Turbulence measurements in NSTX

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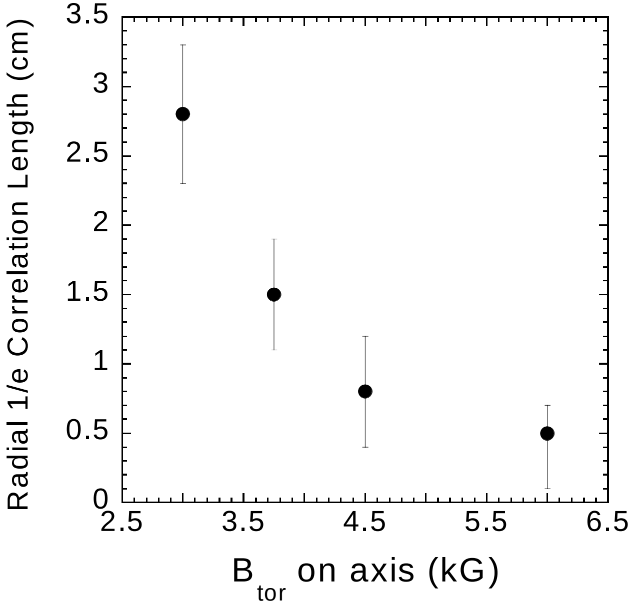
Measurement needs for turbulent transport studies in NSTX

- **Broad range of turbulence measurements**
  - we need to monitor and characterize low k (ITG) turbulence in NSTX plasmas
  - we need to investigate the existence of high k (ETG) turbulence in the core
  - we should not forget magnetic fluctuations in a high beta device such as NSTX !
- **Spatial coverage**
  - NSTX has to improve spatial coverage of turbulence measurements (e.g. core)
  - need to cover a wide range of plasma conditions: flexibility is important
- ***Comparison with theoretical predictions and other fusion devices***
  - measurements should allow detailed experimental cross checks and comparison with theory/ computation predictions (e.g. GS2 and GYRO?)
  - comparison with other devices will be very important to reveal the unique features of the ST
- **Detailed profile measurements**
  - comparison with theoretical predictions ***requires*** that an array of ***accurate*** profile measurements be available on NSTX.
  - needed profiles include q profile, density, ion and electron temperatures, impurities, magnetic and electric fields (ExB flow), etc.

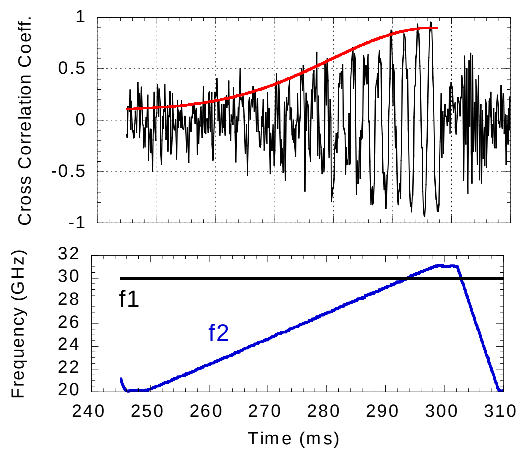
Low k turbulence

Correlation length measurements - strong scaling with field

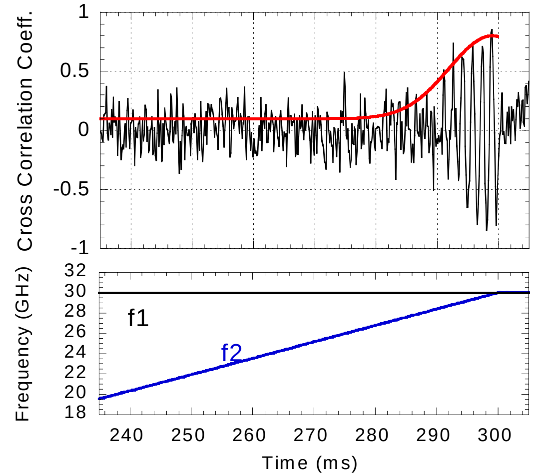
Δr versus B_{tor} on axis



Example Raw Data



1/e Δr ≈ 1.5 cm



1/e Δr ≈ 0.8 cm

B_{tor} = 3.75 kG, Ip = .85 MA
Shot 108223, NB Source A,
L_n≈11 cm

B_{tor} = 4.5 kG, Ip = 1 MA
Shot 108215, NB Source A,
L_n≈10 cm

- Reflectometer is 20-30 GHz O-mode homodyne system ($n_{CR} \approx 0.5\text{-}1.0\times10^{13}$ cm^{-3})
- Cutoff layers (30 GHz) <u>5-7 cm inside LCFS</u>
- L_n varies from ≈ 8 to 16 cm
- Fluctuation frequencies 20 - 500 kHz correlated

Future Plans for correlation system

- **Data analysis continues from recent run.**
  - strong correlation length scaling with magnetic field consistent with Neon puff data (JHU)
  - need to look at scaling with ρ_i. Compare with DIII-D data and gyrokinetic simulations (GS2 limited at the edge?).
  - maybe can connect with Langmuir probe and other measurements in edge plasma.

