Turbulence Study of ETG &ITG on NSTX

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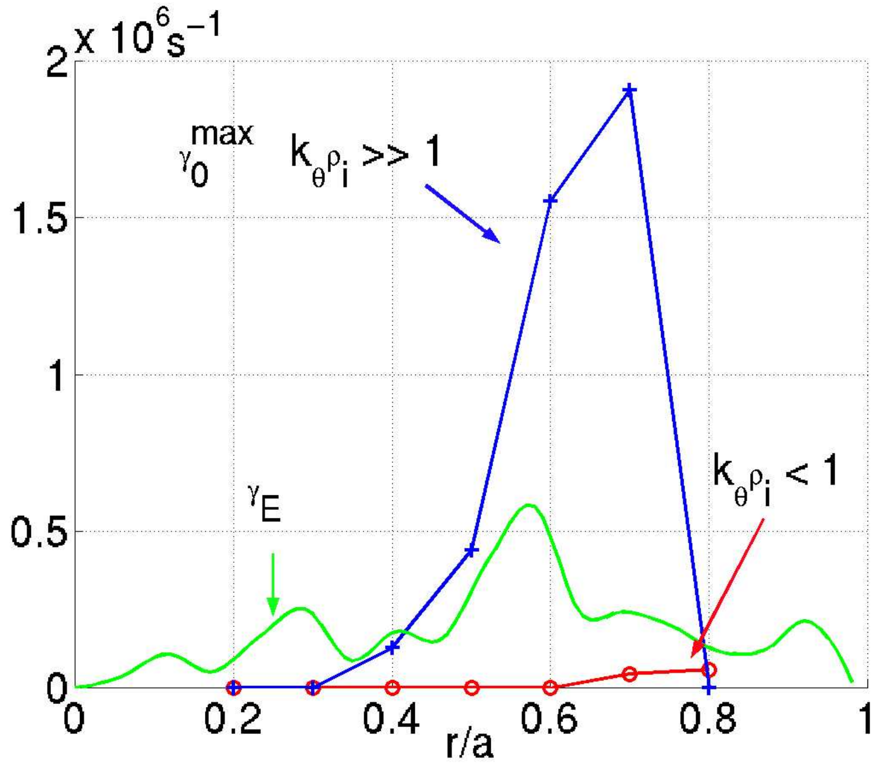
Introduction

- Importance of transport physics based on ETG modes in Toroidal devices
  - Scattering system that can explore ETG driven modes (high ***k*** and small amplitude requires high sensitivity & resolution which can distinguish the spectra from ITG
  - Suitable scattering system for this experiment
    - **Physical constraints**
    - **Source and detection system**
- Semi-local measurement of edge turbulence (ITG) by FIReTIP system
  - FIReTIP system has a capability to address semi-localized edge density and fluctuation at the edge (ITG)
  - L/H transition and other applications
- MIR system for ITG study (Tobin)

Transport Physics based on ETG Driven Turbulence Modes on ST

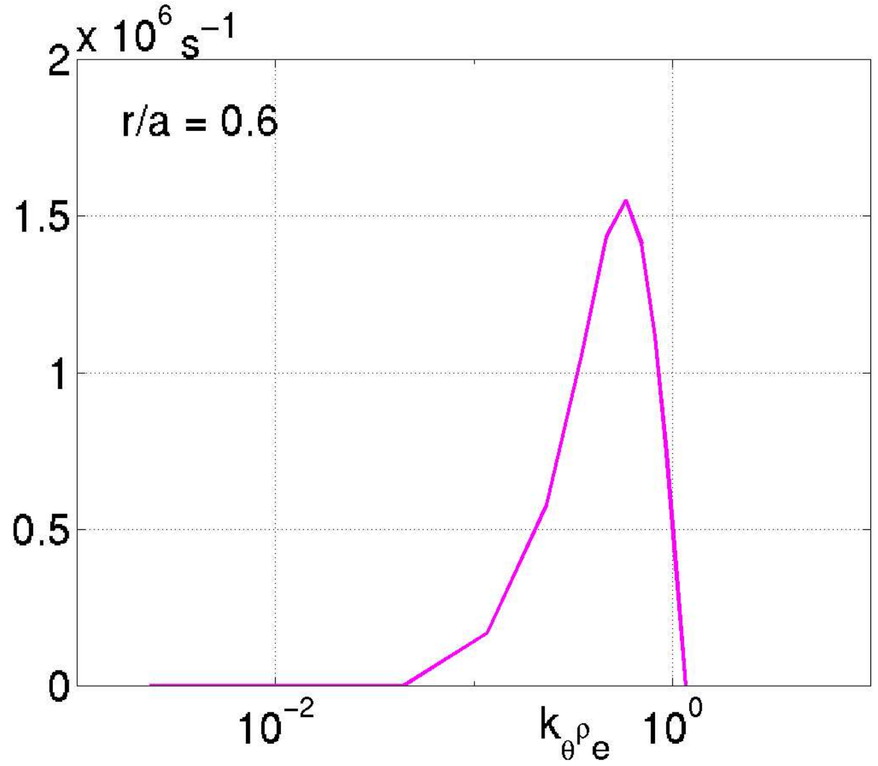
- Micro-stability Analysis using GS2, NBI Heated Plasma on NSTX
  - ETG modes ($k_e\rho_i >> 1$); unstable for r/a >0.4
  - ITG modes ($k_e\rho_i <1$); stable for for entire r/a $:\gamma_0^{max} \sim < \gamma_E$
  - E x B shearing rate, γ_E, dominated by $\nabla_r V_\varphi$ NCLASS, W. Houlberg



Bourdelle

Wavenumber Spectra

- ETG modes around $k_\theta \rho_e \sim 0.6$, where k_θ is 36 cm^{-1}
- Nonlinear simulation of ETG shows the peak of spectrum around $k_\theta \rho_e \sim 0.1–0.2$, where $k_\theta \sim 6$ - 12 cm^{-1}
  - Tool: linear local GKEM initial value code GS2



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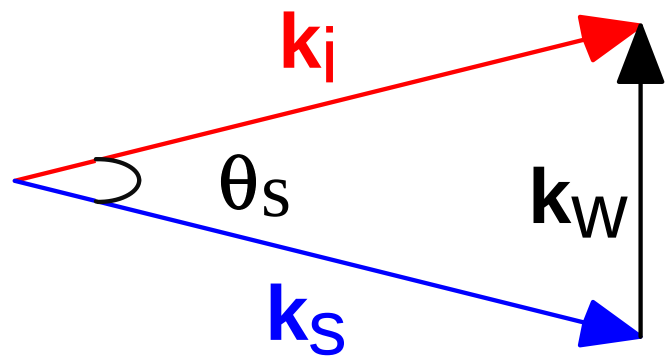
Scattering Theory for Turbulence Study

- Scattering is a powerful tool
  - Spatial resolution **(~5 cm)** is determined by scattering angle and beam waist for plane wave case
    - **$L_s = 2\omega_o / \sin(\theta_s)$, ω_o** is the beam waist
    - K-matching condition due to curvature of magnetic field

      K resolution is determined by the size of the beam

      $\Delta \mathbf{k} = 2/\omega_0$, where ω_0 is the beam waist



$$\mathbf{k}_s = \mathbf{k}_i + \mathbf{k}_w$$

$$\omega_s = \omega_i + \omega_w$$

θ_s is the scattering angle

Scattering system for Radial *k*

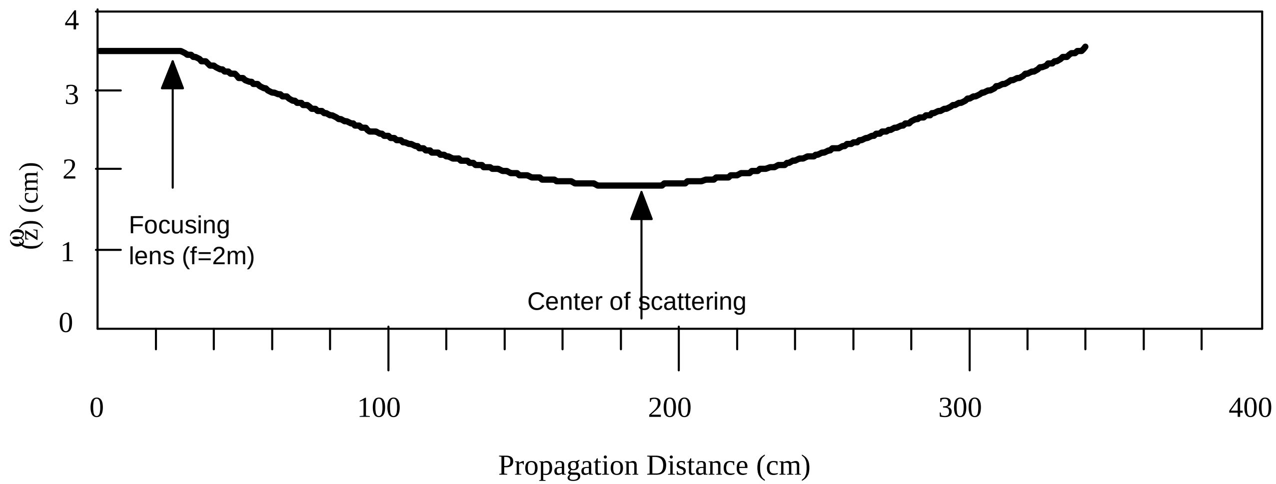
- Radial *k* on NSTX: relevant to transport physics
- ETG modes (an ultra-small fluctuations (below 0.1 % level)
  - Multi-k measurement is essential to distinguish ETG modes from the tail of ITG modes
    - Ranging from 5 cm^{-1} to 40 cm^{-1} from one radial position (0.6 <r/a< 0.8)
    - Absolute/relative calibration of the system is essential
  - S/N ratio should be large with
    - High input power
    - Longer wavelength (P_s prop. λ^2)
    - Maximum transmission at the windows

Proof of principle experiment on NSTX

- Radial wavenumber measurement
  - Relevant measurement for transport physics
  - Three discrete wavenumbers will be measured at ρ=0.65 ~0.8
    - k_r~6 cm^{-1}, k_r~20 cm $^{-1}$ and k_r~30 cm $^{-1}$
- Detection system will be calibrated independently
  - Acousto-optic technique will be used
- Definitive identification of ETG modes
  - Slope of the power spectrum of three wavenumbers will identify that the measured spectrum is ETG or a tail of ITG
  - Large S/N for the target fluctuation

