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Turbulence Radial Correlation Length Measurements in the Core of NSTX

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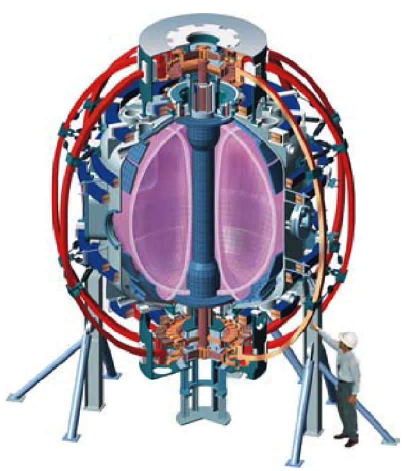

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Abstract

Turbulence Radial Correlation Length Measurements in the Core of NSTX[1] S. KUBOTA, W.A. PEEBLES, N.A. CROCKER, X.V. NGUYEN, UCLA, D.R. MIKKELSEN, R.E. BELL, S.M. KAYE, B.P. LEBLANC, A.L. ROQUEMORE, PPPL, J. CANDY, R.E. WALTZ, General Atomics, M. GILMORE, UNM — Assessment of ion thermal transport via TRANSP as well as linear gyrokinetic stability analyses have suggested that long-wavelength ($k_\theta \rho_i \leq 1$) ITG-like turbulence may be strongly suppressed in the ST. The first direct measurements of long-wavelength turbulence in the core of NSTX have been made using homodyne radial correlation reflectometry. The system has a frequency coverage of $26-40$ GHz (0.84 to 2.0×10^{13} cm^{-3} in O-mode) and has been used to measure turbulence radial correlation lengths in the core ($r/a \sim 0.2-0.8$) of low beam power, L-mode discharges. Scans were performed to observe the scaling of the turbulence and confinement properties: B_t and I_p were varied simultaneously (constant q, ρ^* scan) and independently. Initial analyses indicate correlation lengths in the range of 5-15 cm and decreasing with increasing local magnetic field strength. Comparisons will be made with nonlinear gyrokinetic simulations using the GYRO code.

[1]Supported by U.S. DoE Grant DE-FG03-99ER54527.

Background and Motivation

- In the spherical torus (ST), it has been predicted that core transport due to long wavelength turbulence (ITG, TEM - $k_\theta \rho_s \leq 1$) may be suppressed by increased $E\mathrm{x}B$ shear, T_i/T_e ratio and gradient β effects. Gyrokinetic linear stability analyses of existing NSTX data suggest the growth rate of these modes can be small.

- Assessment of thermal transport via TRANSP for beam-heated discharges on NSTX often indicate low levels for the ion channel.

- Experimentally, direct measurements of turbulence have been carried out in the edge using GPI, the fast reciprocating probe, reflectometry, interferometry, etc. These measurements all show large levels of long wavelength turbulence.

- Recently, correlation reflectometry has been used to measure turbulence radial correlation lengths in the core of peaked moderate density profiles of NSTX L-mode discharges. ***These are the first quantitative measurements of correlation lengths in the core of the ST.***

Goals and Poster Content

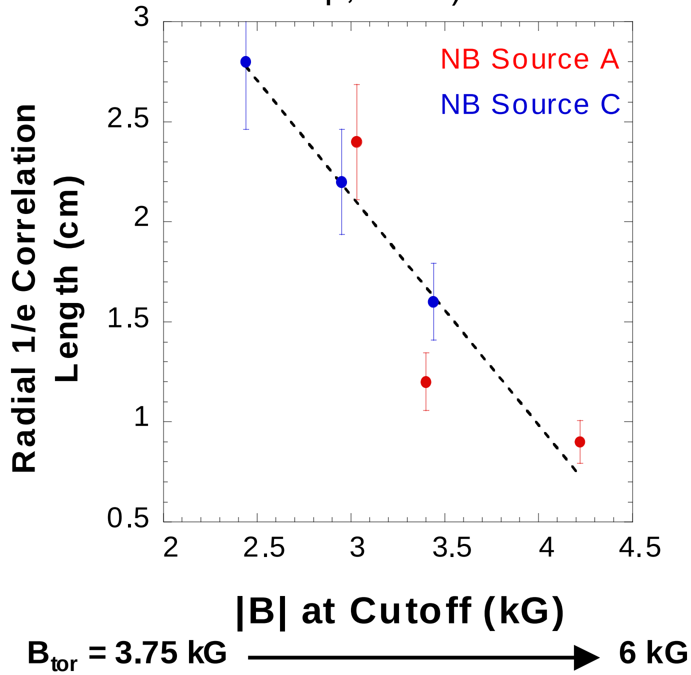
- Short and long term goals:
  - For various discharge conditions, measurement and characterization of **radial correlation lengths** and **fluctuations levels** (N.A. Crocker, JP1.022) using reflectometry.
  - Relation between correlation lengths and confinement properties.
  - Detailed comparison of correlation lengths with those predicted by GYRO (D.R. Mikkelsen, JP1.020).

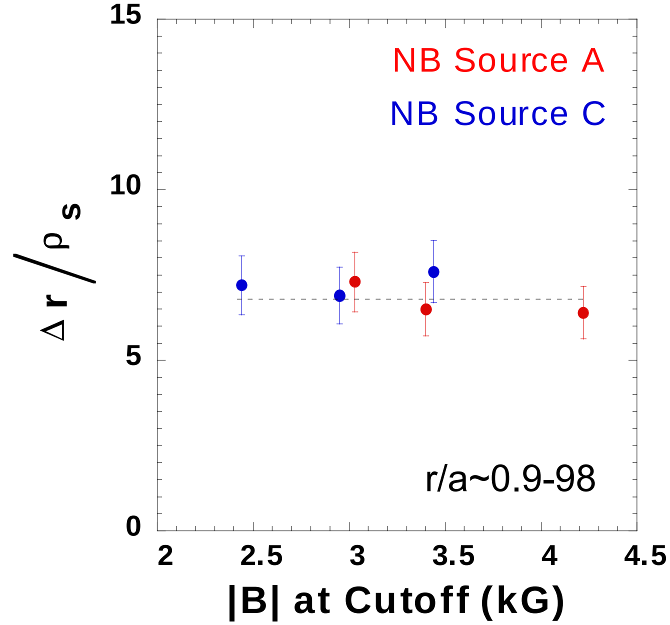
- Poster Content
  - Details of the homodyne radial correlation reflectometer hardware and data analysis method.
  - Initial measurements for low-density L-mode discharges with NB-heating.
  - Analysis of data from attempted ρ^* scan.
  - Effects of fast-ion induced MHD for NB-heated shots on correlation length measurements.
  - Summary and future work.

Previous Measurements with 20-30 GHz Reflectometer

NSTX

(M. Gilmore, US-EU TTF Workshop, 2003)

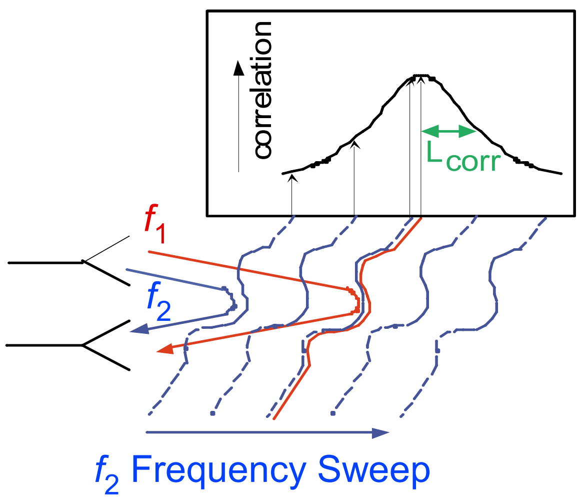




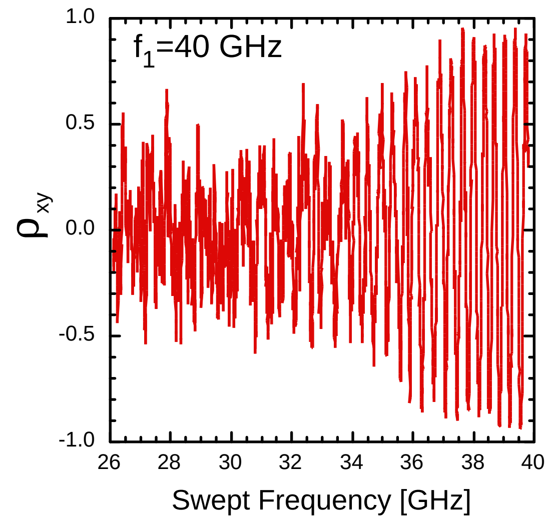
- Measurements utilized 20-30 GHz microwave source (cutoff density ~0.50-1.1x10^{13} cm^{-3}).
- Homodyne radial correlation reflectometry.
- NBI heated low-density L-mode plasmas.
- Cutoff layers (30 GHz) 4-8 cm inside LCFS.
- Fluctuation frequencies 20-500 kHz correlated.