- **Increase spatial coverage by extending frequency range of reflectometer to 60 GHz**
  - allows access to ~ 5 x 10^{13} cm^{-3}
  - however, will still be limited by density profile shape. Can't overcome flat to hollow density profiles on low field machines. Restricts all reflectometry measurements to edge region.
  - elimination of flat to hollow density profiles through density control would be a major benefit.

- **This frequency increase will also allow |B| to be determined deeper into the plasma**
  - need to know profile of |B| (together with Er) to determine ExB shear flow. Er from CHERS, MSE?

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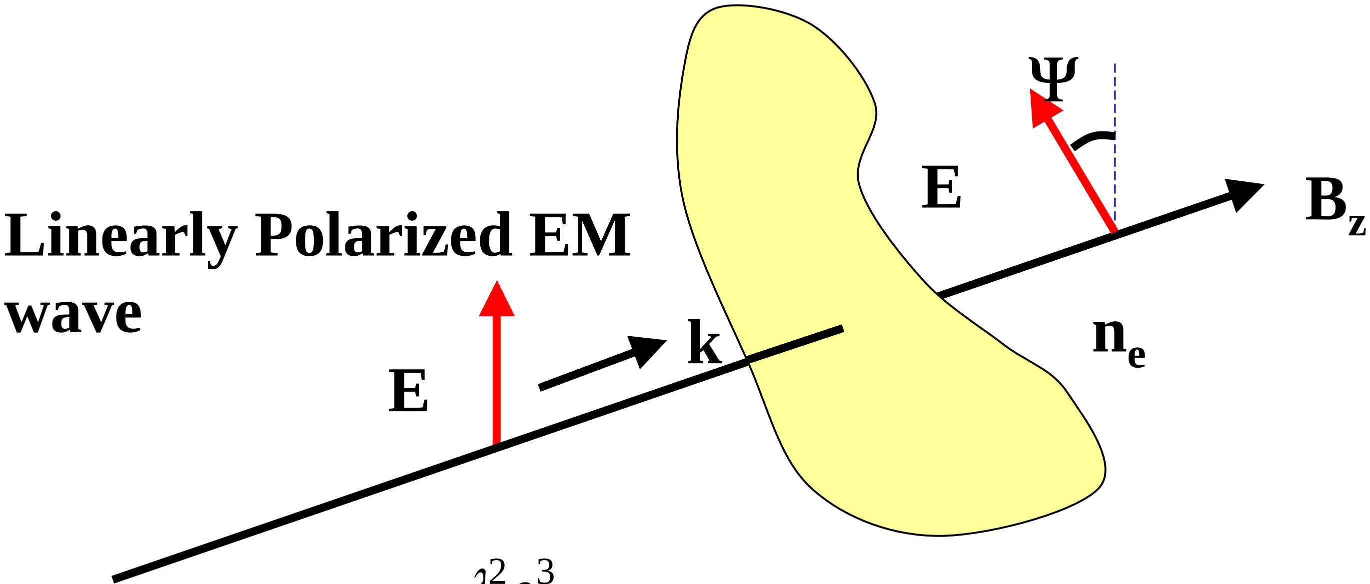
Faraday rotation and interferometry
Absolute low k turbulence measurements on NSTX



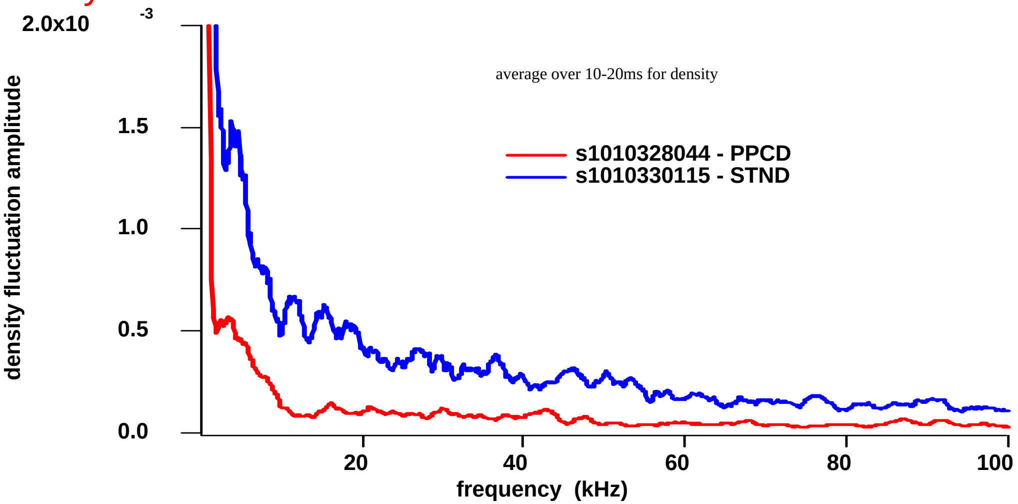
$$\Psi = \frac{\lambda^2 e^3}{8\pi^2 c^3 \varepsilon_0 m_e^2} \int n_e B_z \, dz = 2.62\times 10^{-13} \lambda^2 \int n_e B_z \, dz$$