Characteristics of the input beam

- Radiation source
  - High power microwave source : P_o ~ 300 mW (CW)
  - Wavelength : λ ~ 1.1 mm (280 GHz)
  - Probe beam wavenumber: $k_0 = 57.1\ cm^{-1}$
- Beam waist at the center of scattering volume: ω_o = 2.5 cm



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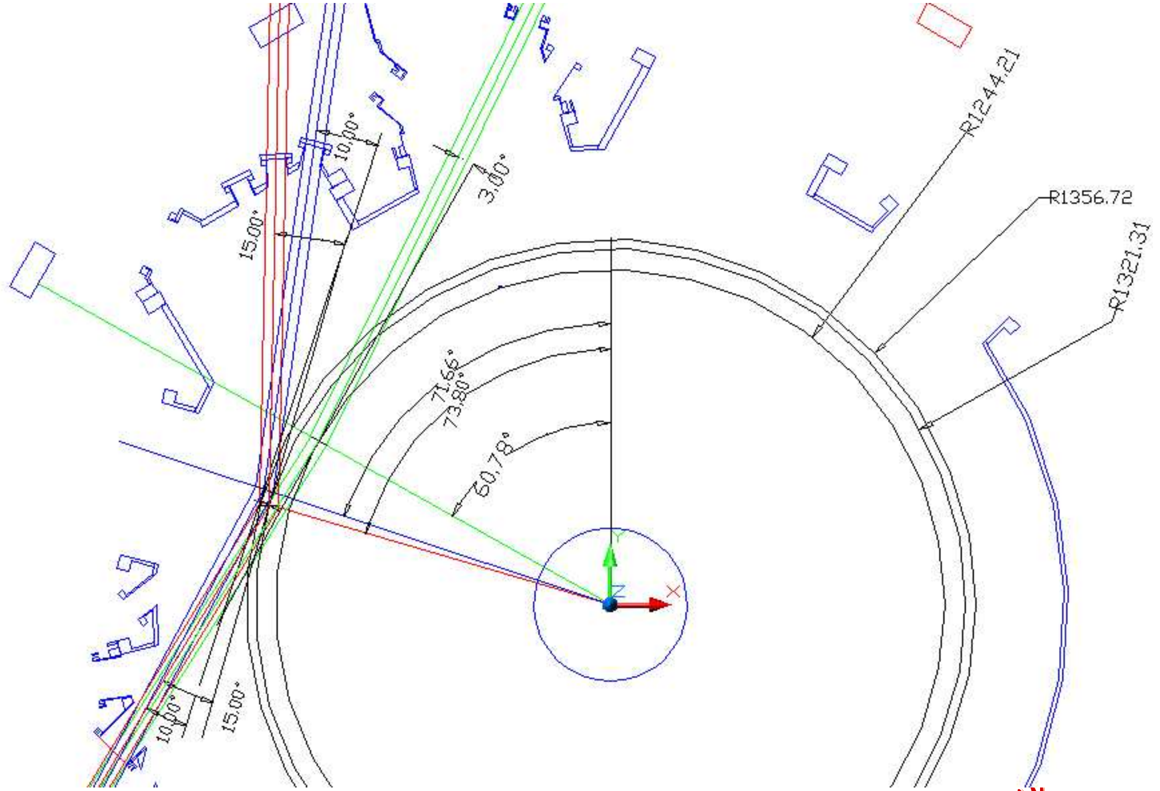
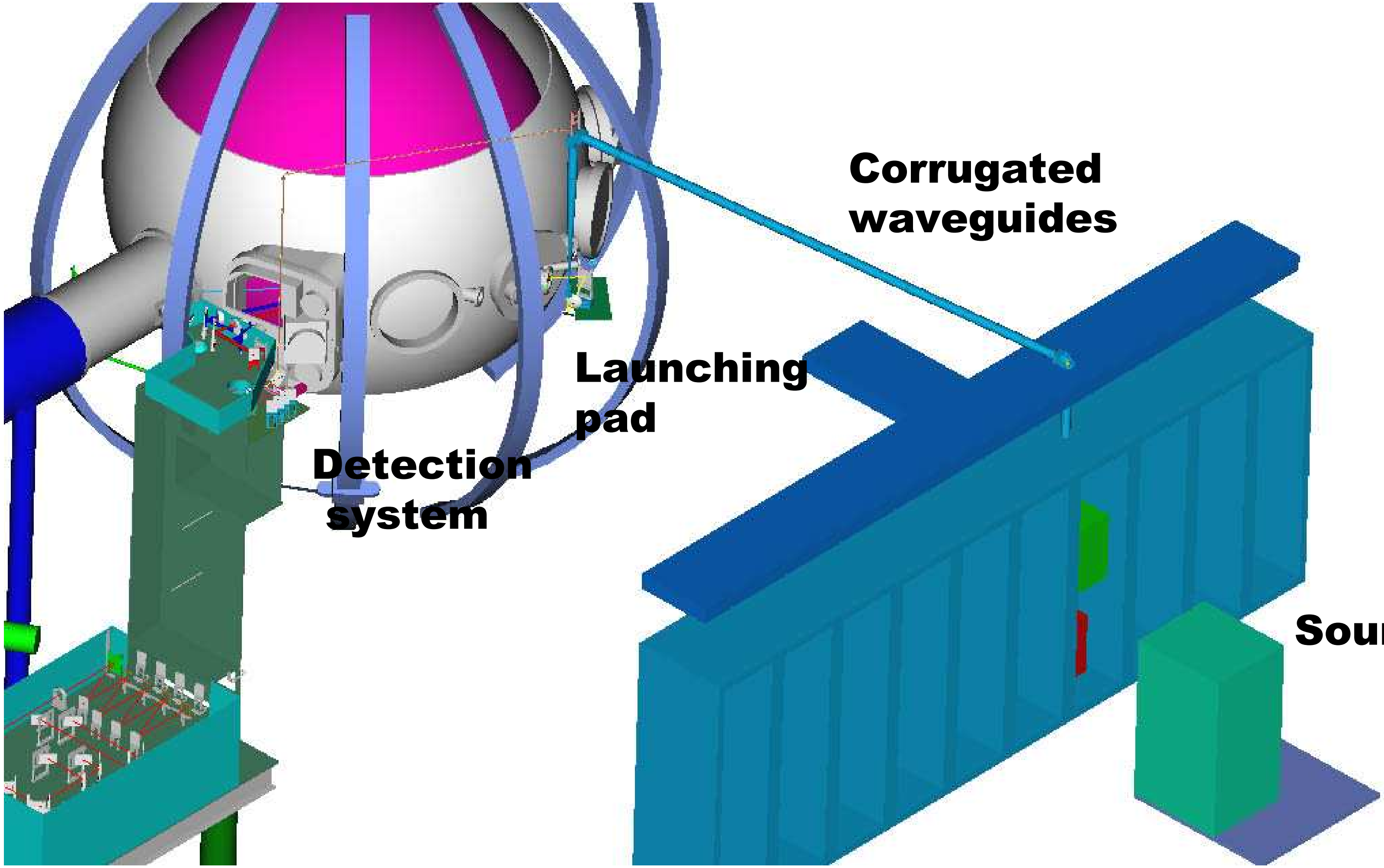
Scattering geometry

- Input beam enters from Bay-I and directed into the vacuum duct
- Two FIReTIP windows at Bay –K and one window at vacuum duct will be used to intercept three scattered signals (~6, ~20, and ~30 cm^{-1})

