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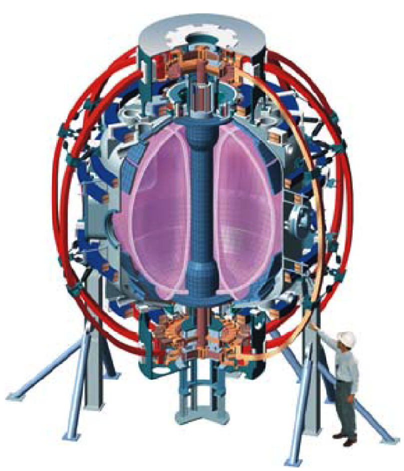
Turbulence Measurements on NSTX Using Millimeter-Wave Reflectometry

S. Kubota



NSTX Physics Meeting
May 22, 2006

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Poster Outline

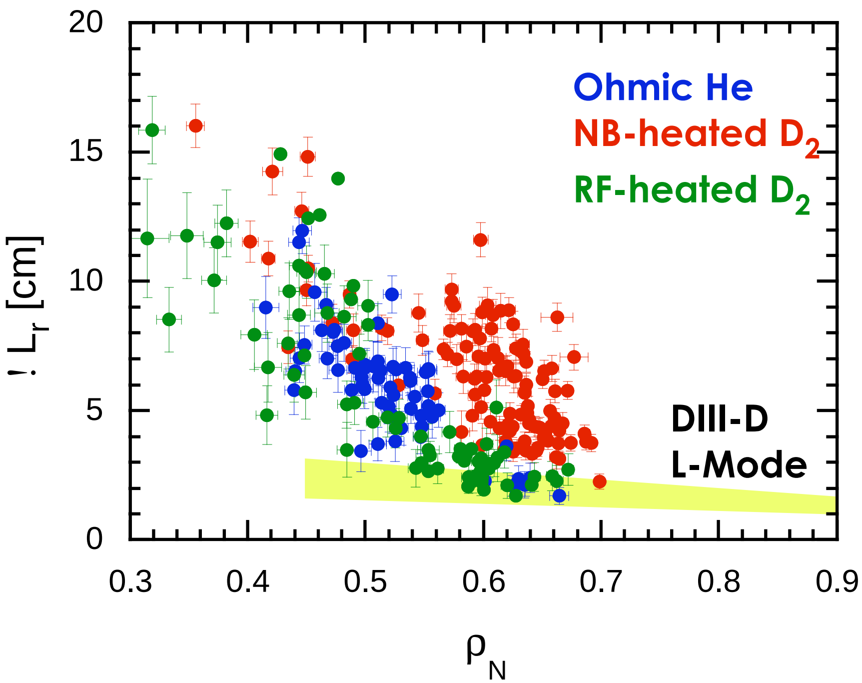
- Background of core turbulence measurements on NSTX.
- Description of reflectometry hardware:
  - 13.5-53.5 GHz FMCW profile system.
  - 30, 42, and 49.8 GHz quadrature channels.
  - 26-40 GHz homodyne radial correlation system.
- Analysis technique:
  - Full-wave simulations with modeled turbulence.
  - Statistical optics techniques for comparison with experiments.
- Overview of correlation length measurements in various NSTX L-mode discharges (NB-heated, RF-heated, He Ohmic).
- Ohmic H-mode discharges show first direct connection between core turbulence properties and confinement.
- Future planned reflectometer capabilities on NSTX.