$$\Phi = \frac{\lambda\, e^2}{4\pi \; c^2 \varepsilon_0 m_e} \int n_e dz = 2.82\times 10^{-15} \lambda \int n_e dz$$

Low k density turbulence
Fast, high resolution interferometry!

- **A fast, high resolution line integrated interferometer can provide important turbulence information on NSTX**
  - on MST and DIII-D interferometry systems have been installed to provide an absolute measure of line integrated fluctuation content at low k (ITG)
  - The interferometer probes the entire plasma and provides a measure of the fluctuation content normalized to the line average density.

MST central interferometer chord fluctuation amplitude spectrum



- **The interferometer monitors all long wavelength (k < 1 cm^{-1}) turbulence and provides an absolute, unambiguous measure of fluctuation content.**

- **Computer simulations should be able to predict trends in this level for different NSTX conditions and make comparisons with this robust measurement.**

Isolating magnetic fluctuations
- polarimetry

Faraday Rotation: $\Psi = c_F \int n_e B_{//} dl$

Taking: $\Psi = \Psi_0 + \tilde{\Psi}$ $\quad n_e = n_0 + \tilde{n}$ $\quad B_{//} = B_0 + \tilde{B}$

Rewriting:

$$\Psi_0 + \tilde{\Psi} = \int n_0 B_0 dl + \int \tilde{n} B_0 dl + \int n_0 \tilde{B} dl + \int \tilde{n} \tilde{B} dl$$

$$\Psi_0 = \int n_0 B_0 dl$$

$$\int \tilde{n} \tilde{B} dl \approx 0$$

$$\tilde{\Psi} = \int \tilde{n} B_0 dl + \int n_0 \tilde{B} dl$$

Magnetic axis: $B_0 \Rightarrow 0$, $\tilde{n}_{m=1} \Rightarrow 0$

Leaving:

$$\tilde{\Psi} \approx \int n_0 \tilde{B} dl$$

$$\tilde{B} \Rightarrow \tilde{B}_r$$

For all central chords: $\int \tilde{n} B_0 dl << rms\ noise, \quad \Rightarrow \quad \tilde{\Psi} \approx \int n_0 \tilde{B} dl$