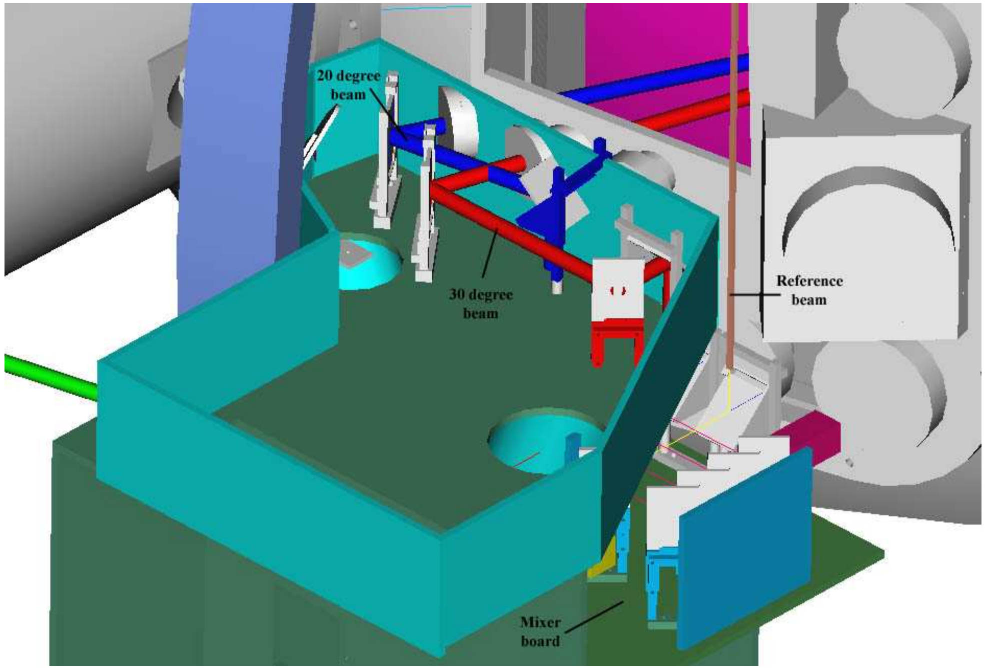


Scattering system design

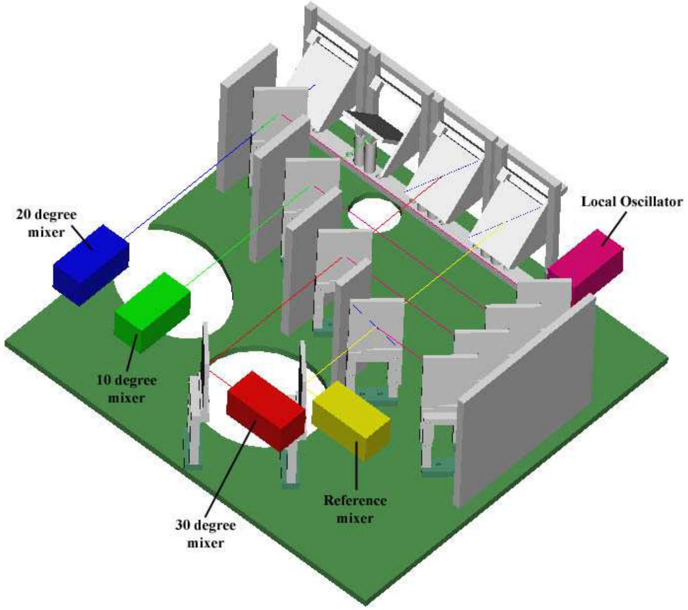


Detection system

- Detection systems are installed on the FIReTIP system tower



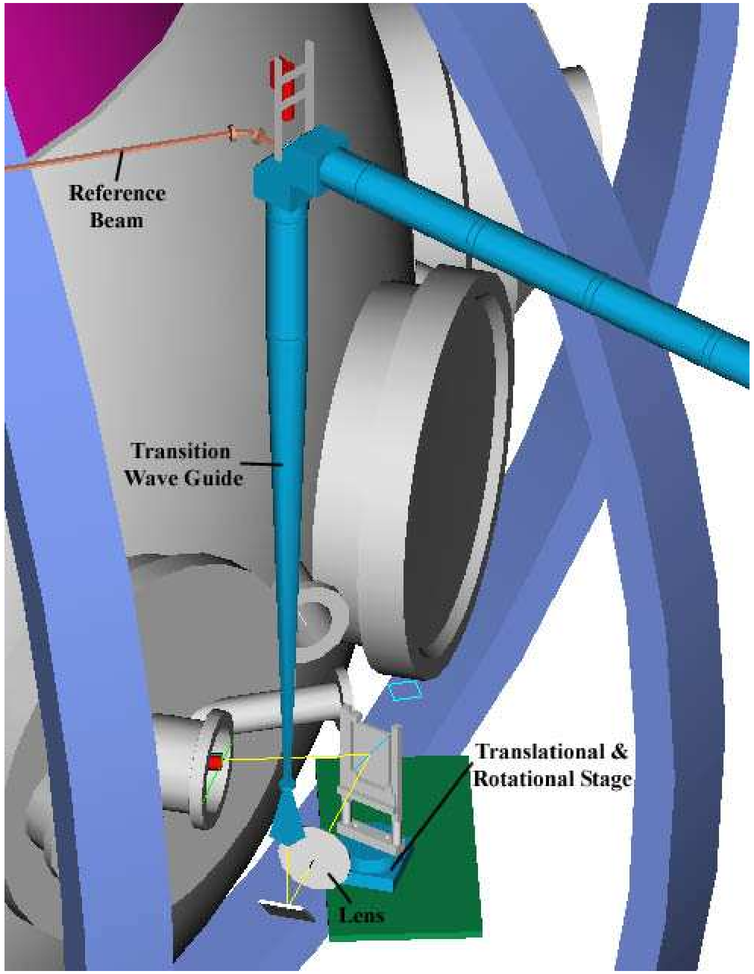
Scattered beams area guided to the detection system

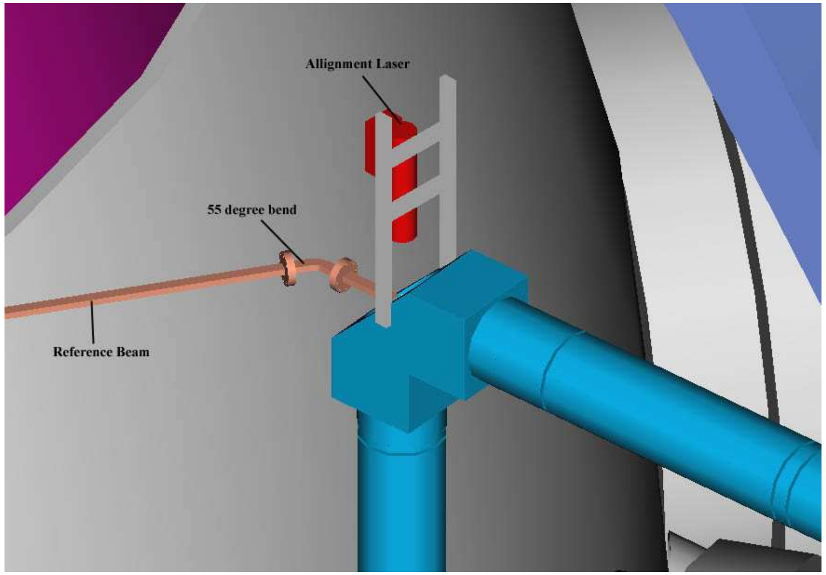


Three channel Detection system

Launching system

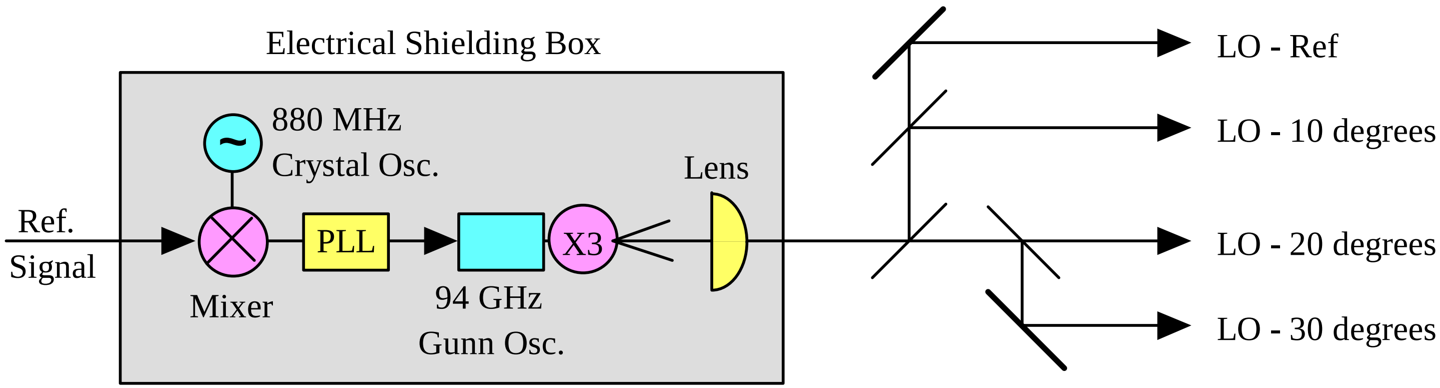
- Alignment laser (visible) is attached to the mitre bend





Pick-off point for
Ref. signal

Frequency Locking and Detection System



- Schematic diagram of the solid state 280 GHz LO source, the arrangement to phase-lock the source to an 880 MHz crystal oscillator, and the use of beamsplitters and mirrors to provide LO signals for the four receiver mixers.

Estimation of the Scattered Signal Level

- Scattered Power is

$$P_s = \frac{1}{4} P_i \left[\frac{\omega_p}{\omega_i}\right]^4 k_i^2 L_{\|} L \left[\frac{\tilde{n}}{n}\right]^2 \left[\frac{2}{k_\perp \omega}\right]^2$$

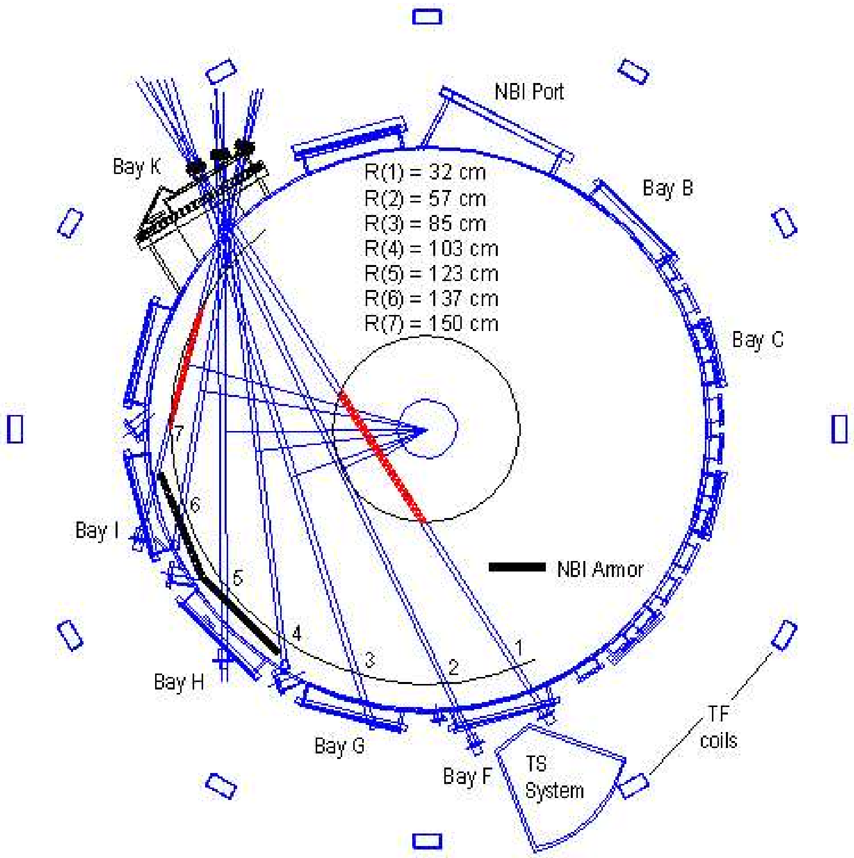
  - Where P_i is the incident power, ω_p is the plasma frequency, ω_i is the probe beam frequency, L is the scattering length, $L_{||}$ is the length of the scattering region along the magnetic field. The average spectral power density is given as

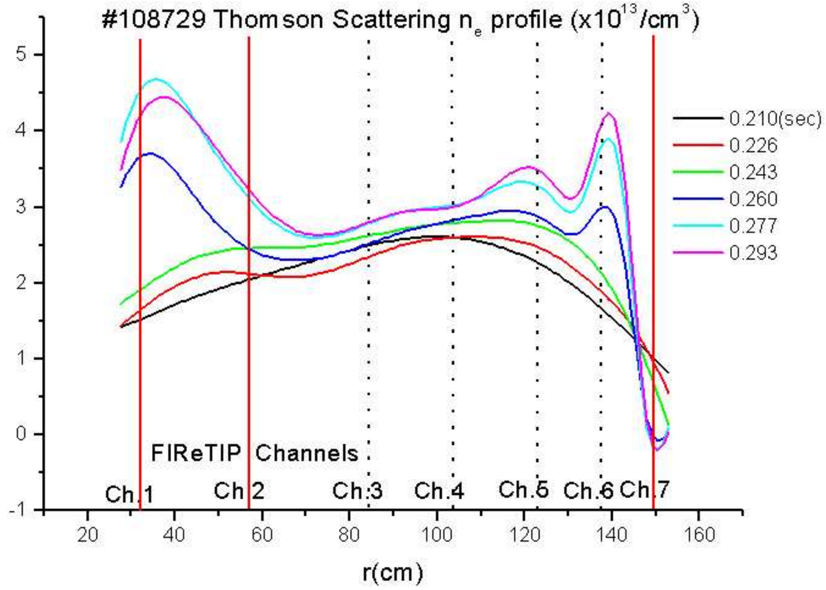
$$\tilde{n}^2 = \frac{< S >}{(2\pi)^3} (\pi k_\perp^2) \frac{2\pi}{L_{\|}}$$