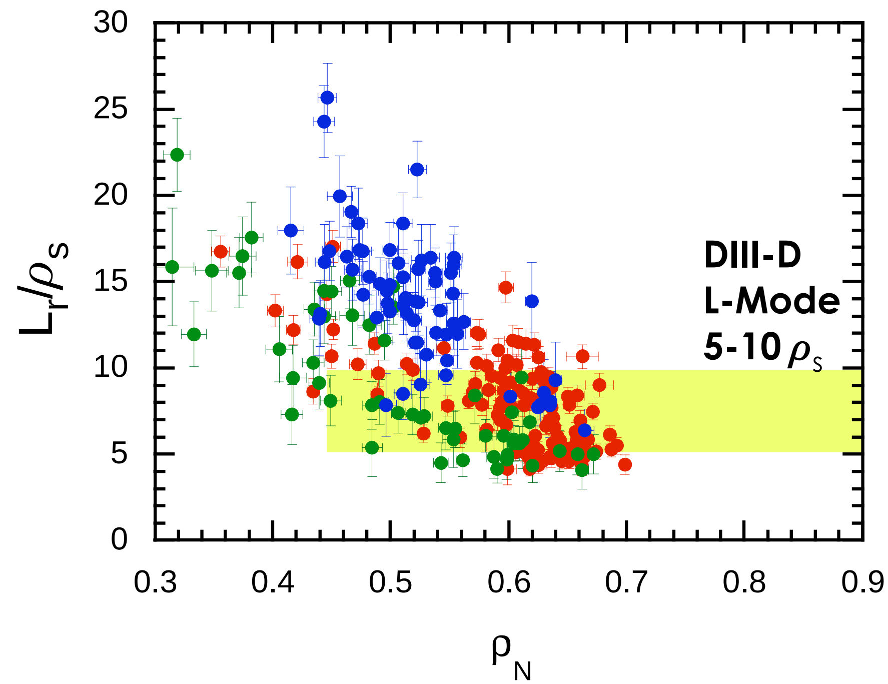
Background and Motivation

- Core transport of long wavelength turbulence (ITG modes, TEM's, micro-tearing modes with $k_\theta \rho_s \leq 1$) thought to be suppressed due to increased ExB shear, T_i/T_e ratio and gradient β effects.
- Reflectometry on NSTX has focused on measuring density fluctuation levels and radial correlation lengths in low density L-mode discharges.
- Reflectometer correlation lengths (L_r) are calculated from 1/e decorrelation distance of homodyne signals and show similar values over a wide variety of discharges (NB- and RF-heated, He Ohmic). Typical results:
  - L_r increases from ~2 cm near edge to ~10-20 cm in core. These values are ~5-20 x ρ_s. Correlation lengths always increase towards the core.
- **Recent studies using full-wave simulations have shown that density turbulence correlation lengths (L_n) can be different from L_r.**
- **Focus of present study:**
  - **Simulated turbulence with full-wave simulations to estimate values of L_n and $\delta n/n$.**

L_r Compared in a Variety of L-Mode Plasmas

Ohmic(He)/NB-heated(D_2)/RF(D_2)