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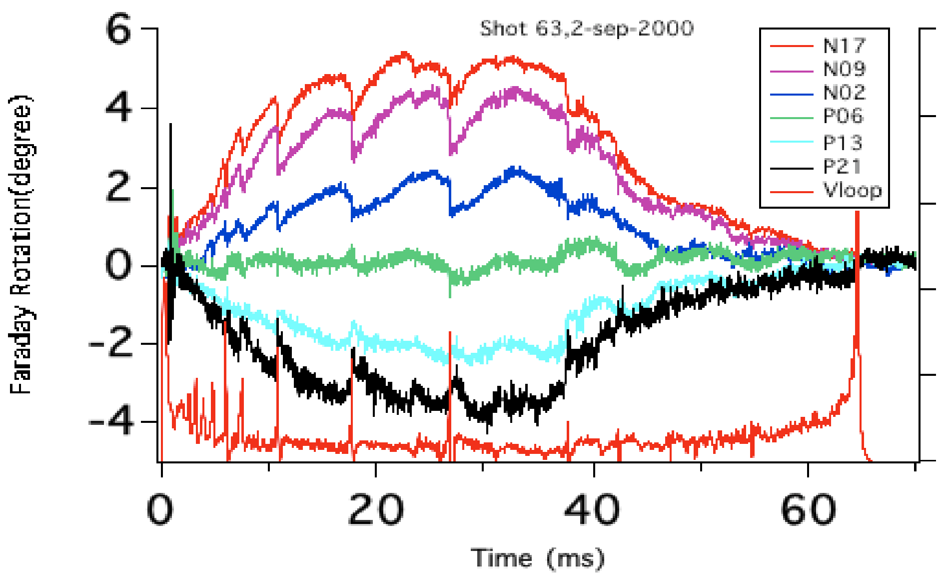
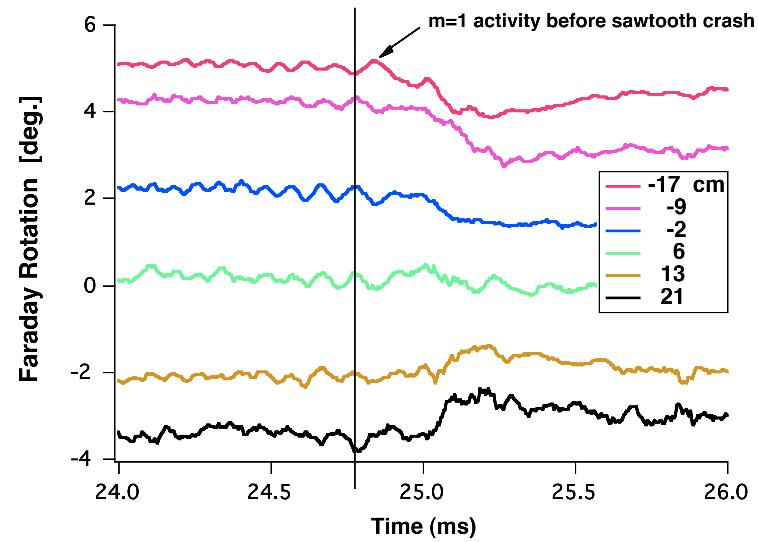
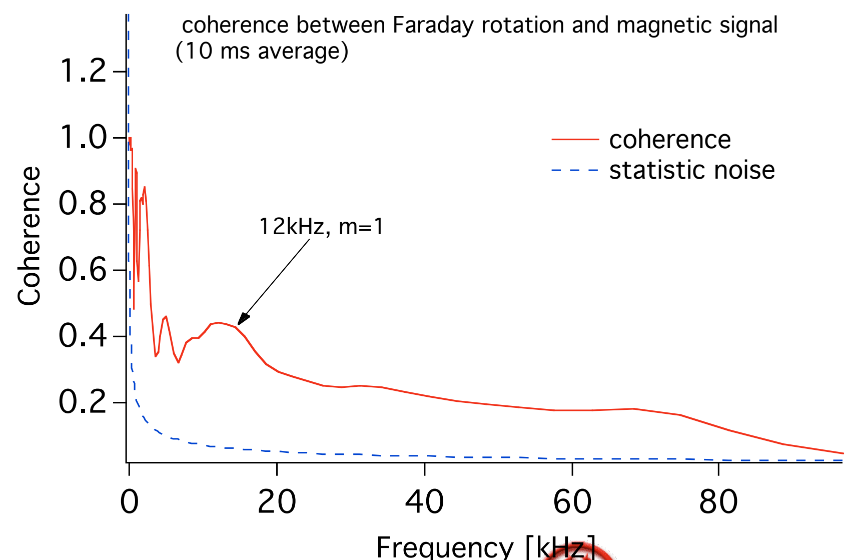
Fast polarimetry data from MST





Digital analysis of polarimetry data indicates fast "sawtooth" events with m=1 precursors.

Correlation with Mirnov coil seen at 12 kHz (m=1) mode and finite correlation to frequencies ~100kHz