Principle of Homodyne Radial Correlation Reflectometry

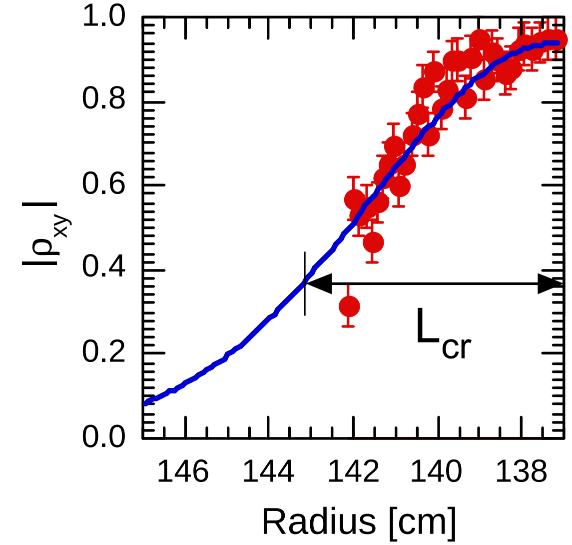
Principle of Radial Correlation Length Measurements



Correlation Coefficient Function vs Swept Frequency



Correlation Coefficient Function Envelope vs Radius



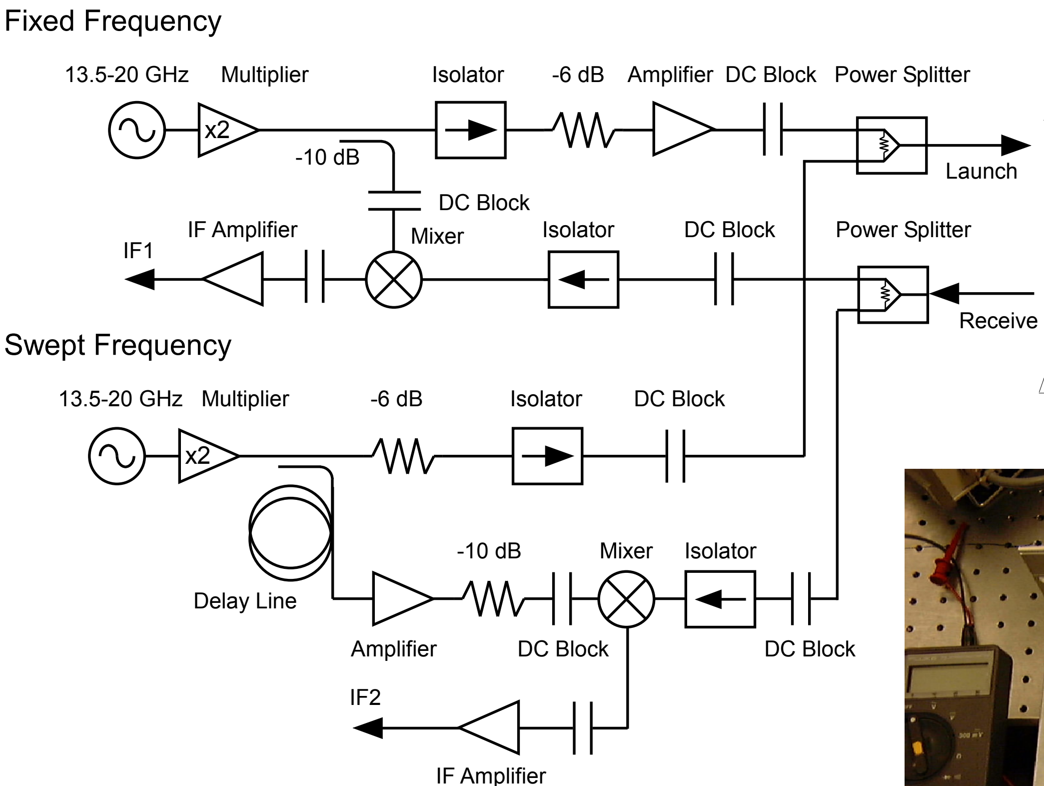
- Fixed frequency f_1 and swept frequency f_2 with identical launch and receive horns reflect from different cutoff layers in the plasma.
- **Correlation coefficient function** of homodyne signals x and y is modulated by the swept DC phase of f_2.

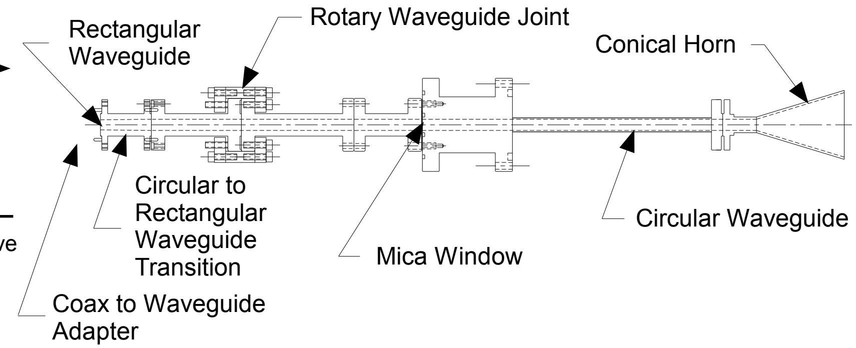
$$\rho_{xy} = \frac{\langle (x - \langle x \rangle)(y - \langle y \rangle) \rangle}{\sqrt{\langle (x - \langle x \rangle)^2 \rangle} \sqrt{\langle (y - \langle y \rangle)^2 \rangle}}$$

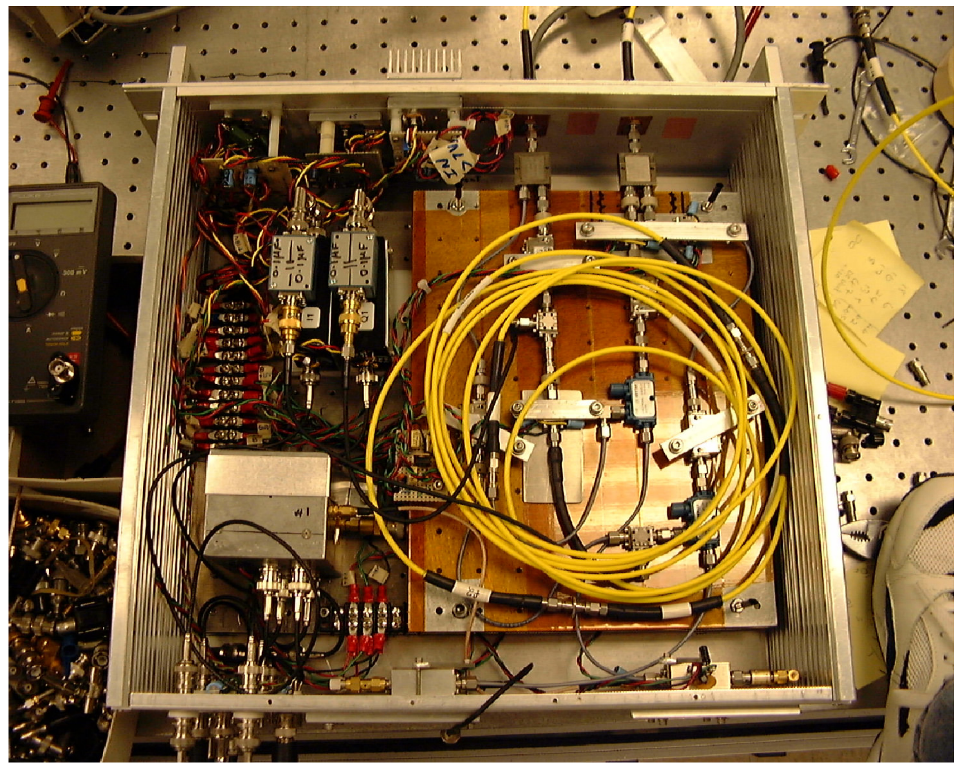
- Envelope of correlation coefficient function mapped from from frequency to radial position using density profiles from Thomson scattering.
- Correlation length L_{cr} is defined here as the *e*-folding distance of the correlation coefficient function envelope (best fit to Gaussian).