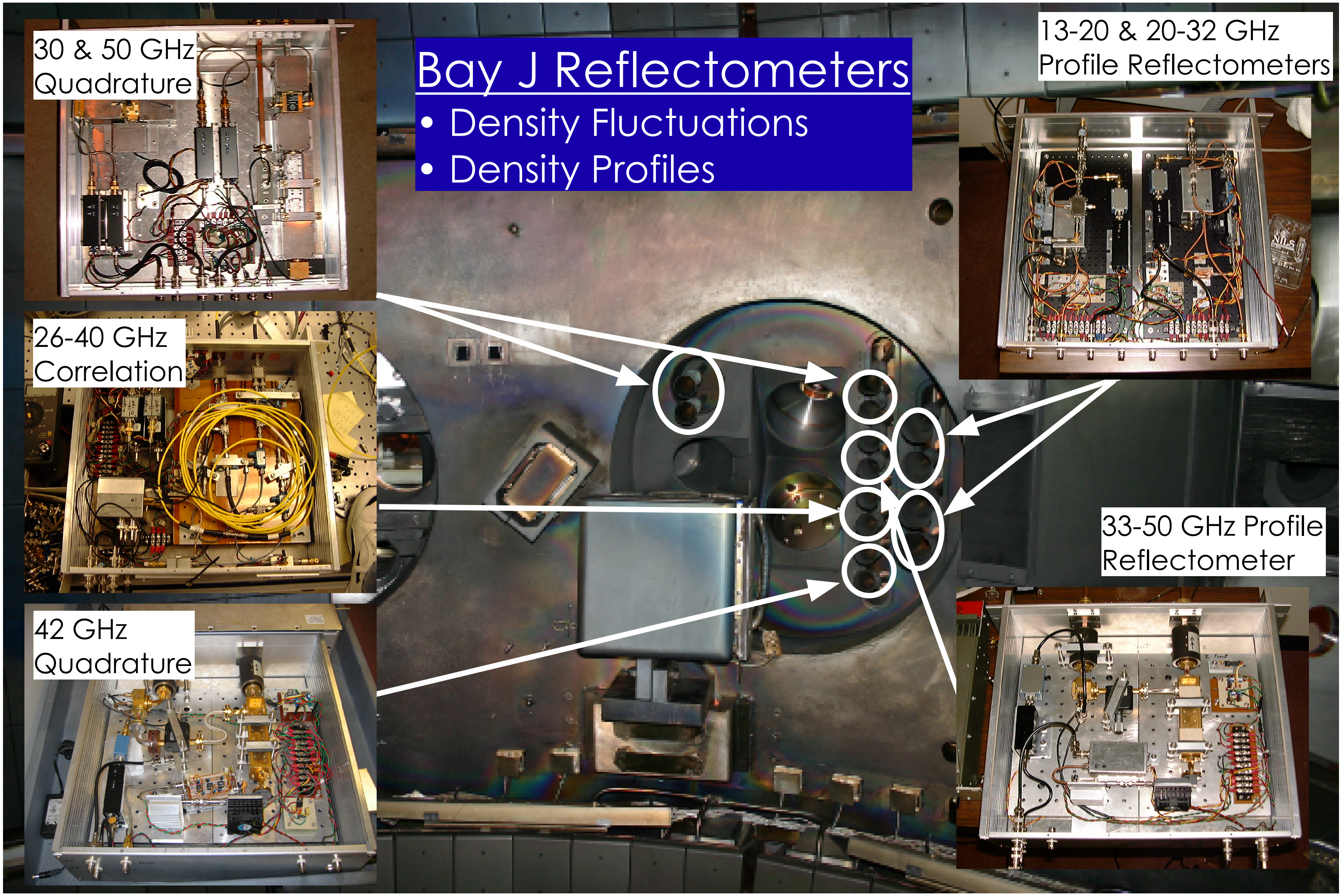




- Ohmic (He), RF- & NB-heated L-modes.
  - L_r~2-15 cm from r~0.7-0.3 are seen irrespective of heating method.

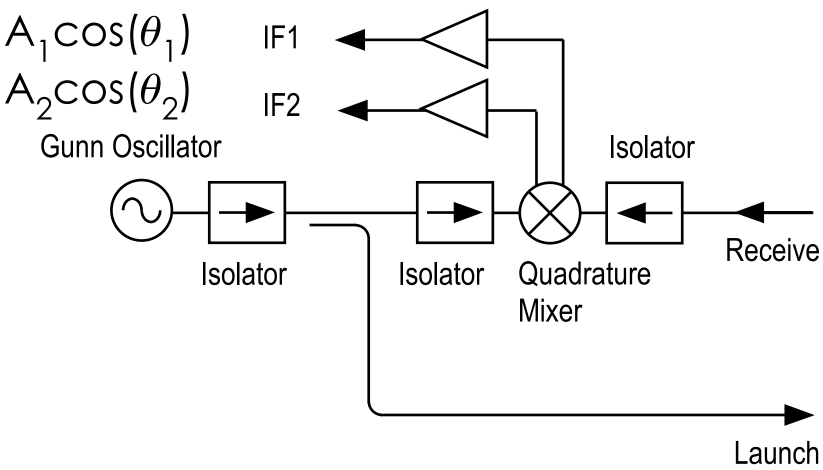
- Dependencies:
  - Seems to scale with ρ_s.
  - L_r and L_r/ρ_s decrease with radius.
- **Really want turbulence correlation length L_n instead of L_r to look at scaling, etc.**