  - For P_i = 100 mW, L~$L_{||}$=5 cm, n_o=2.5x10^{13}cm^{-3} and ω_o =3 cm, P_s=4.5x10^{-9} W.
  - Detection system with NEP of 2000^{o}K and 8dB conversion loss will provide a minimum detectable power of 7 x 10^{-13} W for ~2 MHz bandwidth
  - S/N is ~2000

ITG edge turbulence/density via FIReTIP

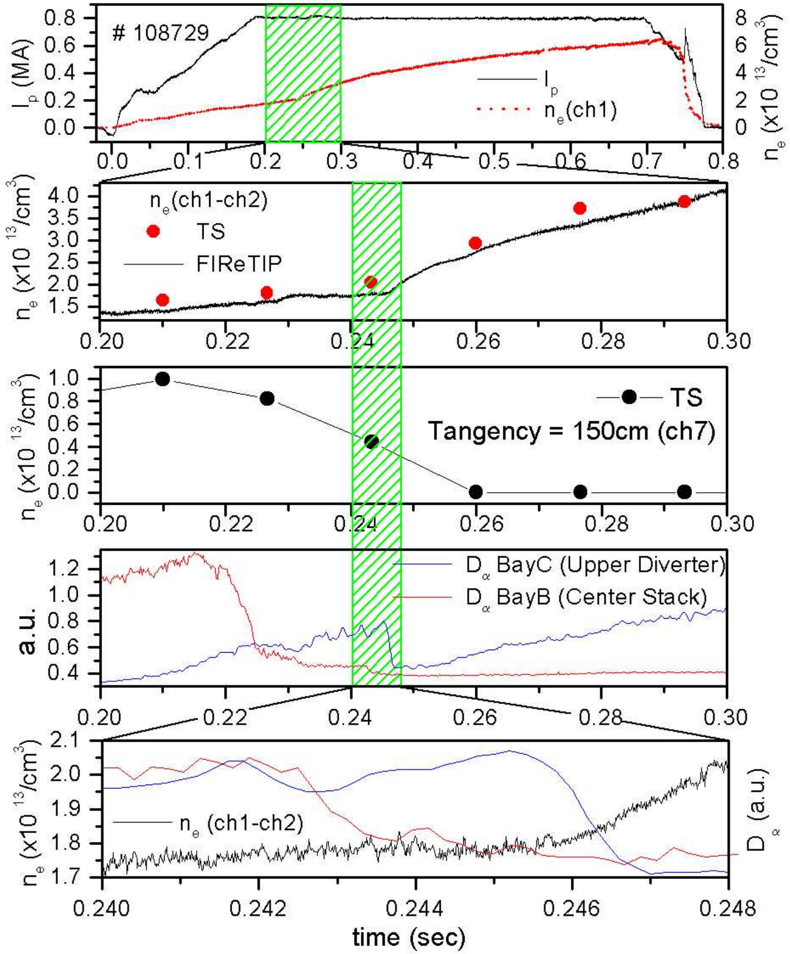
- Two edge channels (inside and outside) can measure semi-localized density and turbulence (absolute)





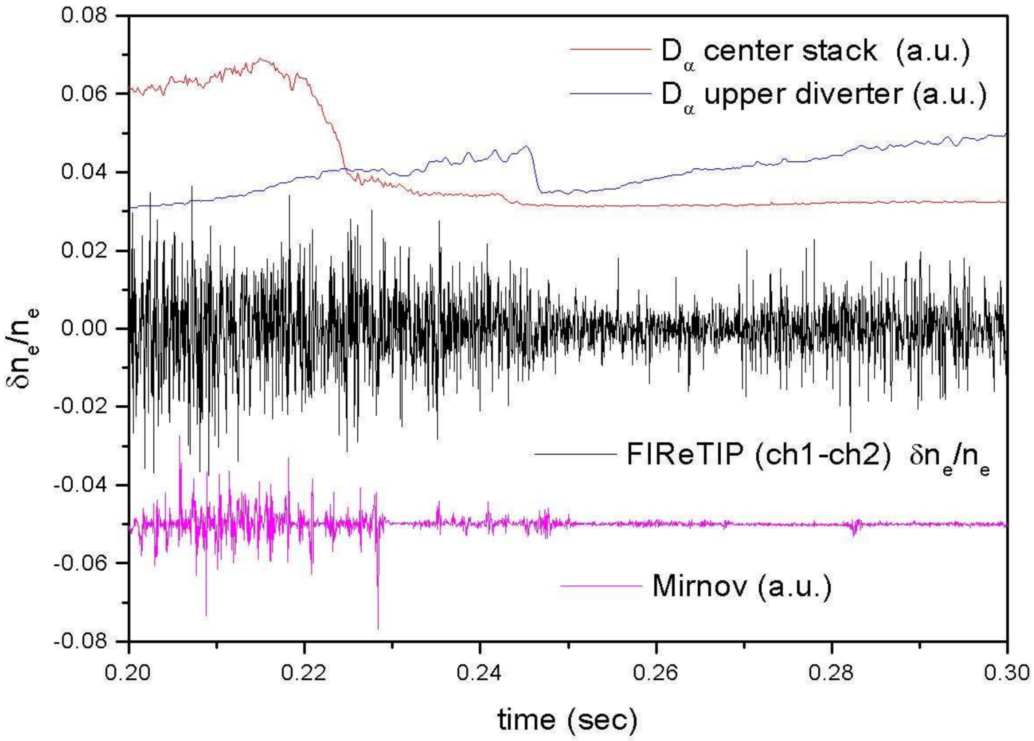
Chordal positions wrt Thomson density profile

Edge density rise during L/H transition



- Inner edge density, well correlated with D_α(divertor) indicates a sudden rise during L/H transition
- Similar data from outer edge channel (ch7) will be available in the next run (in/out symmetry, density flow, etc.)

Density Fluctuation during L/H transition



First time observing phase fluctuation on ST

- Phase fluctuation suppression
- Near absolute calibration (~4 % level fluctuation)
- IF system for the low frequency fluctuation measurement will be installed

Microwave Imaging Reflectometry for fluctuation measurements on NSTX

PPPL – U.C. Davis Collaboration

Presented by

Tobin Munsat

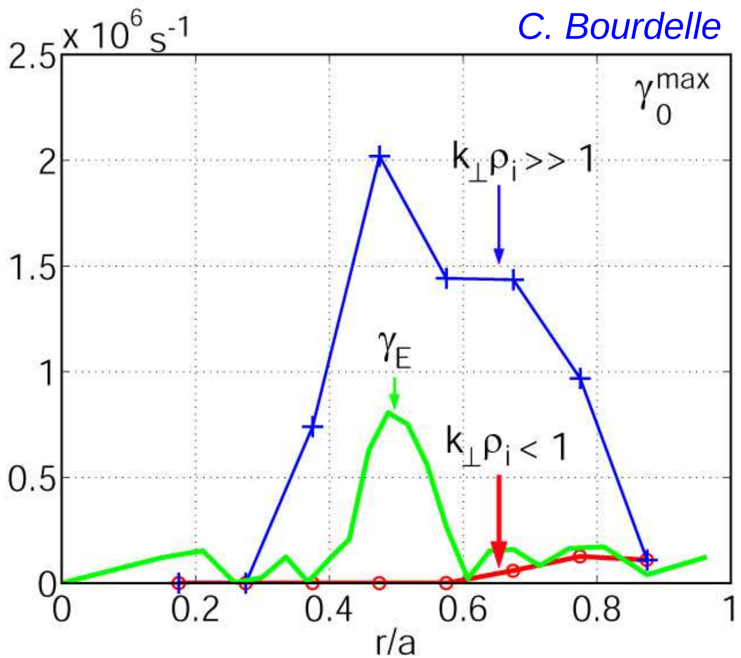
PPPL

NSTX Research Forum
PPPL Princeton, NJ
September 12, 2002

Turbulent fluctuations in NSTX

- ITG turbulence ($k_\perp \rho_i \approx 0.2\text{-}1.0$) implicated in all standard explanations of ion transport

- Experimental assessment of long wavelength turbulent fluctuations lags far behind numerical simulations



- Physics needs:
  - Survey capability for fluctuations over many $k_\perp$ values and spatial locations
  - Spatial resolution (radial/poloidal) of long wavelength modes
  - Core measurements
  - Comparison of turbulence characteristics with conventional tokamaks
  - Comparison of turbulence characteristics with numerical simulations

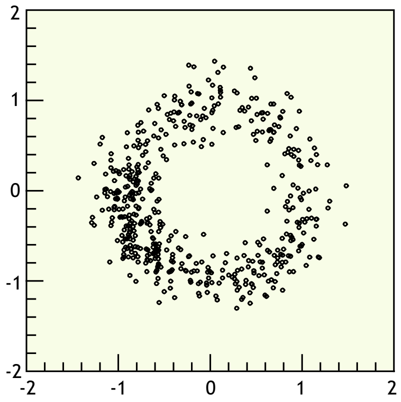
Effect of Fluctuations on 1-D Reflectometer Signal

- Reflectometer signals (here TFTR) corrupted by interference from reflected wave components
- Power spectrum and amplitude distribution verify randomized interference pattern

TFTR microwave signal phase plots

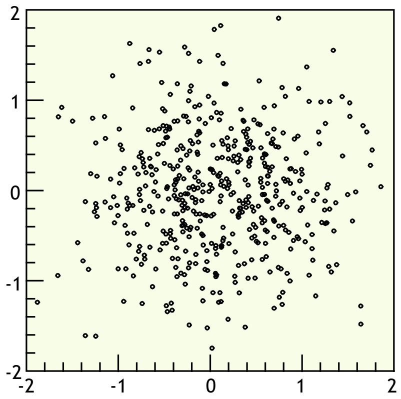
Weak turbulence

(clean signal)