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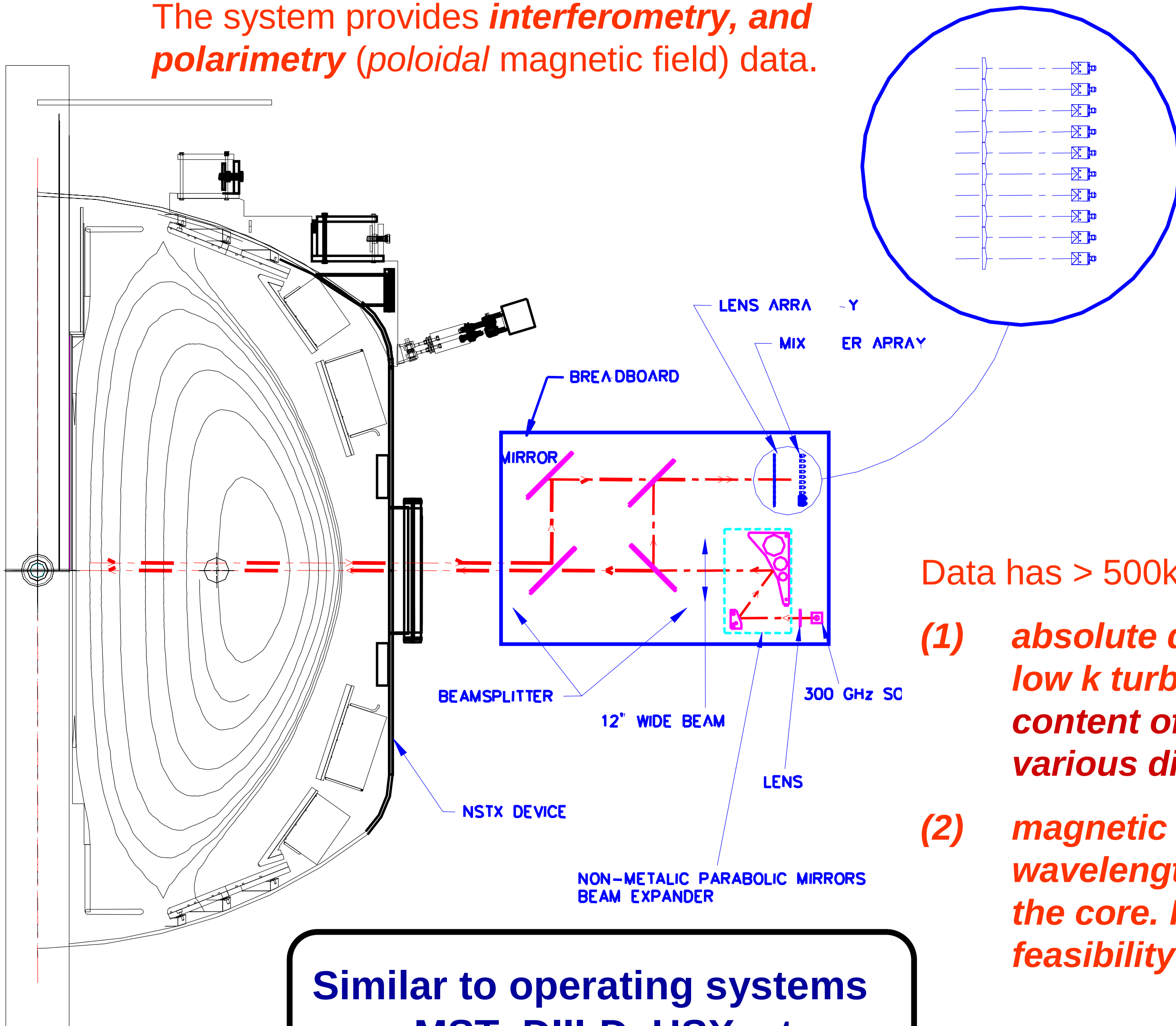
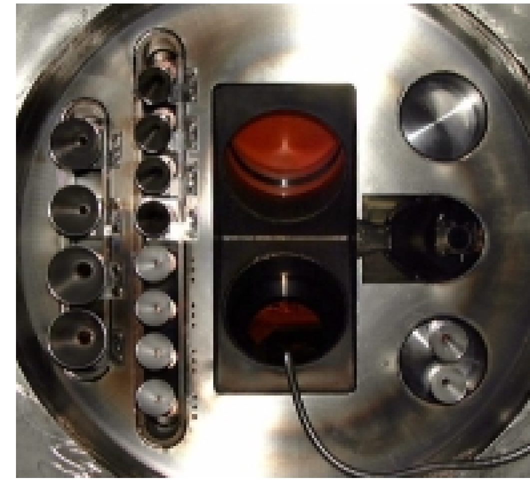
Implementation of sensitive, multichannel "fast" interferometry & polarimetry on NSTX

The system provides ***interferometry, and polarimetry*** (*poloidal* magnetic field) data.





Inside view of midplane Port J

Data has > 500kHz bandwidth and would provide

(1) ***absolute density fluctuation content of low k turbulence (i.e. total fluctuation content of low k or ITG turbulence in various discharges)***

(2) ***magnetic fluctuation information at long wavelengths – data is weighted towards the core. Recent MST data demonstrates feasibility.***

Similar to operating systems on MST, DIII-D, HSX, etc.

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Future Plans

- **UCLA plans to install a single channel mm-wave interferometer/polarimeter during the current vent**
  - this will confirm our confidence that we can reflect off a carbon tile on the inner wall of NSTX.
  - PPPL will install flat 6 inch long 2 inch wide carbon tile.

- **Utilize this single channel to perform line integrated turbulence measurements at low k (ITG) and also test various polarimeter configurations**
  - This will provide a shot-to-shot monitor of the fluctuation content at low k which can be compared with theoretical predictions for ITG turbulence

- **We will generate a DoE proposal to install a multichannel system onto NSTX.**
  - this would provide the equilibrium information necessary to significantly constrain Jo in EFIT
  - it would also ensure that the channel passing through the current axis will easily be identified
  - this channel would investigate **magnetic fluctuations in high beta NSTX** plasmas.