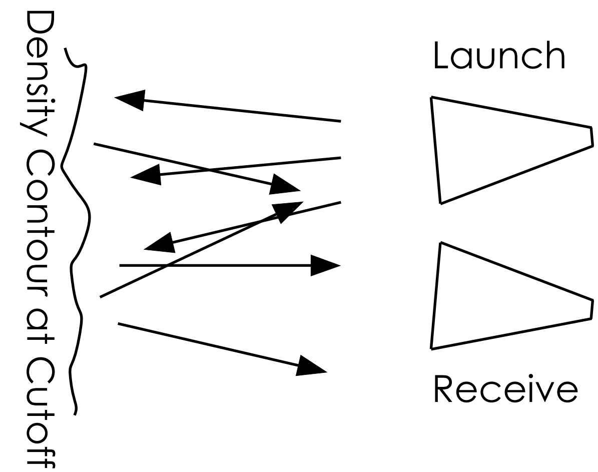
Reflectometer Hardware on NSTX



Homodyne Quadrature Reflectometry

- Reflectometer uses direct-conversion detection:

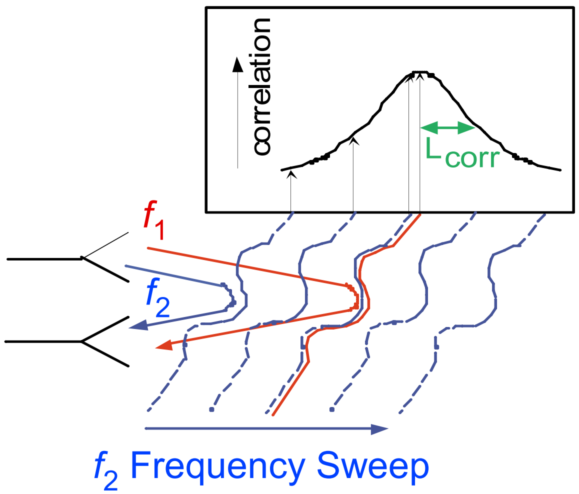




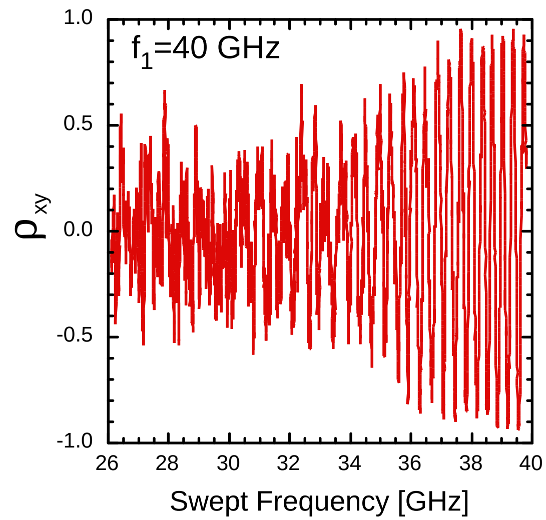
- Complex signal (amplitude and phase information).
- Local measurement of fluctuations near cutoff surface (usually).
- For low *k* coherent fluctuations, phase information alone is sufficient to recover $\delta n/n$ proportional to $\Delta\theta$.
- For higher *k* and turbulent fluctuations, reflectometer response dependent on details of the turbulence as well as antenna geometry (2D effects).

Homodyne Radial Correlation Reflectometry

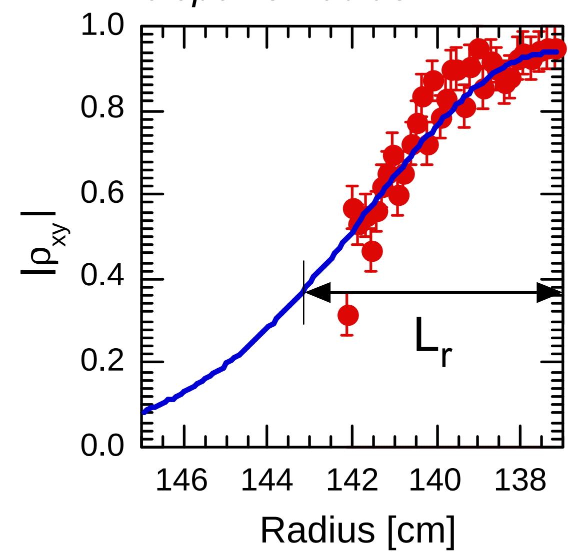
Principle of Radial Correlation Length Measurements