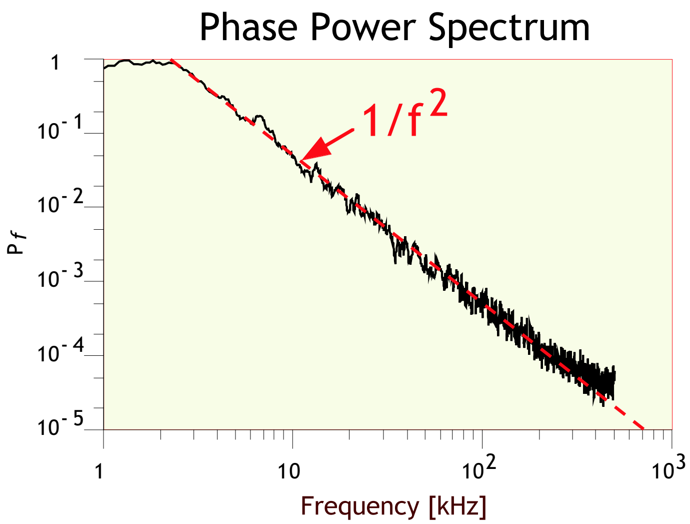


Strong turbulence burst

(distorted signal)

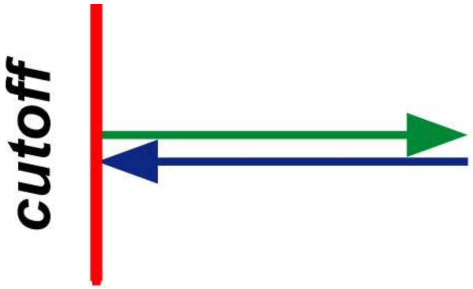


Spectral information lost for strong turbulence case

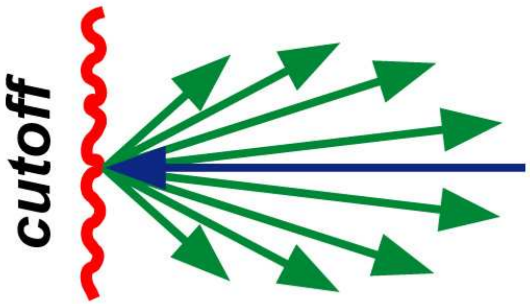


E. Mazzucato, *et al.*, Phys. Rev. Lett. **77**, 15 (1996)

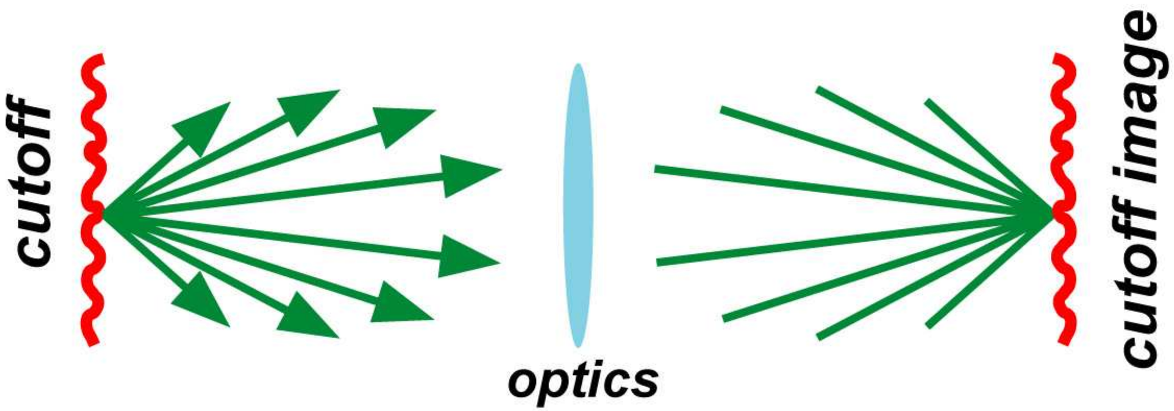
What is Microwave Imaging Reflectometry?



1-D fluctuations:
straightforward
interpretation

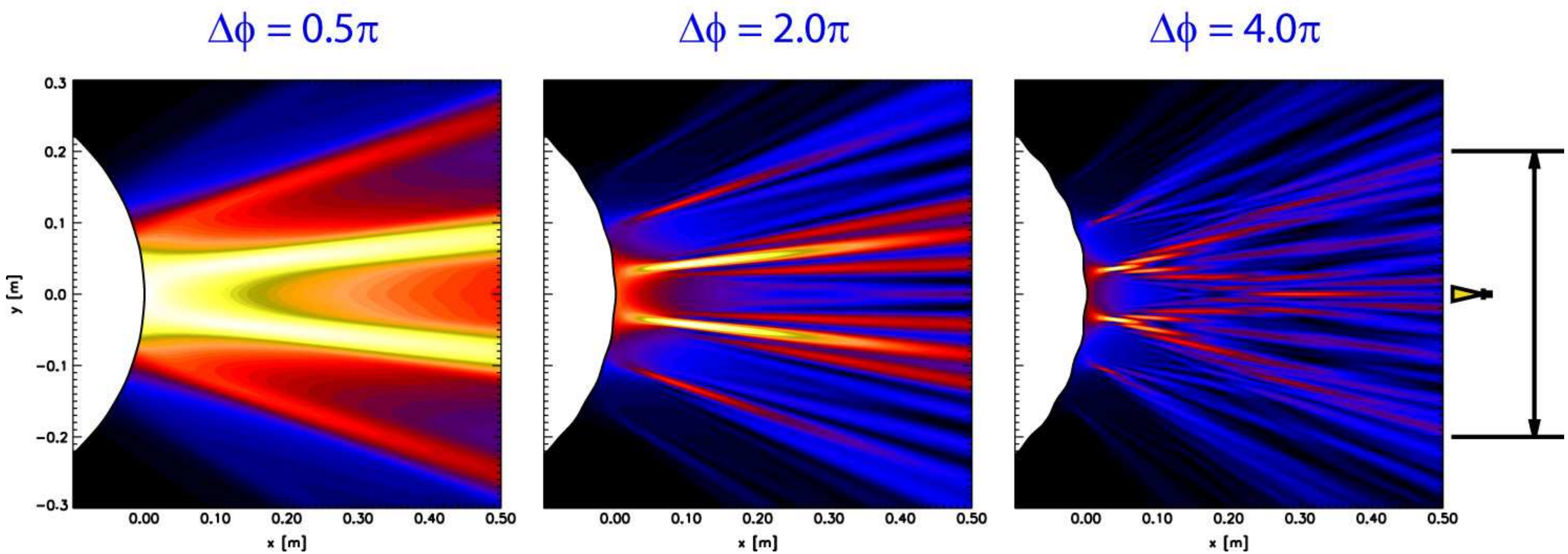


2-D fluctuations can
lead to interference



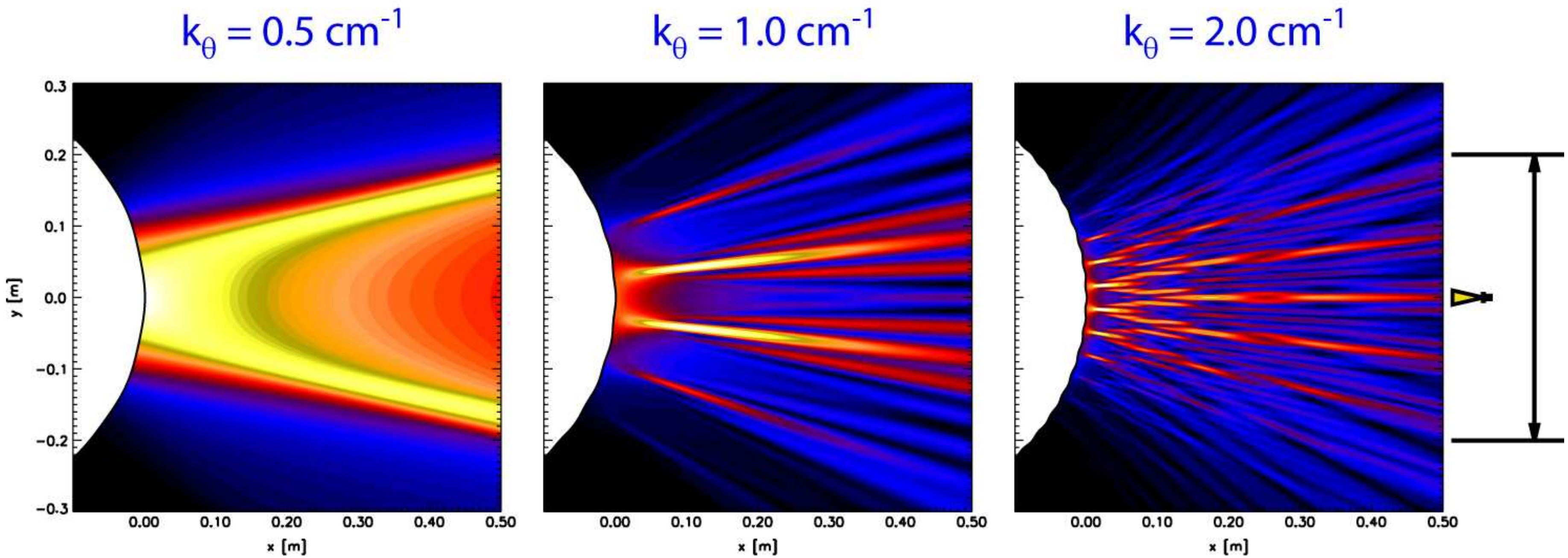
Imaging can restore phase front

Reflected field amplitude demonstrates interference patterns with increasing $\Delta\phi$ ($\tilde{n}/n$)