Details of Current Reflectometer Hardware

NSTX

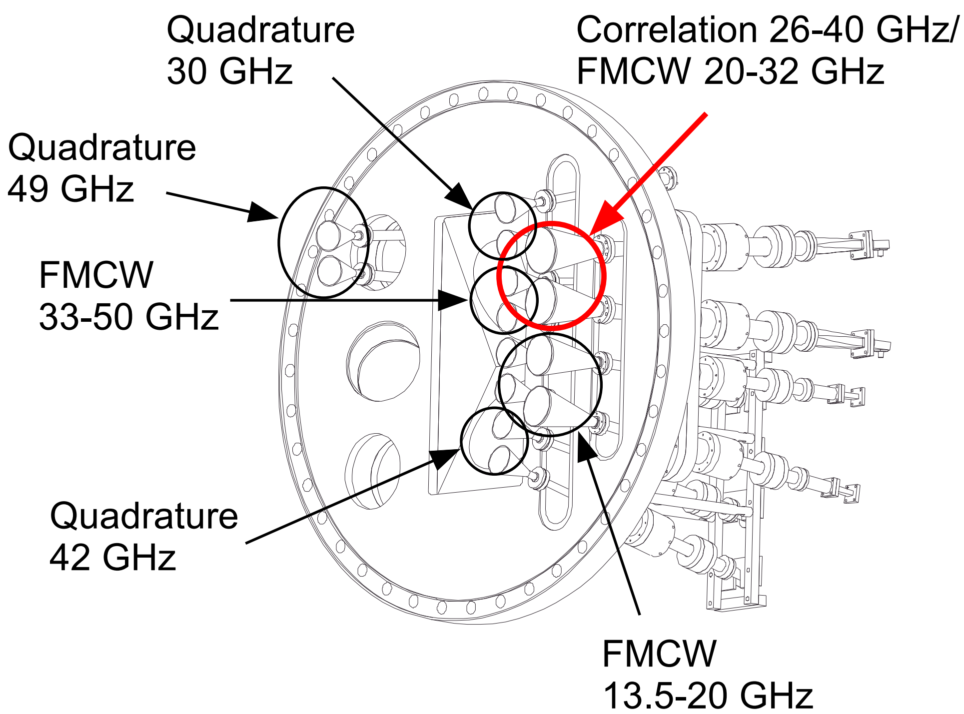


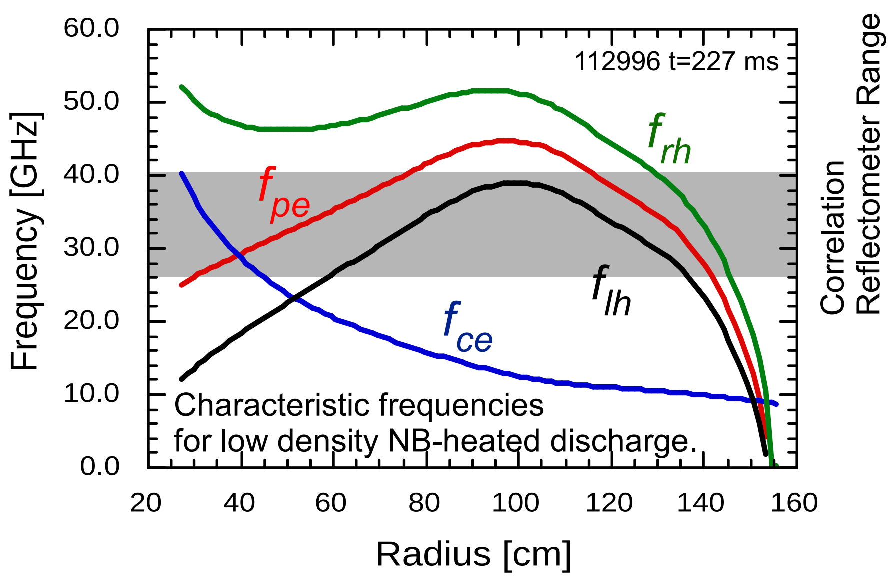


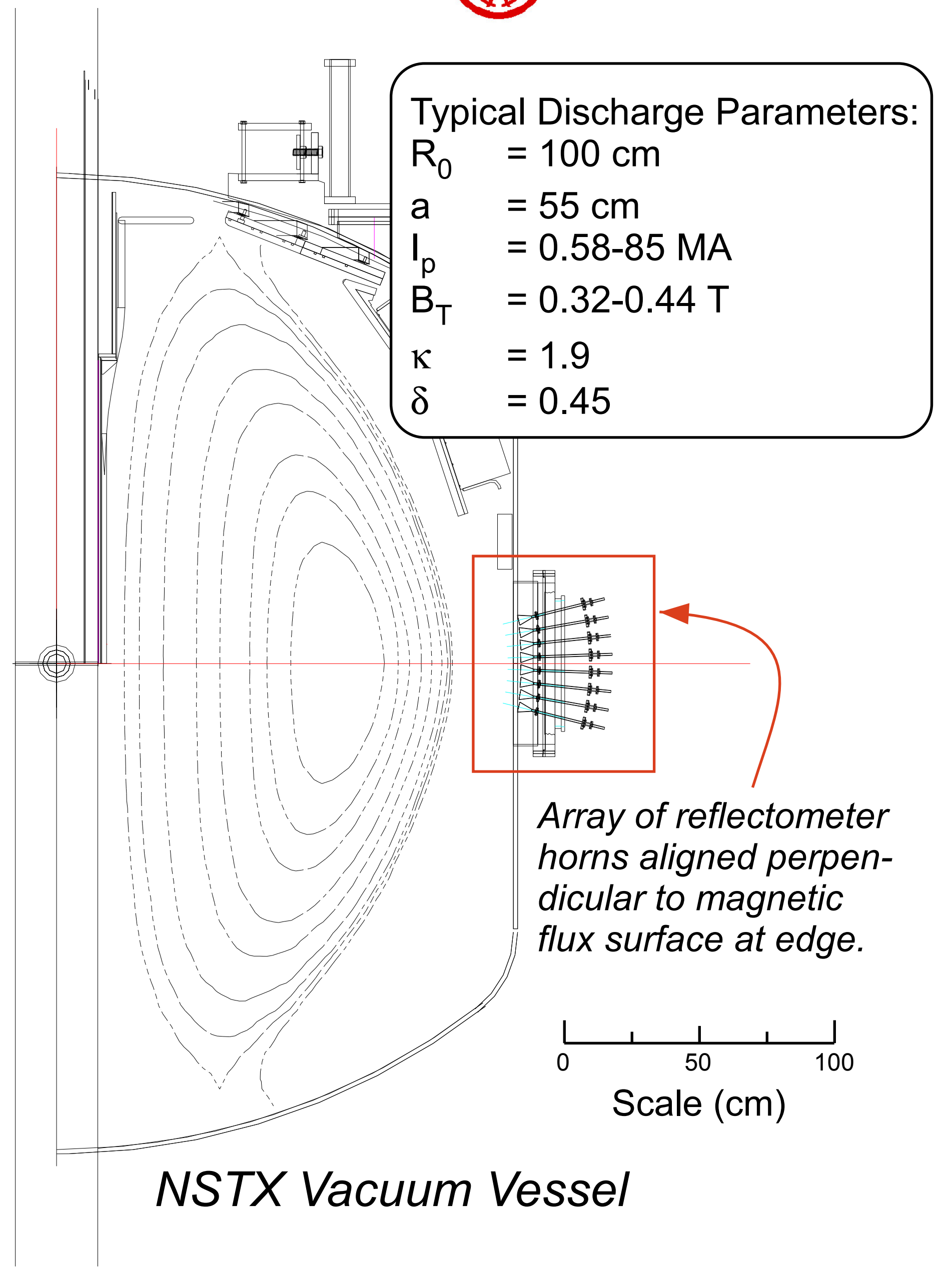


- 26-40 GHz, n_{cr}~0.85-2.0×10^{13} cm^{-3}.
- Voltage-controlled HTOs for fast sweep rates.
- Both source and DAQ (8 MSa/s) PC-controlled.
- ~14 ft of coaxial cable (roundtrip) between equipment and machine.
- Launch and receive polarization determined via rotary waveguide joint.