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_r is defined here as the *e*-folding distance of the correlation coefficient function envelope (best fit to Gaussian).

Role of Simulations with Modeled Turbulence and Full-Wave Code

- **Experiment**
  - Real turbulence in 3-D space evolving in time.
  - Reflectometer response from turbulence is time-dependent complex signal dependent not only on turbulence properties but also on stationary background profiles as well as antenna geometry, etc.
  - Statistical properties of reflectometers signal usually equated to statistical properties of turbulence (spectra, level, correlations, etc.). This is in general not correct.
- **Simulation of Turbulence**
  - Use simple model for density fluctuations with certain statistical quantities as input (k and ω spectra, $\delta n/n$, correlation length and time).
- **Full-Wave Code for Reflectometer Response**
  - Background profiles (density, temperature, flow, etc.) are estimated from other diagnostics.
  - Accurate geometry of plasma with respect to reflectometer horns.
- **Comparison Between Experiment and Simulation**
  - Use statistical optics.

Turbulence Model

NSTX

- Superposition of sinusoids with random phase and obeying:

$$\frac{1}{n^2}\langle\tilde{n}_1\tilde{n}_2\rangle = \left(\frac{\tilde{n}}{n}\right)^2 \exp\left(-\left(\frac{\Delta t}{\tau}\right)^2\right) \exp\left(-\left(\frac{(\Delta\mathbf{r}+\mathbf{v}\Delta t)\cdot\Delta\mathbf{k}}{2}\right)^2\right) \cos\left(\mathbf{k}_m\cdot\Delta\mathbf{r}\right)$$

$\tilde{n}/n$: density fluctuation level

τ: correlation time

$\Delta\mathbf{k}$: wavenumber spread

$\mathbf{k}_m$: wavenumber mean

$\Delta\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$

$\Delta t = t_2 - t_1$

- Turbulence is homogeneous.
- For present study ignore τ and $\mathbf{v}$.

PPPL 2-D Full-Wave Code (FWR2D)