$k_\theta = 1.25\ cm^{-1}$

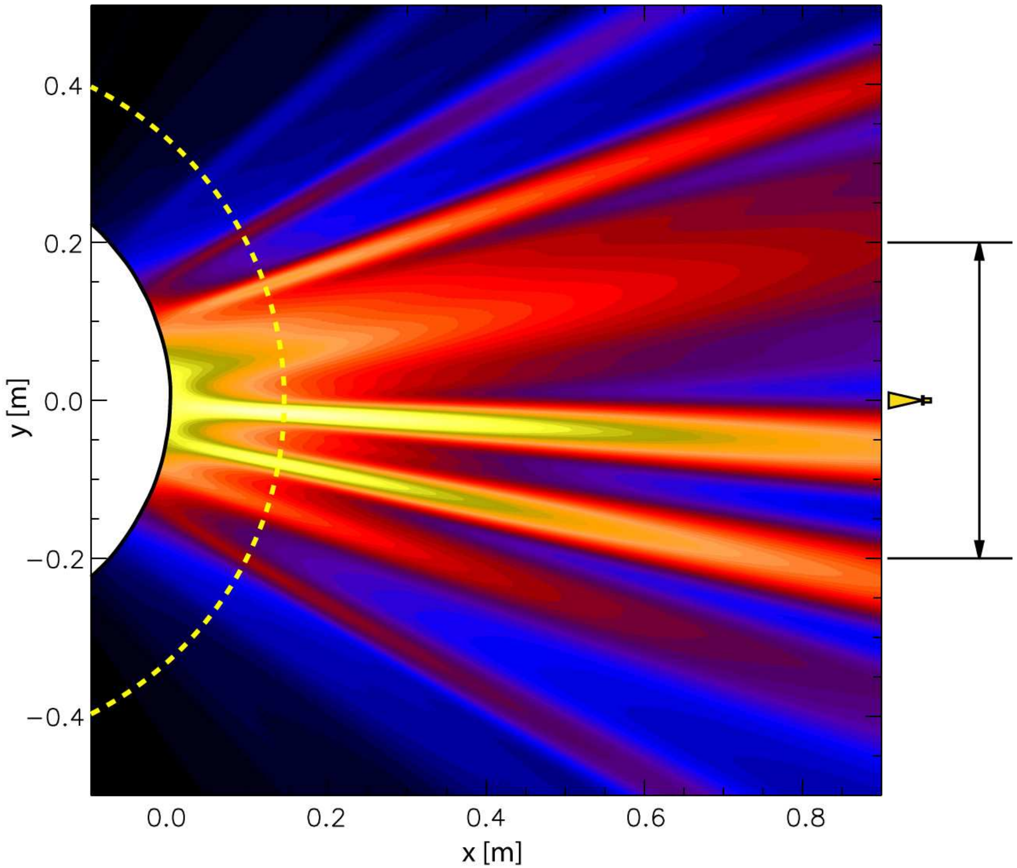
Reflected field amplitude demonstrates interference patterns with increasing k_θ



$$\delta\phi = 2\pi$$

Summary of Target Reflector Response Expressed as Diffraction Distance

Δk_θ = 1.0 cm^{-1} , <δϕ> = 0.5π

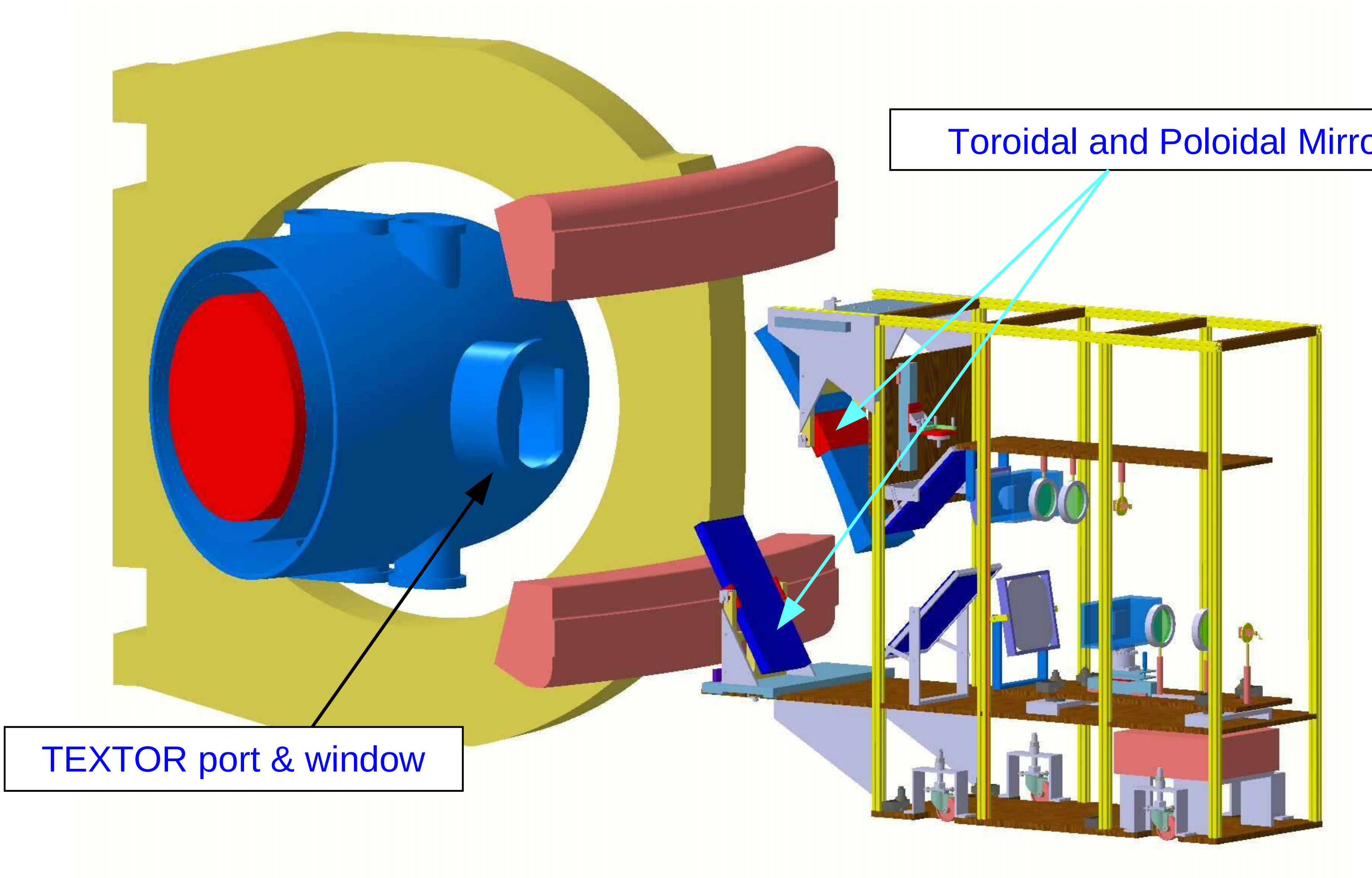


Critical distance beyond which interference becomes significant is described by *diffraction distance*

$$D = \frac{2\,k_0}{\left(1+\sigma_\varphi\right)^2 \Delta k_\theta^{\,2}}$$

For NSTX parameters of $\sigma_\phi = \pi/4$ ($\delta n_e \approx 1\%$), $\Delta k_\theta = 1$ cm^{-1}, $D \approx 5$ cm

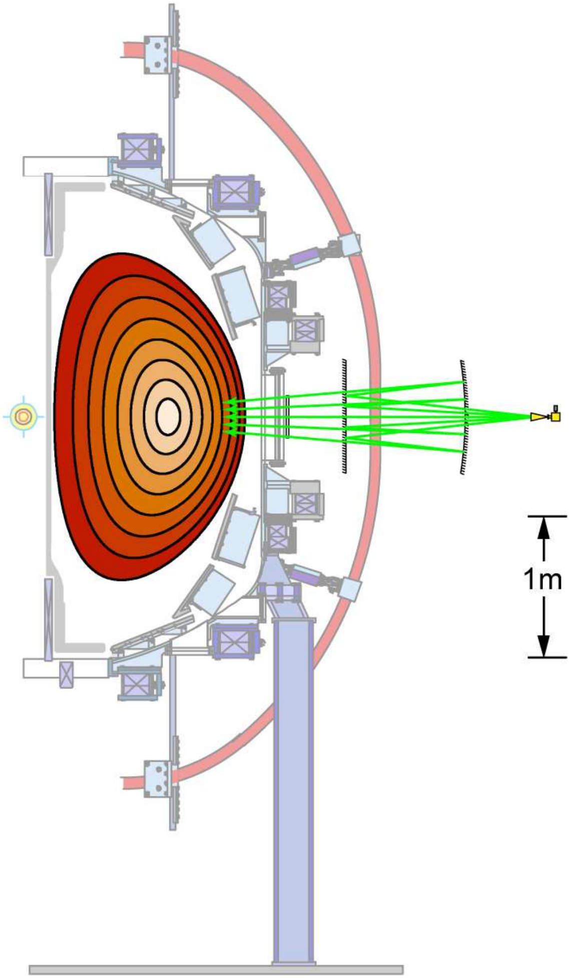
Combined MIR/ECEI Imaging System Under Development for TEXTOR



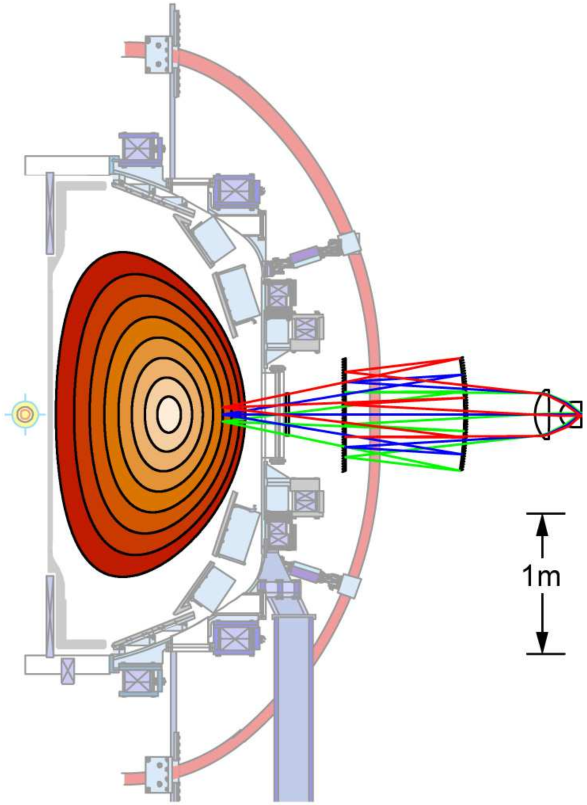
TEXTOR resumes operation November 2002

MIR geometry on NSTX

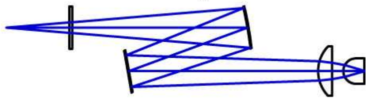
Illumination



Detection



Top View

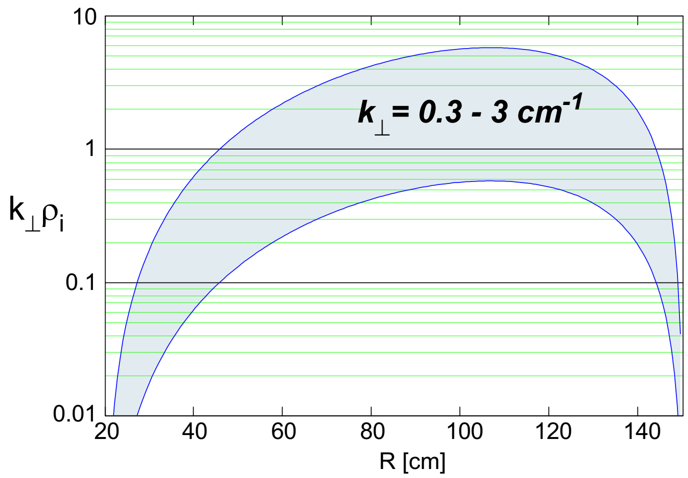


MIR Issues for NSTX

- *Poloidal coverage:*

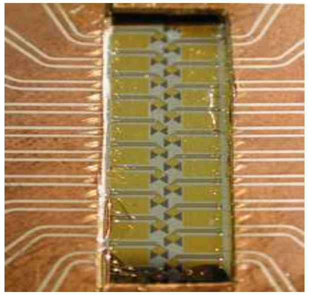
  ~ 12 cm (full angular coverage)