Reflectometer Diagnostics at NSTX Midplane

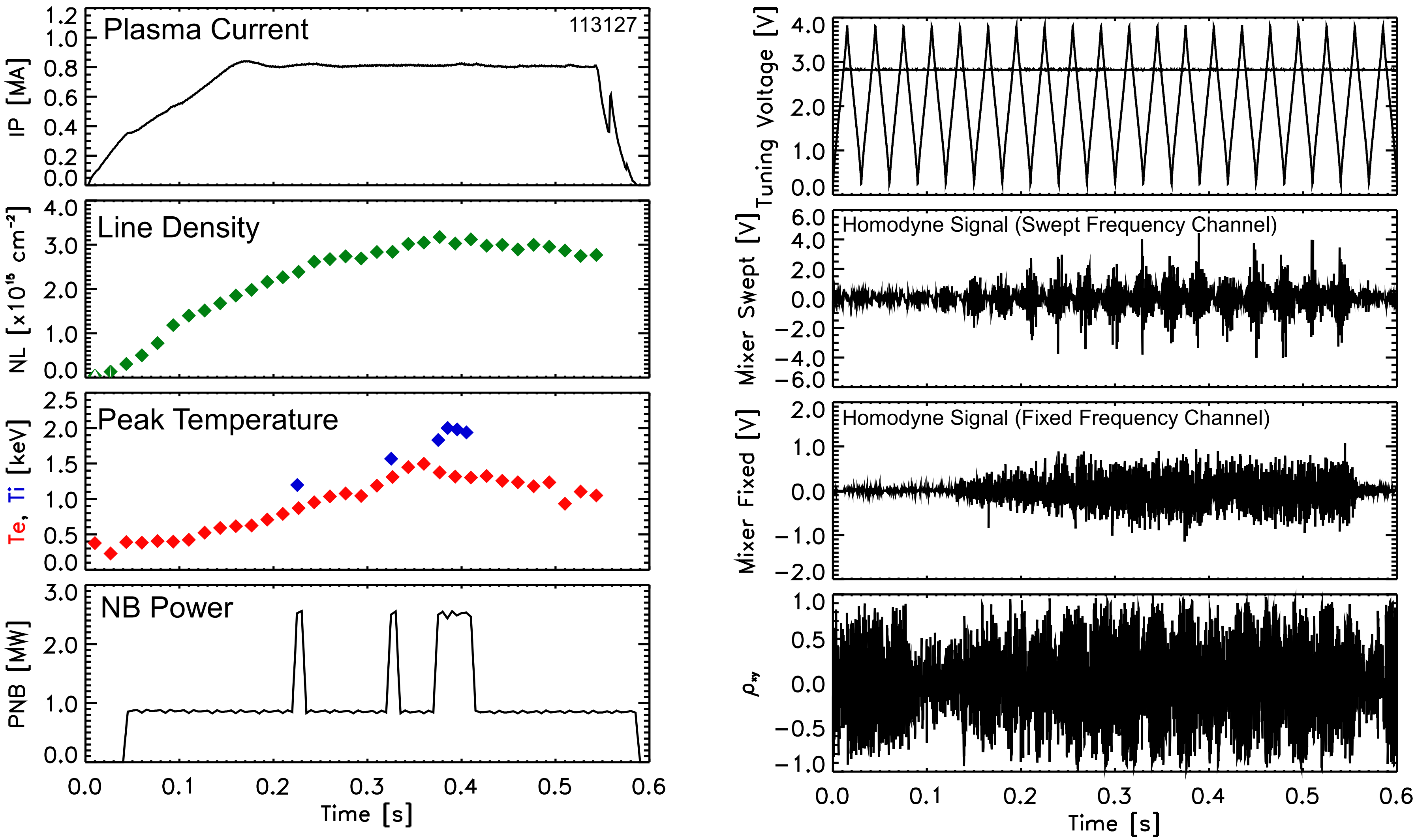




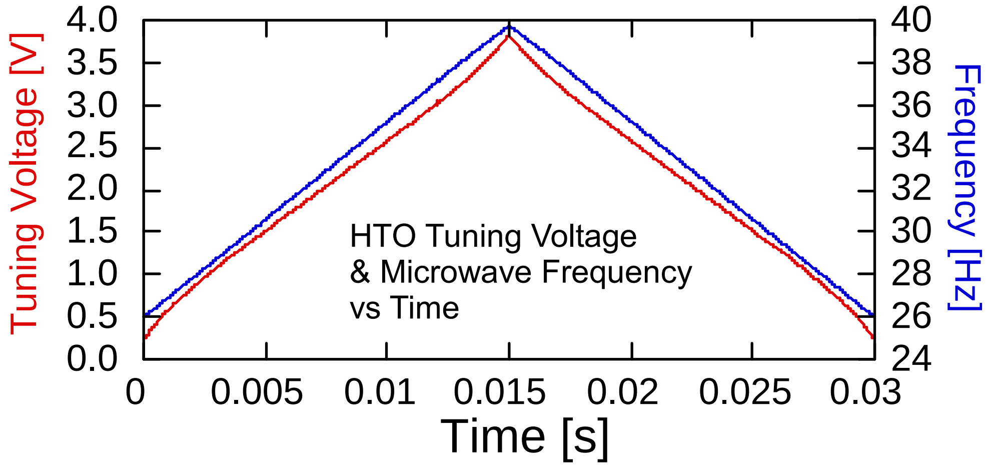


Discharge Waveforms and Reflectometer Signals

NSTX



Frequency Sweep Linearization & Path Length Adjustment



$$\frac{d\phi}{dt} = 2\pi \frac{\Delta L}{c}\frac{df_{\rm rf}}{dt}$$

ΔL = difference between probe and reference paths

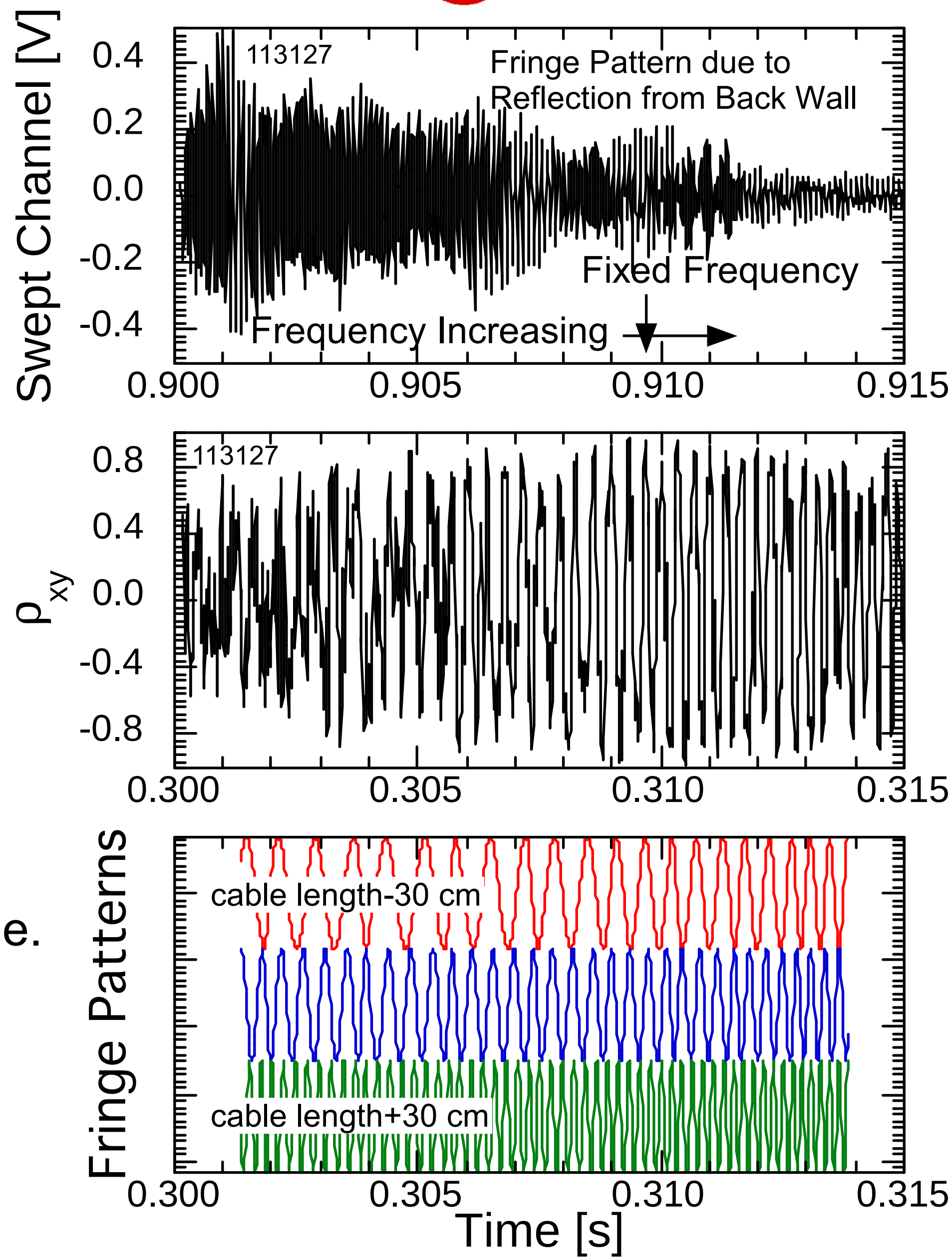
$f_{\rm rf}$ = microwave frequency

$\cos\phi$ = fringe pattern of ρ_{xy}

- Reference path length L_r is fixed. Probe path length L_p depends on transmission line (coaxial cable or L_t) and plasma profile.

$$\Delta L(f_{\rm rf}) = \underbrace{2\int_{r_a}^{r_c} \mu(r, f_{\rm rf})dr}_{\text{plasma contribution}} + L_t(f_{\rm rf}) - L_r(f_{\rm rf})$$

- Number of fringes per full band sweep adjusted by varying cable length.



Details of L_{cr} Estimates and Normalizations

NSTX

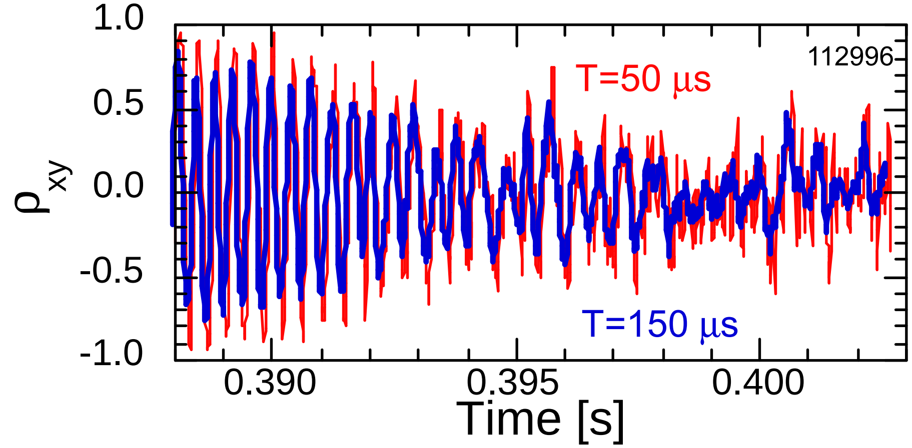
- Averaging window T for ρ_{xy} must be small to catch fringe pattern (T~50 μs). Larger T reduces variance but smooths peaks.
- Significant fringe peaks identified by height and spacing.
- Error in L_{cr} can be several cm from uncertainty in MPTS measurements.
- For L_{cr} of several cm, background n_e, T_e , T_i, and B profiles can change significantly over this distance. For gyroradius normalization, these values are taken at the midpoint radius between the the fixed frequency cutoff and the 1/e location.
- For L_{cr} estimates, an alternative to ρ_{xy} is the **coherency function** γ_{xy}:

$$\gamma_{xy}^2(f) = \frac{\left|\langle G_{xy}(f)\rangle\right|^2}{\langle G_{xx}(f)\rangle\langle G_{yy}(f)\rangle} \qquad \overline{\gamma}_{xy}^2 = \frac{\int \gamma_{xy}^2(f)\langle G_{xx}(f)\rangle df}{\int \langle G_{xx}(f)\rangle df}$$