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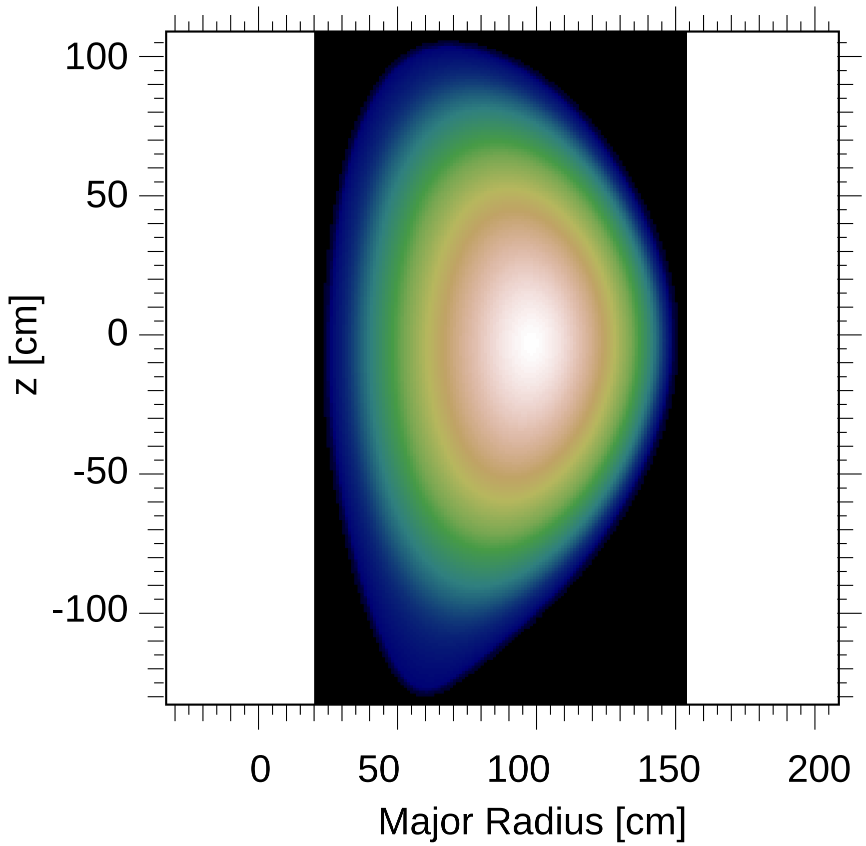
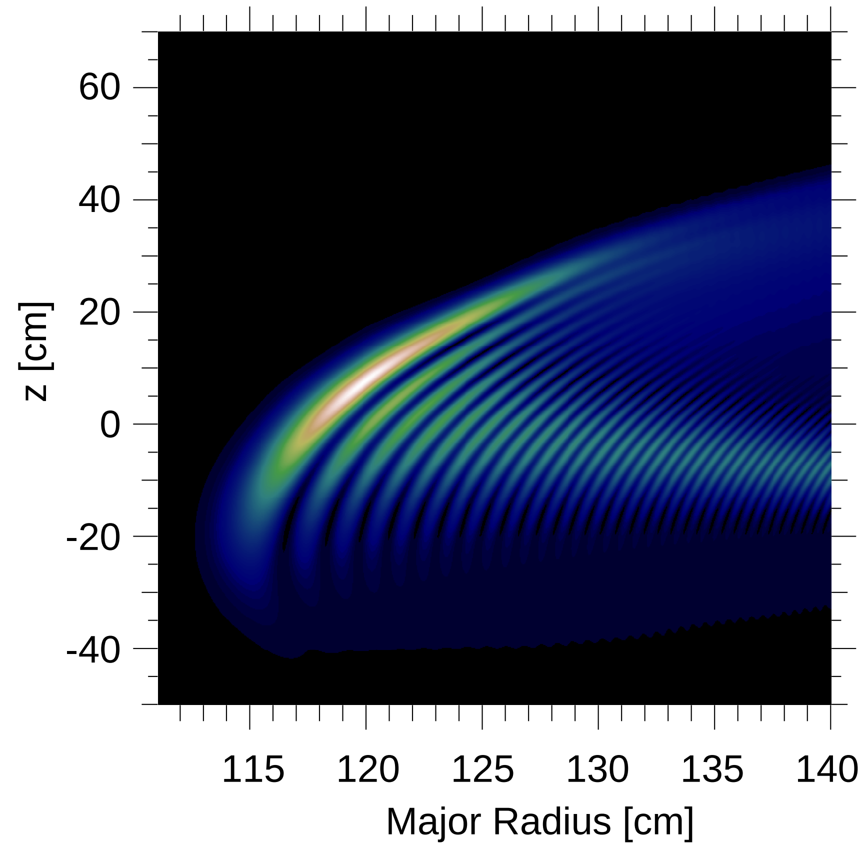
Density Contours



Wave Amplitude for 42 GHz O-Mode



- 2-D density and temperature contours from MPTS or reflectometer and EFIT.
- Propagation of electric field amplitude E(x,t) described by

$$2i\omega \frac{\partial E}{\partial t} + \mathcal{L}E = 0, \qquad \mathcal{L} = c^2\nabla^2 + \omega^2\varepsilon$$

- ε is O- or X-mode dielectric.
- E.J. Valeo, G.J. Kramer, R. Nazikian, Plasma Phys. Control. Fusion 44, L1 (2002).