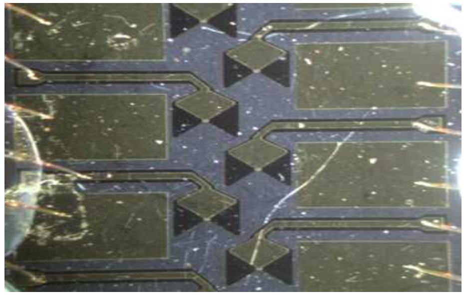
  ~ 20 cm (reduced angular coverage)
- *Spatial resolution: ~ 1 cm*
- *k_θ resolution: ~ 0.3-3 cm^{-1}*

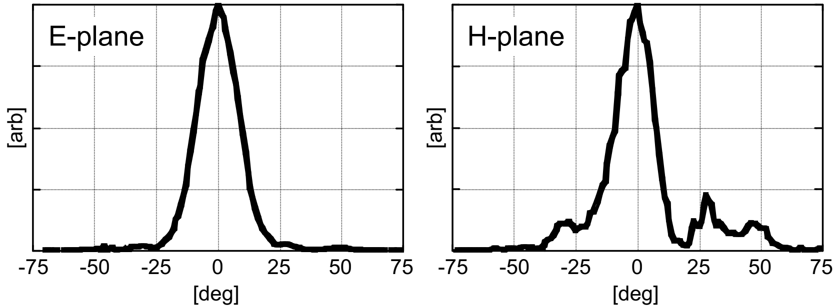


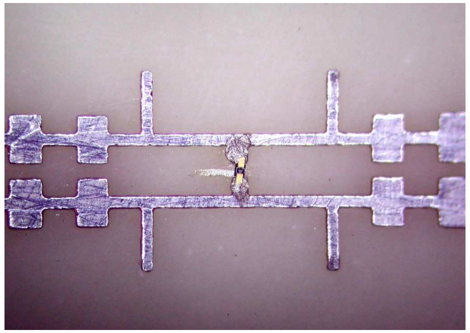
- *Simultaneous localized measurements at many poloidal and radial locations $\rightarrow$ time-resolved mapping of k_θ and k_r*
- *Extends range of measurable fluctuation levels and wavenumbers over conventional reflectometry techniques*
- *Large vacuum window required (~30 cm)*
- *Ongoing experiment on TEXTOR supports development, enables cross-platform comparisons*

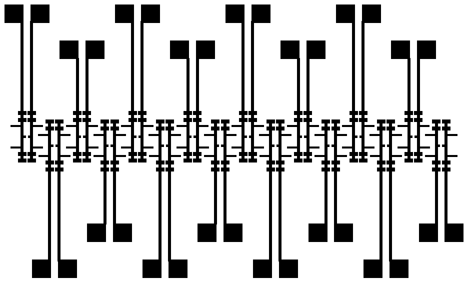
Detector Technology Supports MIR Implementation











- Detector array development enables imaging schemes
- Integrated detector/mixers inexpensively provide multiple channels
- Printed array elements enable scale-up to large arrays
- New dual-dipole antenna provides ~15% bandwidth, with increased sensitivity and cleaner patterns than previous antennas
- Ongoing research effort to improve performance

Conclusion

- Microwave Imaging Reflectometry can provide:
  - *Poloidally resolved density fluctuation measurements*
  - *Radially resolved density fluctuation measurements*
  - *Wavenumber resolution relevant to ITG turbulence*
  - *Extended parameter range for even single-point measurements*

  - *Development of NSTX system enhanced by TEXTOR work*
  - *Plasma elongation/access on NSTX better than TEXTOR*
    - *(improves coverage and resolution)*
  - *Large window required*

Supplementary slides

Complete MIR Diagnostic Can Be Characterized Off-Line

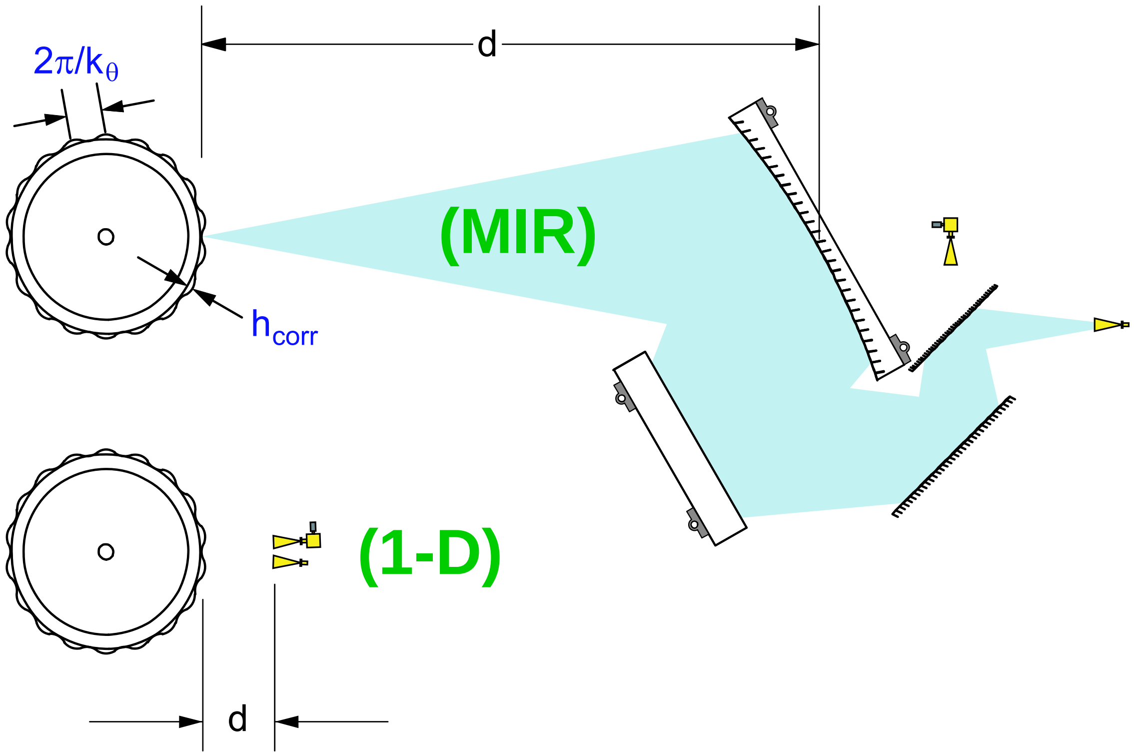
Known corrugated reflectors used to characterize complete MIR system response to range of k_θ and $\delta n/n$, and to compare performance of 1-D and imaging techniques

<u>Tested Targets:</u>

$k_\theta = 1.25\text{-}2.5\ cm^{-1}$

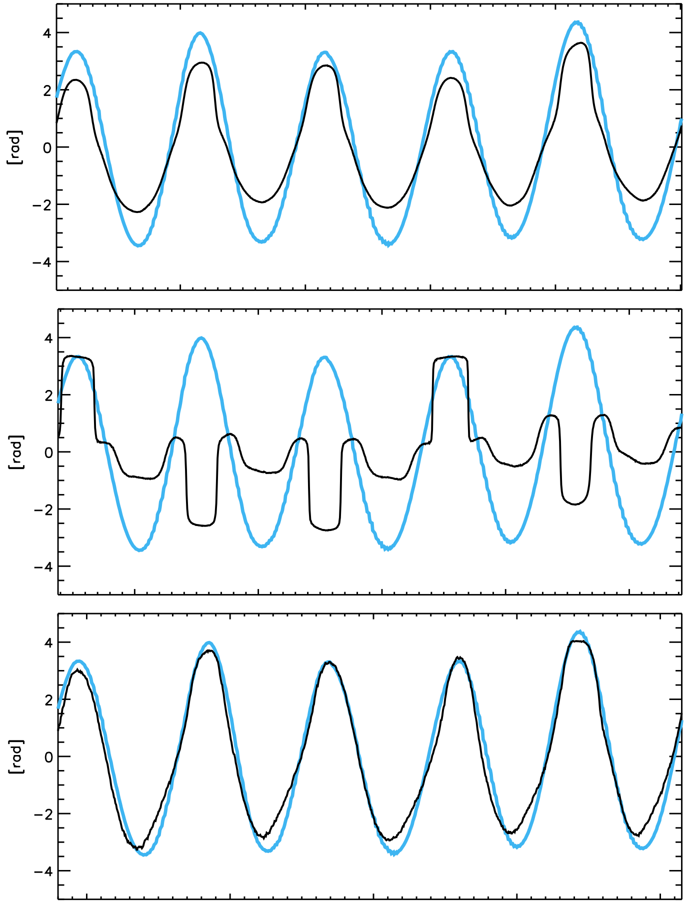
$\delta\phi = \pi - 2\pi$

$(\delta n/n \sim 0.5\text{-}1\%)$



Surface corrugation precisely measured with Leica "Laser Tracker" visible interferometer, used as reference for measurements

Reflectometer signals from rotating wheel demonstrate fundamental advantage of imaging



- Conventional (1-D) System

  d=10 cm

- Conventional (1-D) System

  d=30 cm

- Imaging System

  d at image focus

Blue curve is measured reference

$k_\theta = 1.25\ cm^{-1}$, $\delta\phi \approx 2\pi$ → $\tilde{n}/n \approx 1\%$