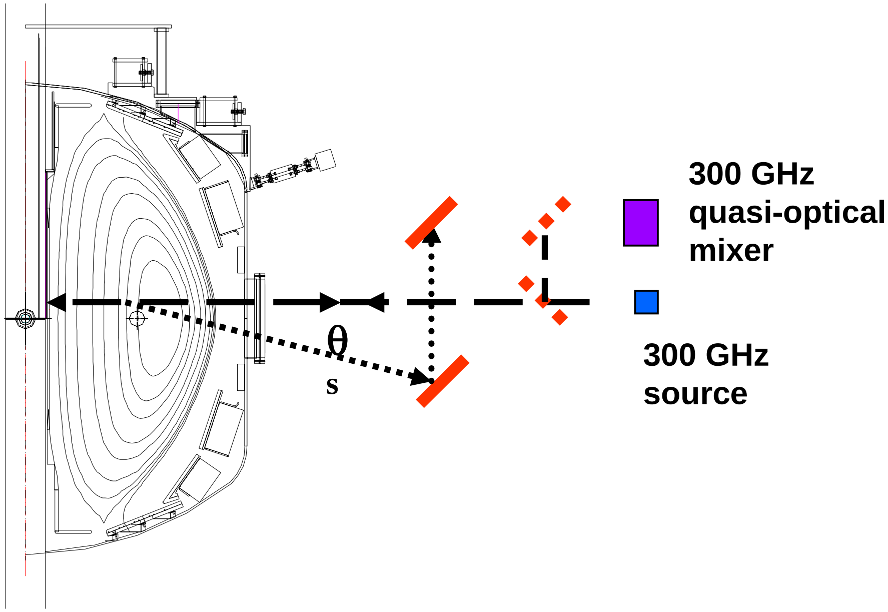
High k turbulence – ETG modes

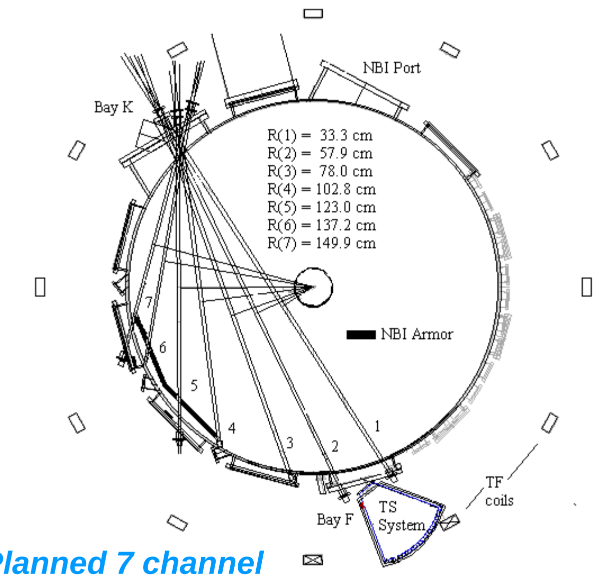
- **Collective scattering is the best (probably the only) method of investigating short wavelength turbulence.**

- **Different approaches**
  - (1) Scatter in approximate poloidal plane and localize using large magnetic field pitch angle.
    - Probe perpendicular wavenumbers. Geometry awkward - difficult to get radial information because of large variation in pitch angle.
  - (2) Scatter in horizontal tangential plane and localize using toroidal field curvature.
    - Probe radial wavenumbers. Well-suited to CO_2 laser scattering – eliminates refraction issue. Sensitivity not great but better than 100-200 micron. Need a multi-view tangential system to obtain spatial information since data localized to tangent radius.
  - (3) Employ large angle back-scattering techniques to probe radial k
    - Simple approach. Utilizes low frequency, high power sources. Probes the high end of ET mode wavenumber spectrum

- **Initial focus – is there ANY clear evidence that high k turbulence exists in NSTX**
  - On NSTX, UCLA plans to focus on (3) in short-term
  - Also good alternative approach for DIII-D. However, focus there is on (1)

Poloidal and tangential scattering geometries





Planned 7 channel FIRETIP system

Scattering in ~ poloidal plane allows large angle forward scattering to probe large k.

Matching to varying pitch angle provides localization radially – requires large viewport to accommodate large pitch angle variation

Scattering at small angles in horizontal tangential plane with infrared wavelengths probes radial wavenumbers.