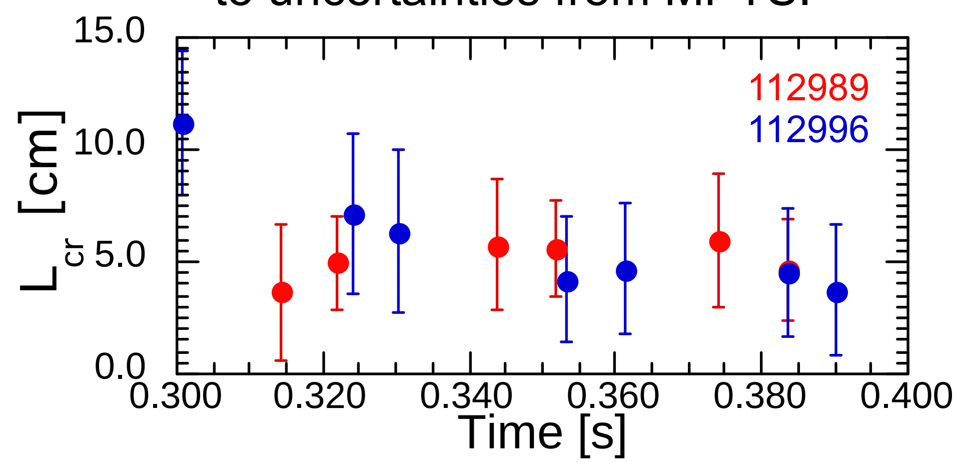
Since good time resolution is required to resolve fringe peaks, ρ_{xy} is used exclusively here.

- Airy width w_{Airy}=0.48 $L_n^{1/3}\lambda_0^{2/3}$~1 cm.

Effect of averaging window T.

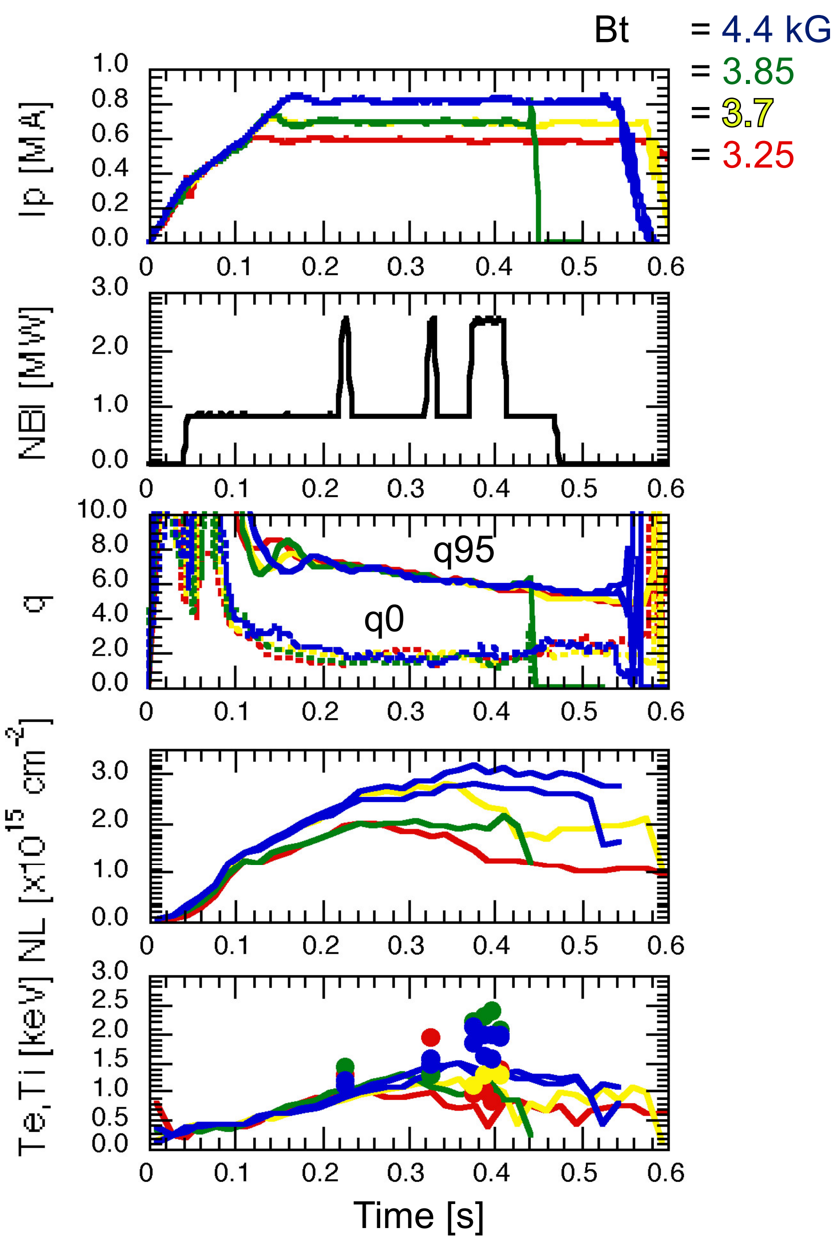


Typical error bars in L_{cr} due to uncertainties from MPTS.