Statistical Optics

- Coherent Reflection (strong function of $\delta n/n$):

$$G = \frac{|\langle E \rangle|}{\sqrt{\langle |E|^2 \rangle}}$$

- Normalized Cross-Correlation or L_r (strong function of L_n and $\delta n/n$):

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

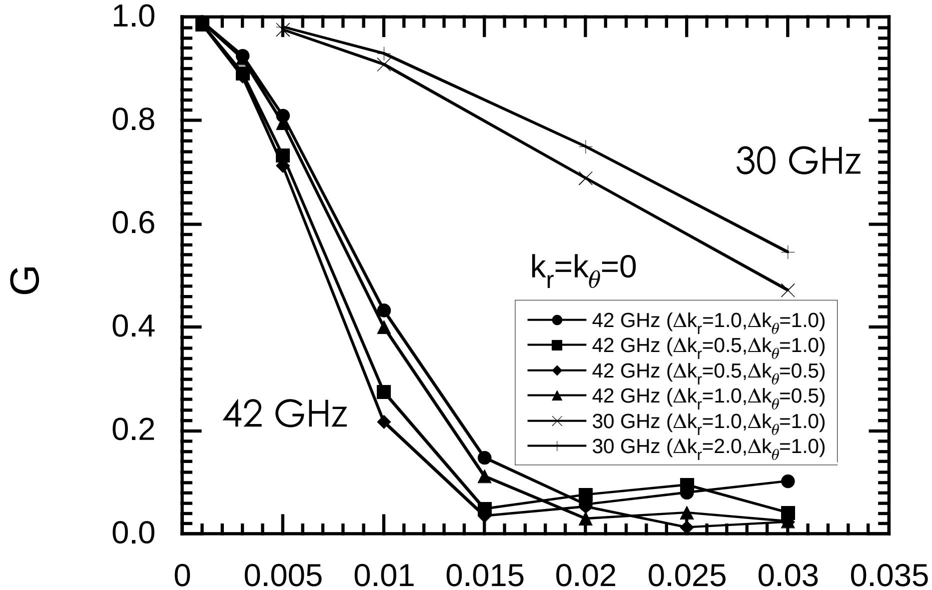
- Fluctuation Index:

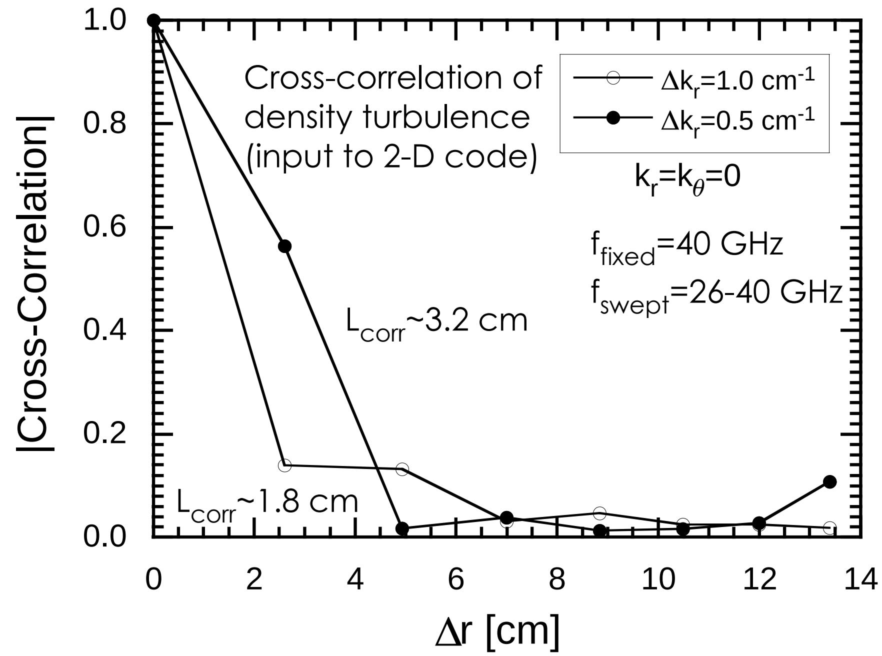
$$F = \frac{\sigma(|E|)^2}{\langle |E|^2 \rangle}$$

