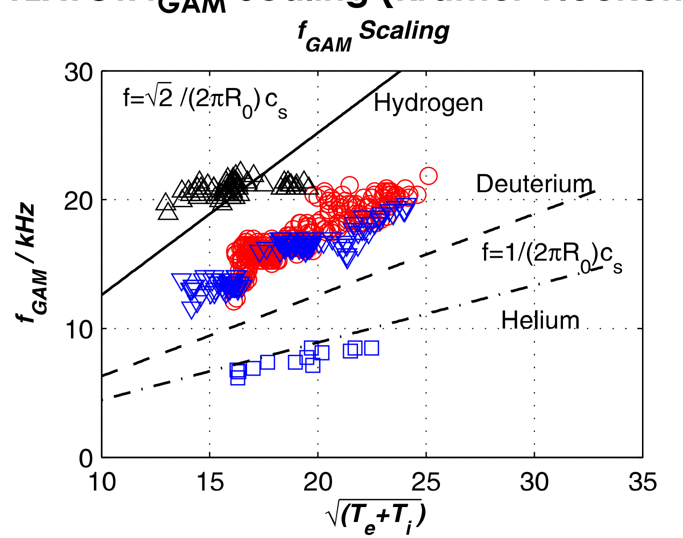
Background radial v_θ profile (~1 ms).



Time Evolution of v_θ (Preliminary)



TEXTOR f_{GAM} Scaling (Kramer-Flecken)



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