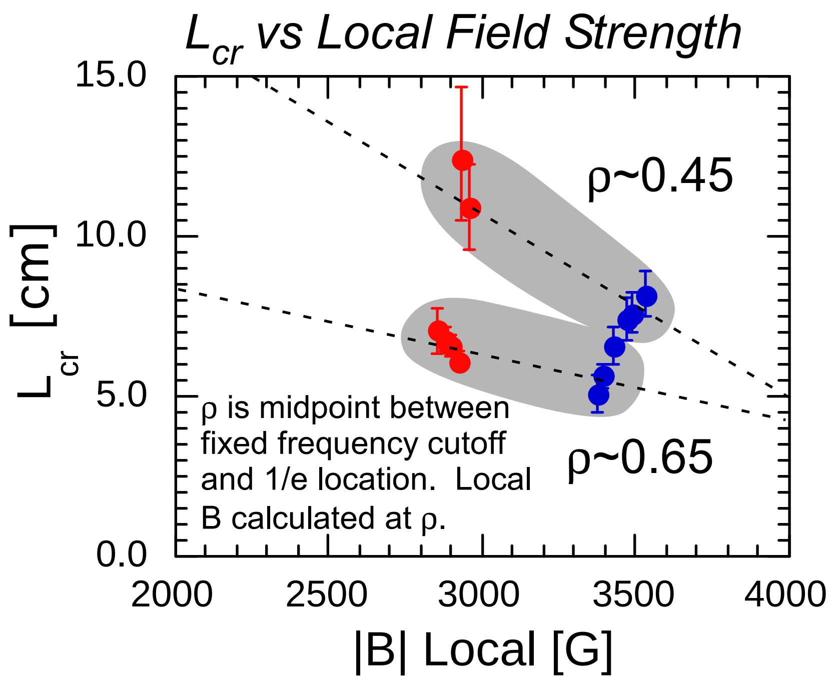


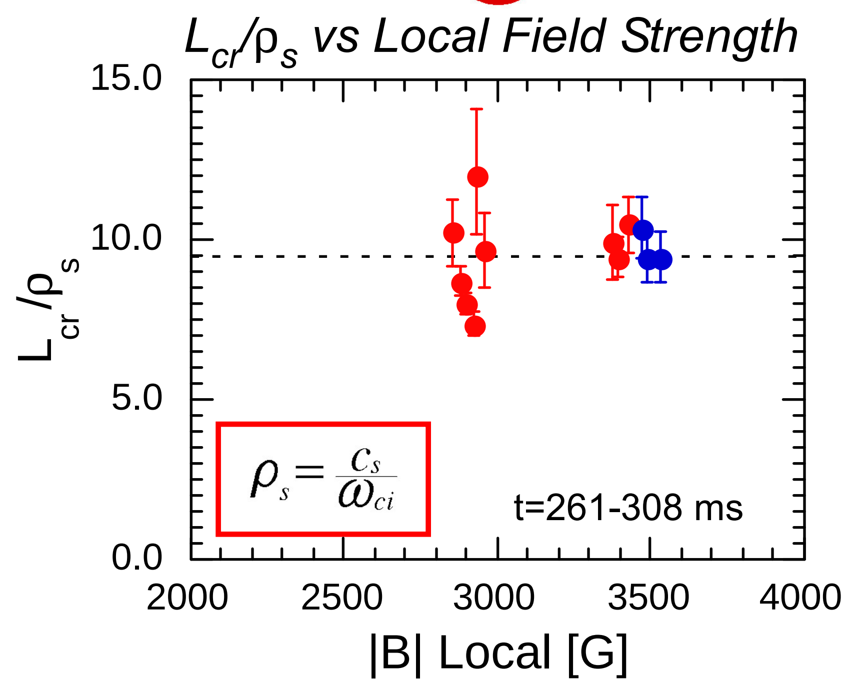
Experimental Conditions for ρ* Scan

- Various scans were performed:
  - ρ* scan at constant q: B_t=3.25-4.4 kG with corresponding I_p=580-850 kA.
  - I_p Scan at fixed B_t=4.4 kG: I_p=680-850 kA.
  - B_t Scan at fixed I_p=680 kA: B_t=3.7-4.4 kG.
- Scan of radial location by changing fixed frequency of correlation reflectometer: 30, 35, and 40 GHz (n_{cr}=1.1, 1.5 and 2.0x10^{13} cm^{-3}).
- Shots with similar profiles at different conditions were difficult to find.
  - At lower B_t, MHD and beam-driven instabilities (fishbones, TAEs, CAEs?) a problem.
  - Collapse of T_e and n_e due to pressure peaking during middle of discharge.
- Three comparisons presented here:
  - ρ* scan: B_t=3.7 and 4.4 kG, ρ~0.45 and 0.65.
  - ρ* scan: B_t=3.25, 3.85 and 4.4 kG, ρ~0.7.
  - Radial scan for B_t=4.4 kG, I_p=850 kA.

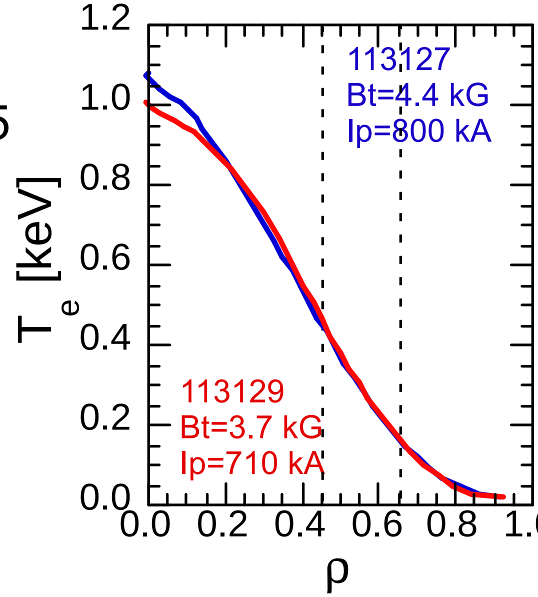


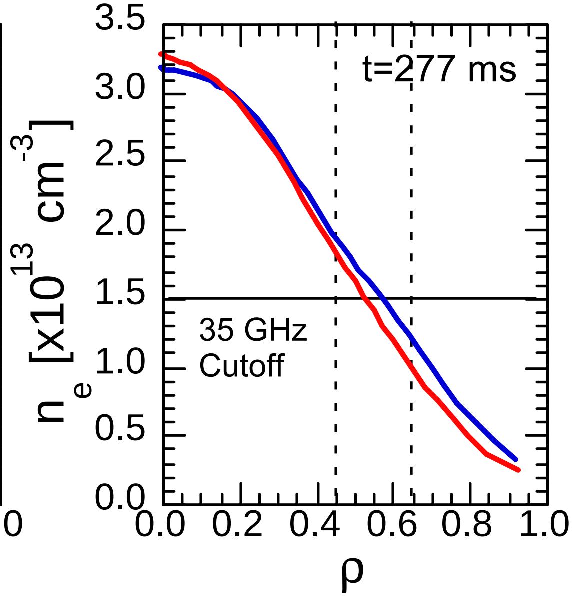
ρ^* Scan: L_{cr}~5-12 cm at ρ~0.45 and 0.65



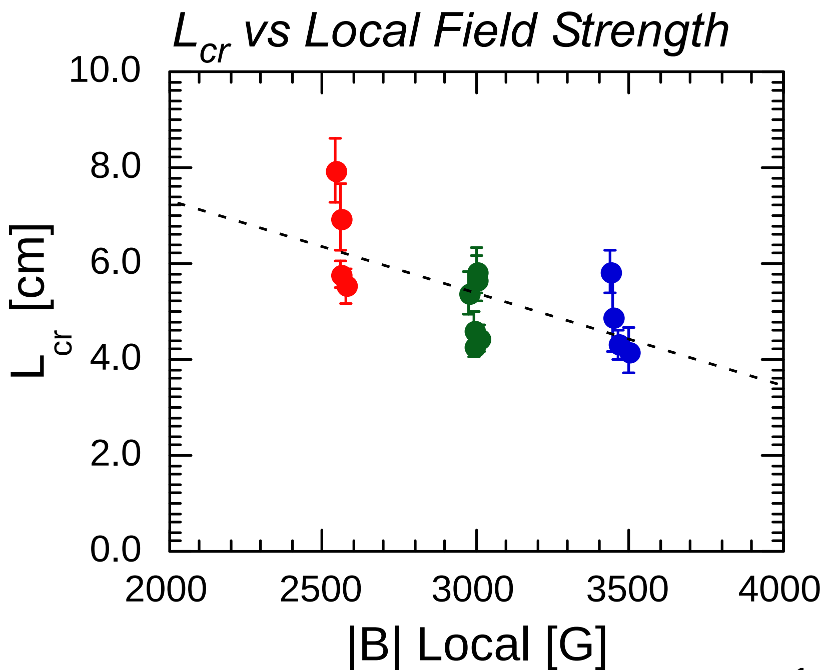


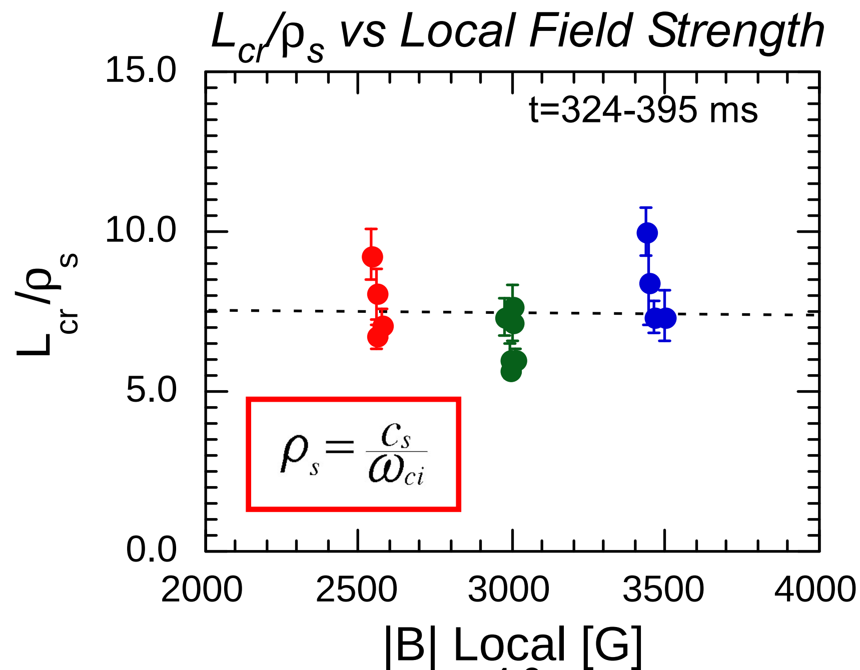
- B_t=3.7 and 4.4 kG, f_{fixed}=35 GHz.
- L_{cr} ranges from 5-12 cm at ρ~0.45 and 0.65; L_{cr} increases inversely with ρ and B.
- L_{cr} normalized by ρ_s is roughly constant (~9-10).
- Measurement location (ρ) is taken as midpoint between fixed frequency cutoff and 1/e location.