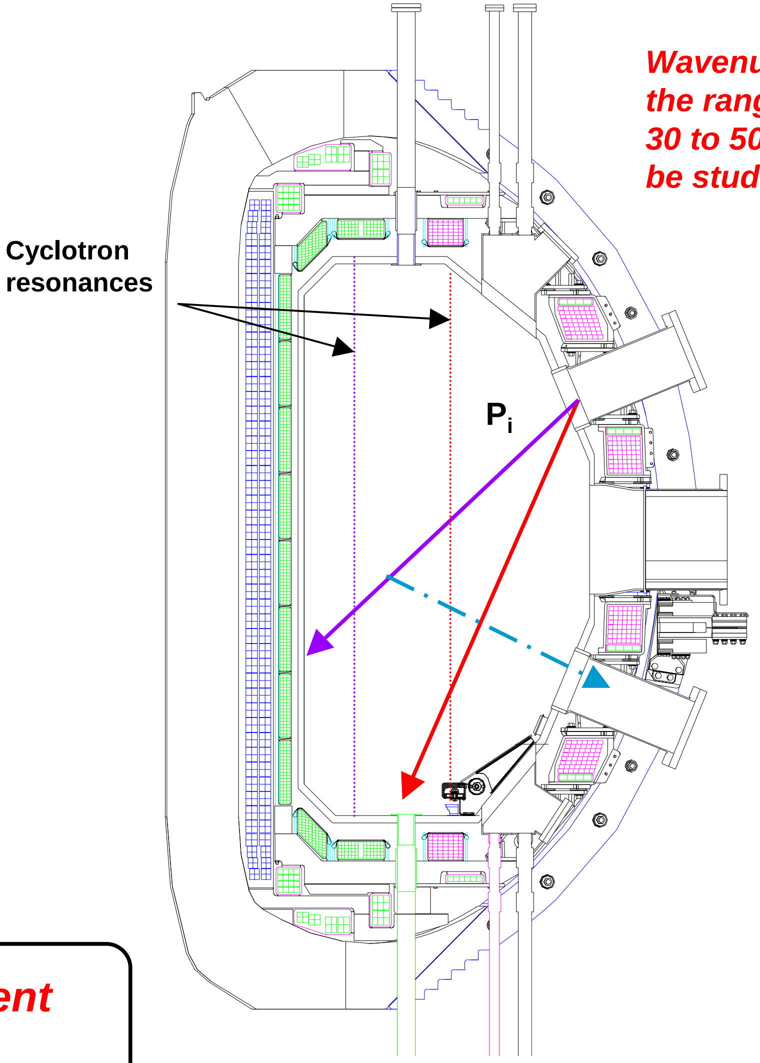
Due to toroidal field curvature localization should be very good – at the tangent radius.

Infrared requires VERY stable optical system

Scattered power will be very small

Alternative low-cost method –
large angle, back-scatter to probe radial k

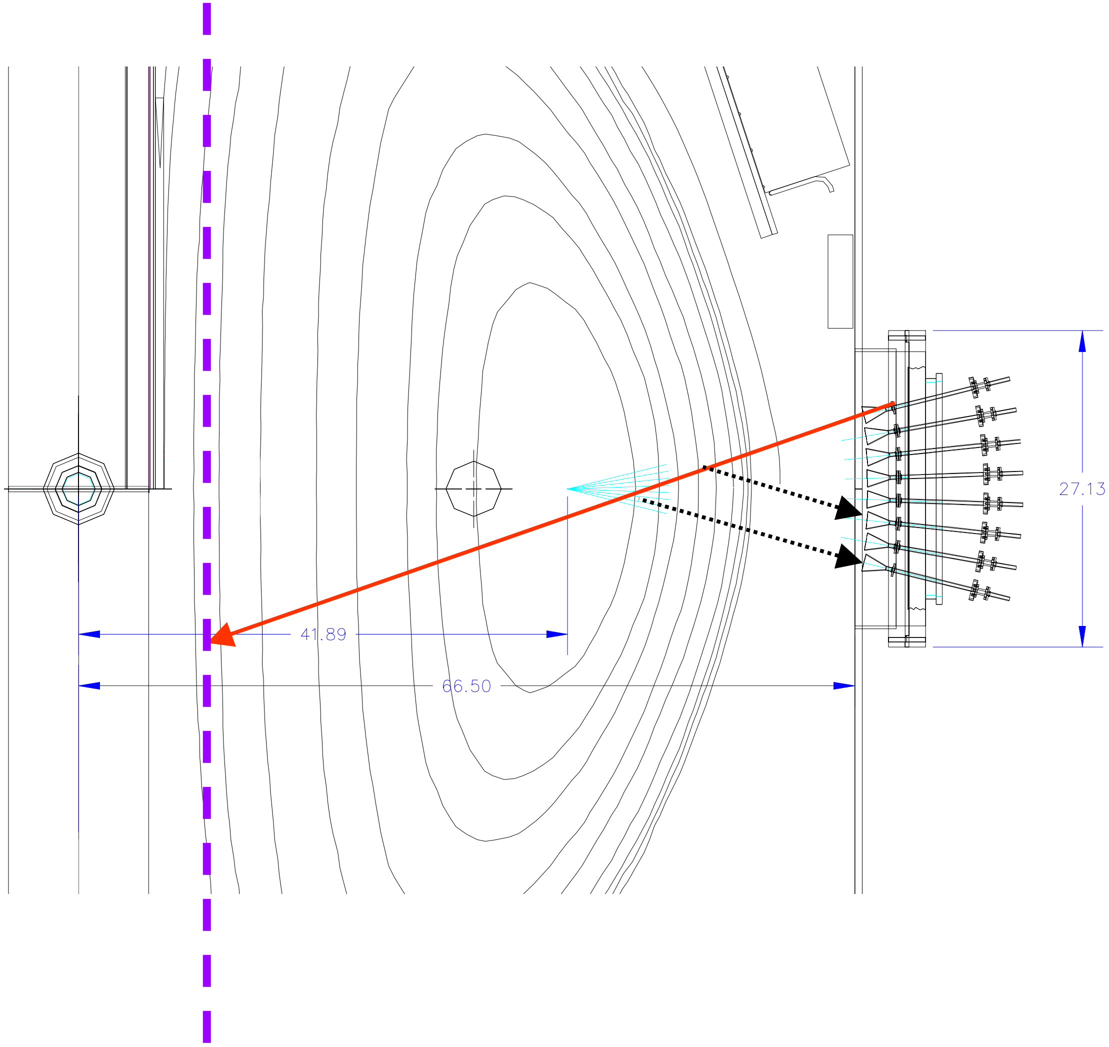
- **On DIII-D Utilize a 110 – 140 GHz source at large scattering angles (90 –135 degrees). This approach has the following advantages**
  - (1) The cyclotron resonance layer can act as an ***effective beam dump***
  - (2) Extensive ***ray tracing codes to account for refraction effects***
  - (3) ***High power*** sources (100 mW - 10W continuous) and ***very sensitive receivers*** are available. Could easily modulate source to differentiate from ECE emission.
  - **This approach on DIII-D requires significant port modification – under study.**