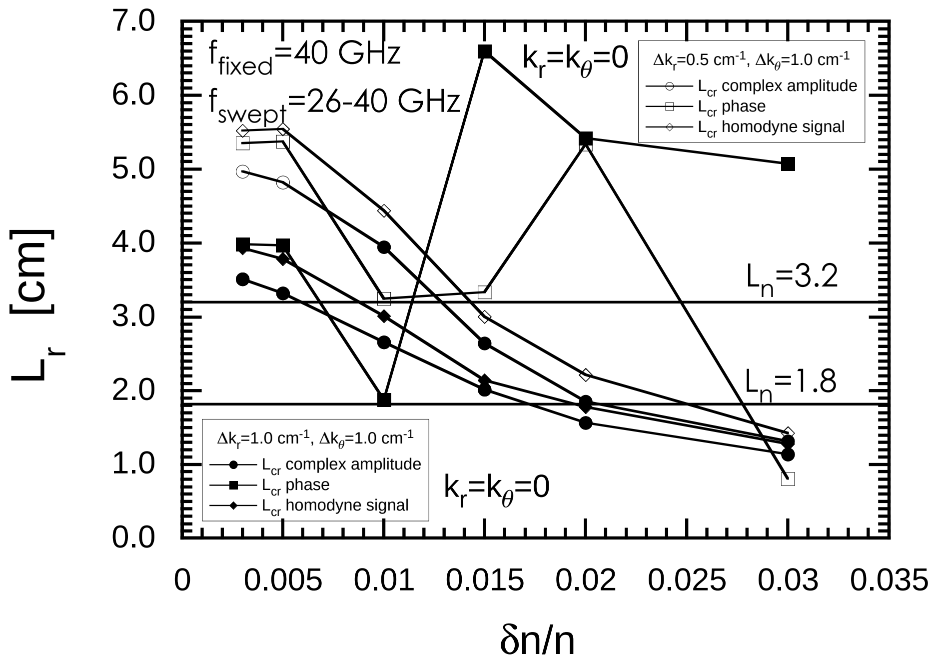
- Elongation Factor:

$$\chi = \frac{\sigma(E)}{\sigma(|E|)}$$

G and L_r from Simulation







- Shot 113115, t=330 ms.
- Comparison of correlation and quadrature reflectometry data with simulations.
- Experimental results:

  G~0.85 for 42 GHz, ~0.7 for 30 GHz.

  L_r=~11.4 cm
- Homodyne tracks complex amplitude L_r well but overestimates slightly.
- **L_r is strongly dependent on $\delta n/n$.**

Work With Simulations is Ongoing

- According to 2-D full-wave code:
  - Phase response not a good measure of turbulence quantities.
  - Homodyne signal and complex signals offer similar L_r. Satisfactory if turbulence is not evolving.
  - L_r can vary significantly from actual turbulence density correlation length. Strongly dependent on $\delta n/n$. Less dependent on other parameters.

- $\delta n/n$ dependence may explain consistent observation of large correlation lengths (10-20 cm) observed in core.

- **Corroboration of code/turbulence model with experiments is still limited. Definitive test to be performed on DIII-D including detailed comparison with BES.**

- Future work:
  - Continue 2-D reflectometry simulations for different plasma conditions. In particular, consider radial variation of turbulence wavenumber spectra and $\delta n/n$.
  - Include flows. Consider decorrelation time, spectra.
  - Comparison with global non-linear gyrokinetic simulations (GYRO).

Future Plans for Turbulence Measurements

NSTX

- **Quadrature detection for correlation reflectometer is the key.**
  - Can trade off spatial resolution for better time resolution (<100 μs).
  - Channels can now be used simultaneously as monitors of the density fluctuation level.
- Can now run profile system simultaneously with accurate estimates of density profile and cutoff location for dynamically evolving profiles.
- In addition to radial correlation, can separate channels for poloidal or toroidal correlation. Can measure **turbulence flow velocity**.