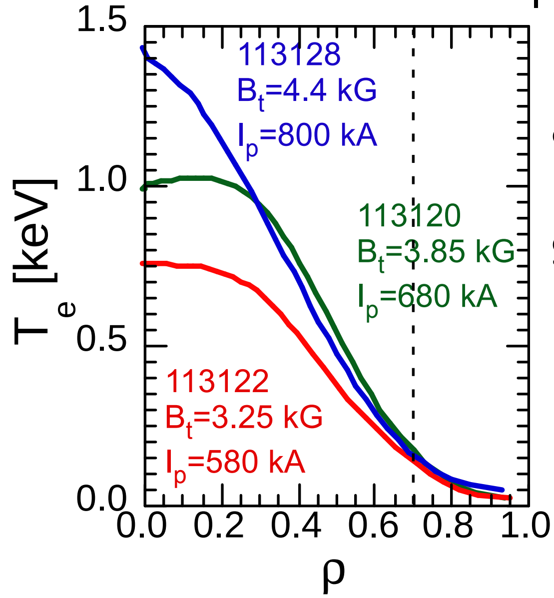


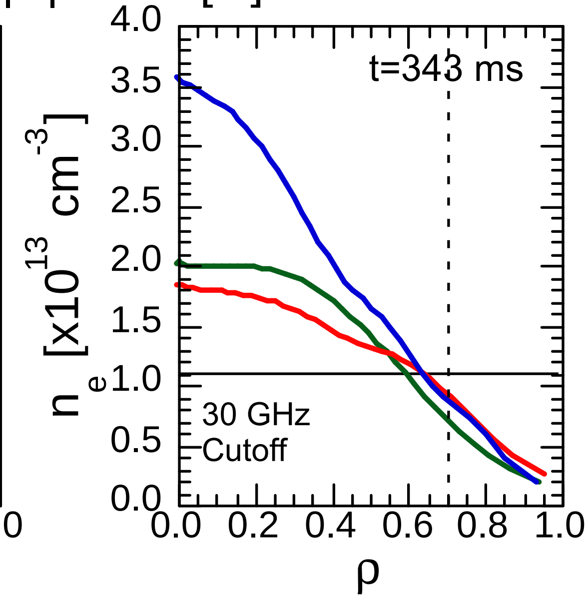
ρ* Scan: L_{cr}~4-8 cm at ρ~0.7





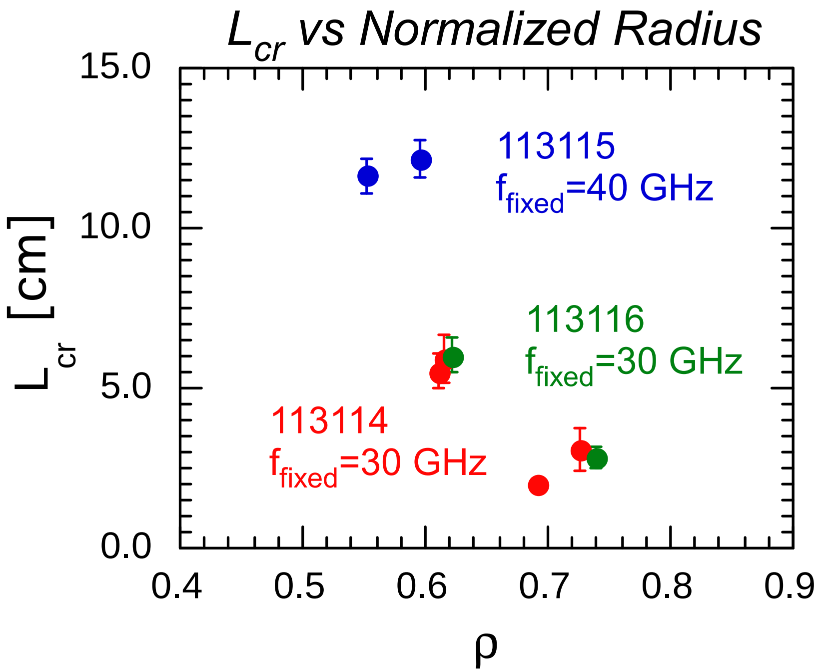
- B_t=3.25, 3.85 and 4.4 kG, f_{fixed}=30 GHz.
- L_{cr}~4-8 cm at ρ~0.7.
- L_{cr} increases inversely with B.
- L_{cr} normalized by ρ_s is roughly constant (~7-8).

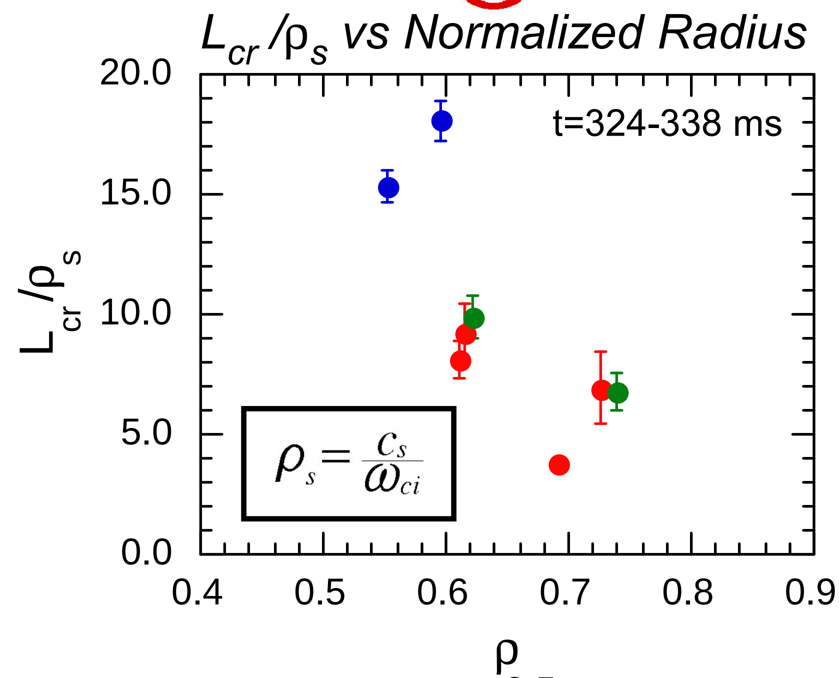




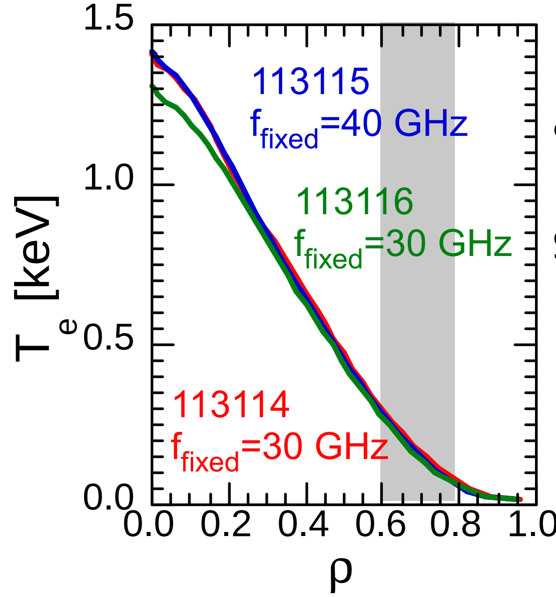
Radial Scan: L_{cr}~2-12 cm at ρ~0.55-0.75

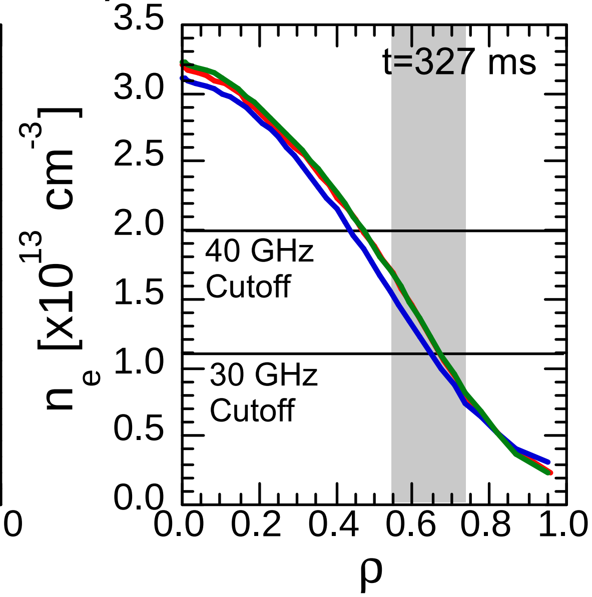
NSTX





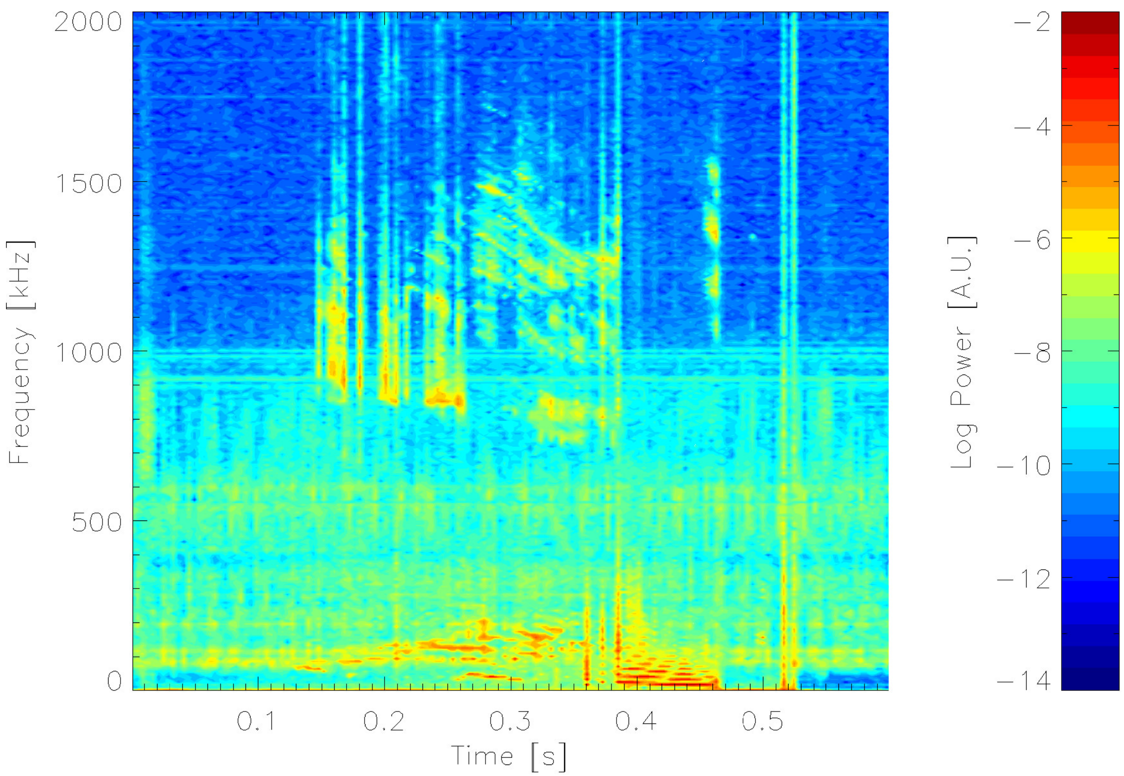
- B_t=4.4 kG, I_p=850 kA, f_{fixed} at 30 and 40 GHz.
- L_{cr} ranges from 2-12 cm over radius of ρ~0.55-0.75.
- L_{cr} increases inversely with ρ.
- L_{cr}/ρ_s varies from 4-18 over this range.