Wavenumbers in the range from 30 to 50cm^{-1} can be studied

On NSTX we may be able to implement VERY EASILY

Implementation of high scattering on NSTX is easier – existing port location can be used



Launch 100 GHz using corrugated waveguide/antenna/lens combination.

Detect backscattered radiation at ~155 degrees using similar waveguide/antennae/lens combinations.

Probes wavenumbers ~ 35- 40 cm-1

Long wavelength (ITG) turbulence scatters incident beam at angles < 10 degrees.

Refraction will not significantly change scattering angle – should be good “contrast” between low and high k.

Probes radial wavenumber – therefore insensitive to pitch angle issues.

Advantages/disadvantages of backscattering approach on NSTX

- ***<u>Advantages</u>***
- **Use of lower frequency produces a very sensitive system capable of detecting extremely small density fluctuation levels**
  - Scattered power ∝ square of incident wavelength
  - Lower frequency sources available at high power
  - Very sensitive receiver systems available at these frequencies.
- **Back-scattering geometry has major advantages**
  - Good contrast with scattering from long wavelength turbulence (ITG)
  - Probes radial wavenumbers - insensitive to variation in pitch angle, negligible Doppler shift
  - Can vary location by using different fixed receive antennae or through steerable antennae.
- **<u>The approach can be implemented quickly and is compatible with existing port J</u>**

- ***<u>Disadvantages</u>***
- **Difficult to vary magnitude of probed wavenumber significantly.**
- **Theoretically it might be preferable to probe perpendicular wavenumbers**

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Summary

- **Turbulence measurements on NSTX should be as broad as possible**
  - Probe both low and high k turbulence: edge and core.
  - ETG and core measurements are currently lacking on NSTX
  - Reflectometry is limited by flat density profiles
  - Don't forget magnetic fluctuations: they could be important in a high beta device such as NSTX!
- **Correlation reflectometry can provide information on long wavelength turbulence as well as magnetic field strength and tilt angle**
  - Already observed strong scaling of correlation length with magnetic field
  - Demonstration of magnetic field strength measurement.
- **A fast interferometry/polarimetry system can also probe long wave turbulence**
  - Interferometry can provide a measure of the total fluctuation content at low k
  - Polarimetry can provide equilibrium information on central current density
  - Polarimetry would also be able to observe radial magnetic fluctuations and set absolute fluctuation levels. Sensitivity levels better than 0 .1 % should be acheivable.

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Summary - continued

- **Collective scattering is suitable for probing high k turbulence**
  - No other technique has been previously proposed for these fluctuation wavelengths
- **Back scattering approach offers very sensitive technique to probe high radial k**
  - Port requirement already satisfied: port availability is going to become a major issue on NSTX
  - Could be implemented quickly
  - May probe too large wavenumbers for ETG – not at the theoretically predicted peak.
- **Tangential and poloidal scattering options need careful consideration**
  - Either approach will require significant port allocation and careful mechanical design to minimize vibrations, misalignment etc.
  - Not as sensitive as back scatter technique
  - Options seem to be 300 GHz poloidal scattering vs infrared tangential scattering: can design optical system to collect a range of wavewnumbers to improve signal.
  - A collaborative system study may yield an optimum design – UCLA, PPPL, MIT, etc.

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