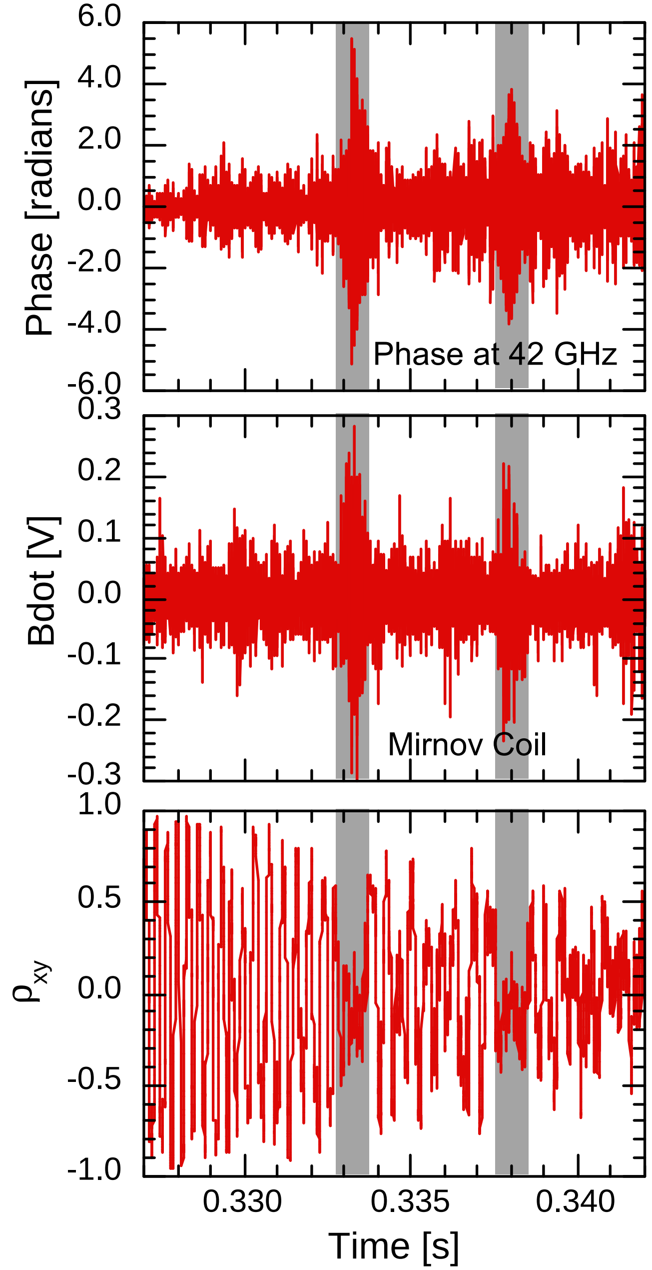




Effect of Fast Ion Induced MHD

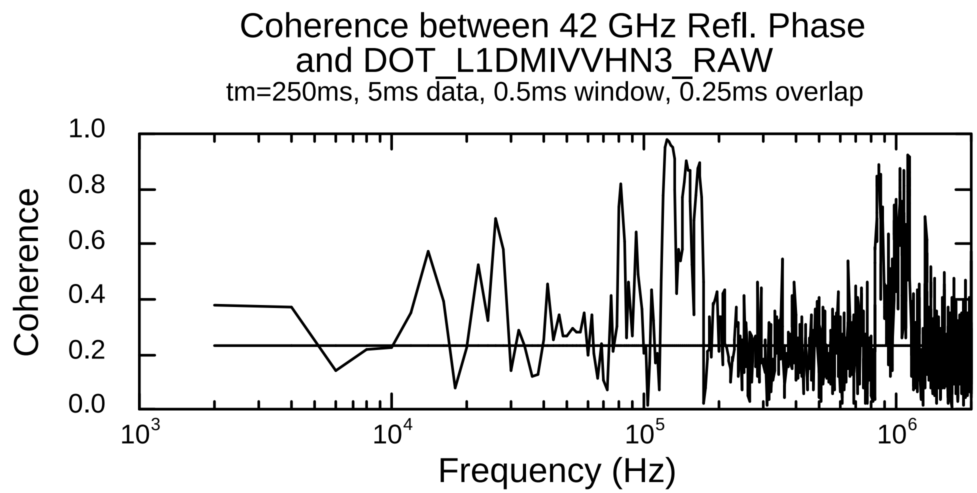
Spectrogram of Mirnov Signal for Shot 112996

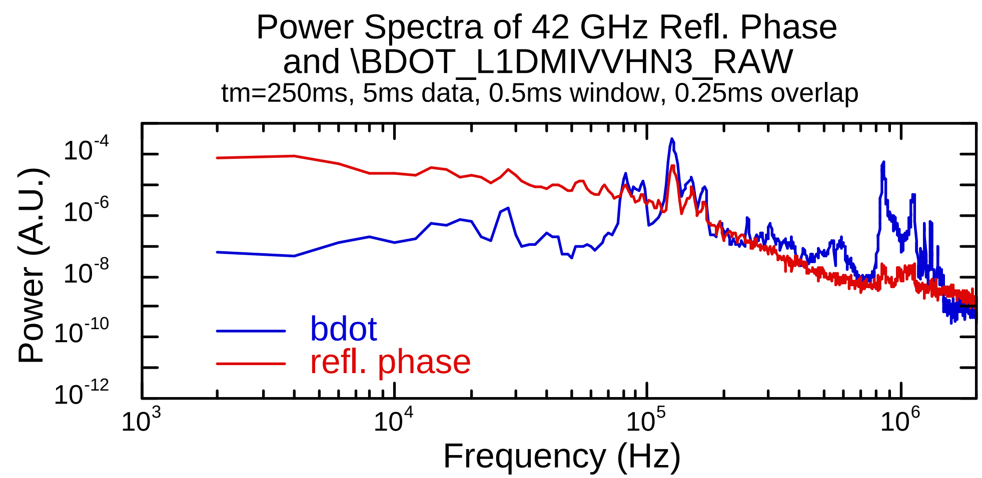




Effect of Fast Ion Induced MHD (continued)

- Large amplitude MHD oscillations due to fast ions (bounce fishbone, TAE, CAE) always present for NB-heated discharges.
- Coherence between Mirnov and quadrature reflectometer phase is high.
- Correlation drops out when amplitude becomes too large (e.g. bursts). These bursts are correlated with similar bursts in reflectometer phase amplitude.
- Contribution of smaller level amplitude ambient MHD to the correlation coefficient is still unclear.





Summary

NSTX

- **L_{cr} measured in the core of the ST for the first time**. Measurements made in peaked moderate density plasmas in beam-heated L-mode discharges.
- During current flattop, values of L_{cr} in the range of 2-12 cm measured over ρ~0.45-0.75. L_{cr}/ρ_s ranged from 3 to 18.
  - Smallest L_{cr} at the largest radius and magnetic field. L_{cr} increases inversely with radius and magnetic field.
  - For matched profiles in the ρ^* scan, L_{cr}/ρ_s at a given ρ is roughly independent of B.
  - L_{cr}/ρ_s increases towards the core (magnitude varies for different discharge conditions).
- For NB-heated discharges, fast-ion induced MHD can be dominant source of high frequency fluctuations in the homodyne signals instead of turbulence. While large amplitude oscillations tend to reduce the correlation, small amplitude ambient oscillations may contribute to the measured correlation lengths.

Future Work

- Further analysis to determine the contribution from fast ion driven MHD will require investigating a larger data set including RF-heated and ohmic-only discharges (with no beam-driven instabilities).

- Correlation with confinement properties for various discharge conditions.

- Role of magnetic shear will require further measurements with MSE.

- Understanding of turbulence-driven transport mechanisms in will require detailed comparison of measured correlation lengths as well as phase (density) fluctuation levels and spectra with those calculated from the output of GYRO. Use of 2-D full-wave reflectometry simulations using the GYRO output as input.

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