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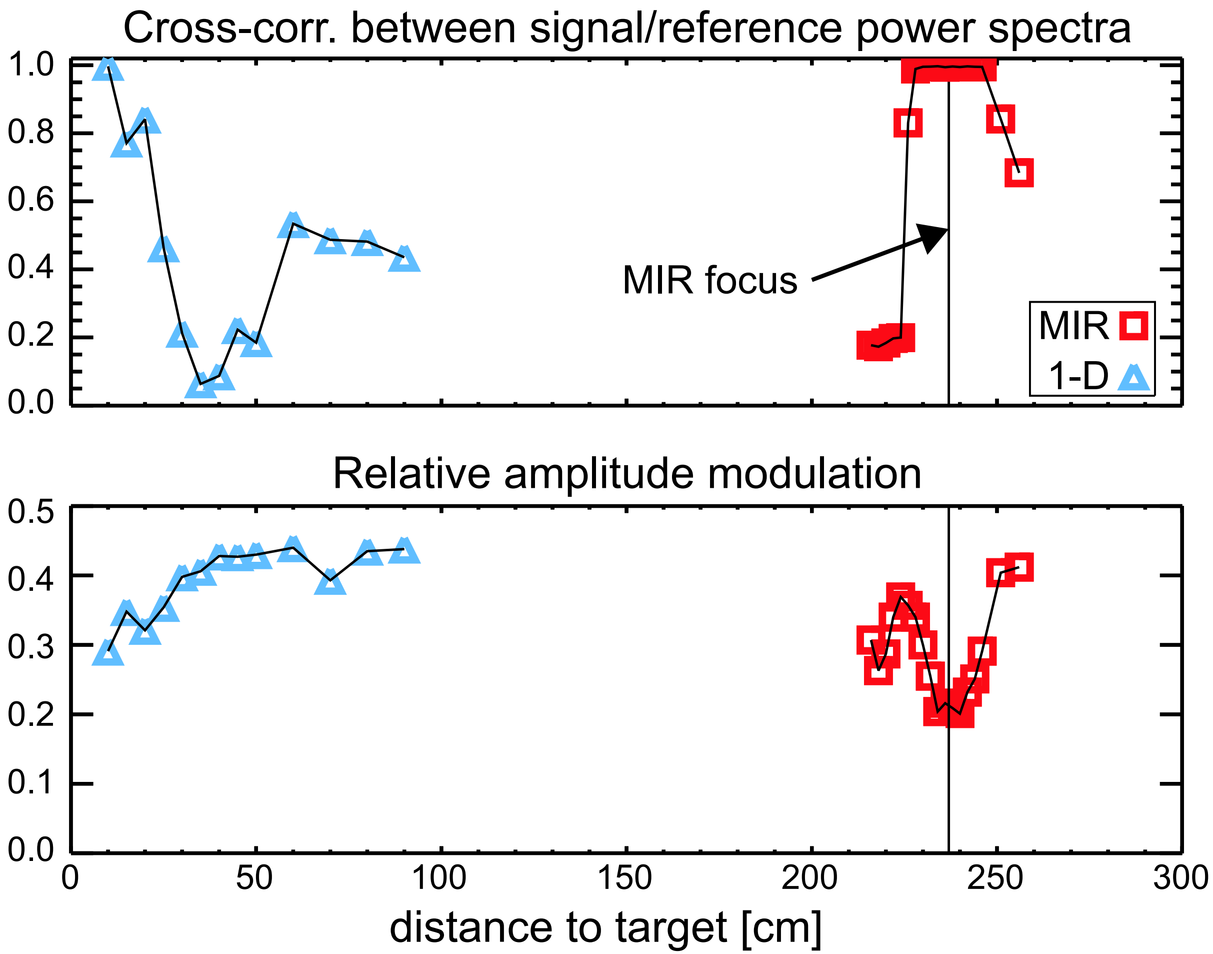
Cross Correlation between Reflectometers & Reference Power Spectra



- 1-D system correlation near unity for d<20 cm
- Decorrelated as d~30 cm
- MIR system near unity in focal range
- Falls off beyond 'depth of field'
- Amplitude modulation suppressed near focus in both systems

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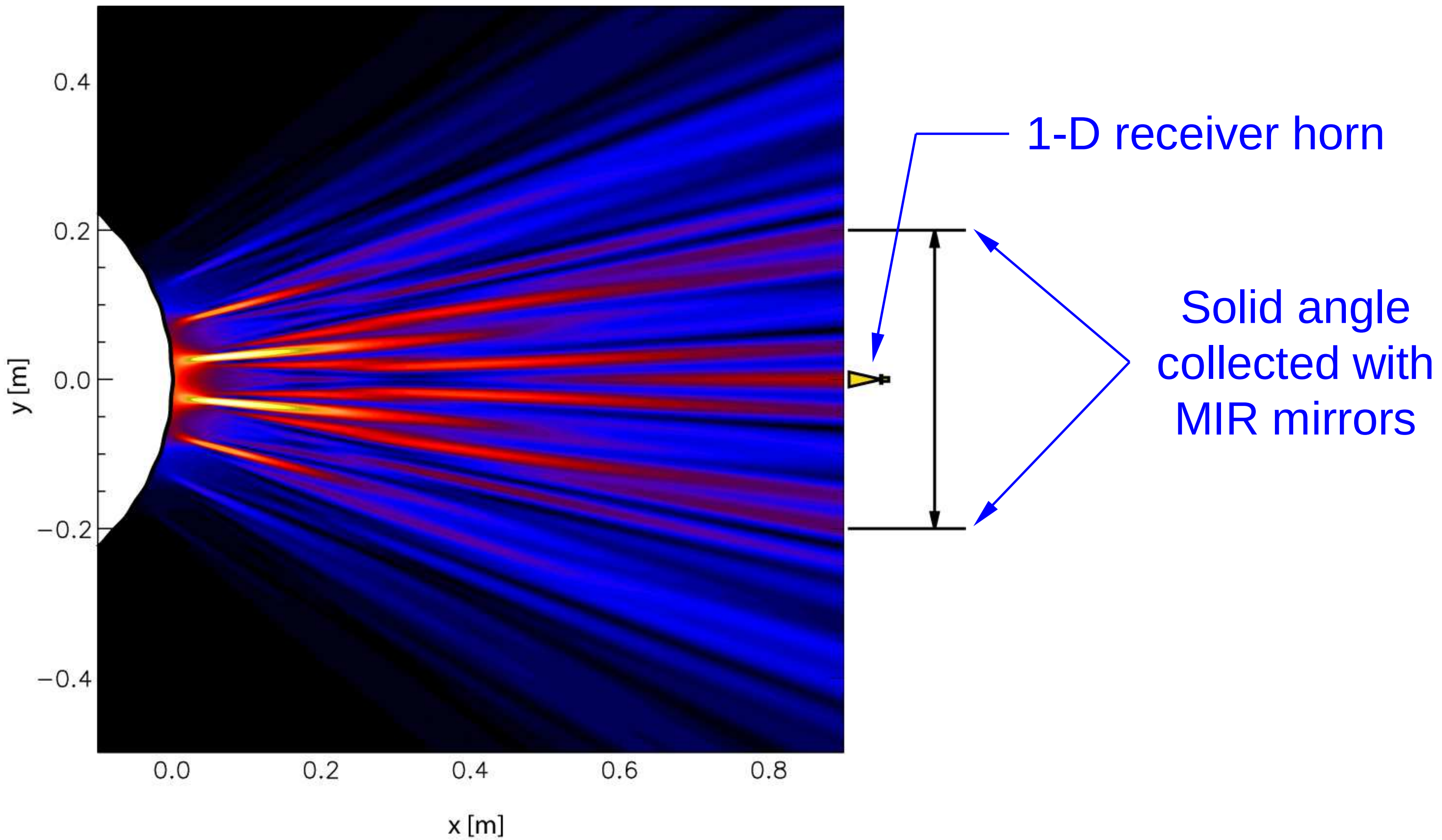
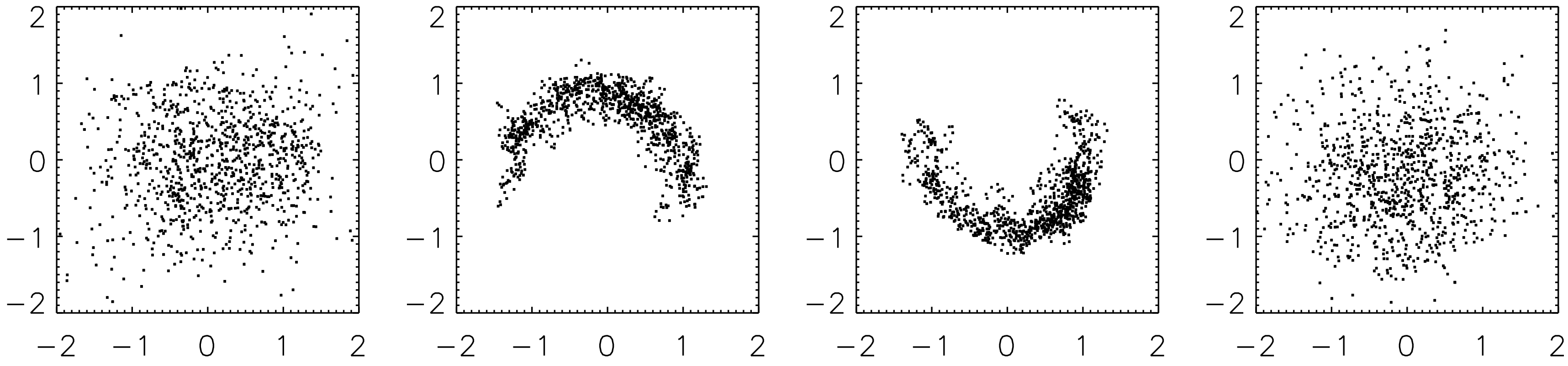
Analytic Solution of Reflected Field

$k_\theta = 1.25\ cm^{-1}$, $\delta\phi = 1.8\pi$

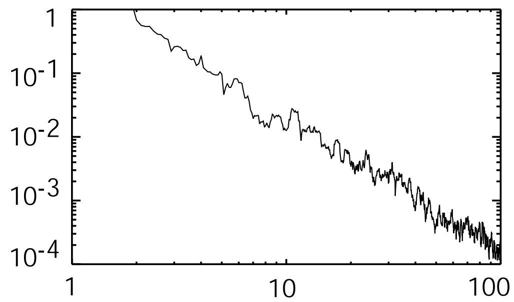


MIR Results from TEXTOR

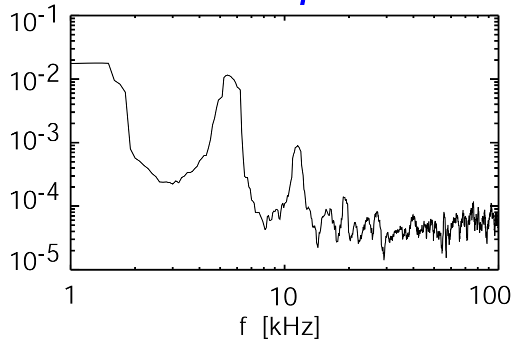
TEXTOR quadrature signals into focus back out of focus



unfocused spectrum



focused spectrum



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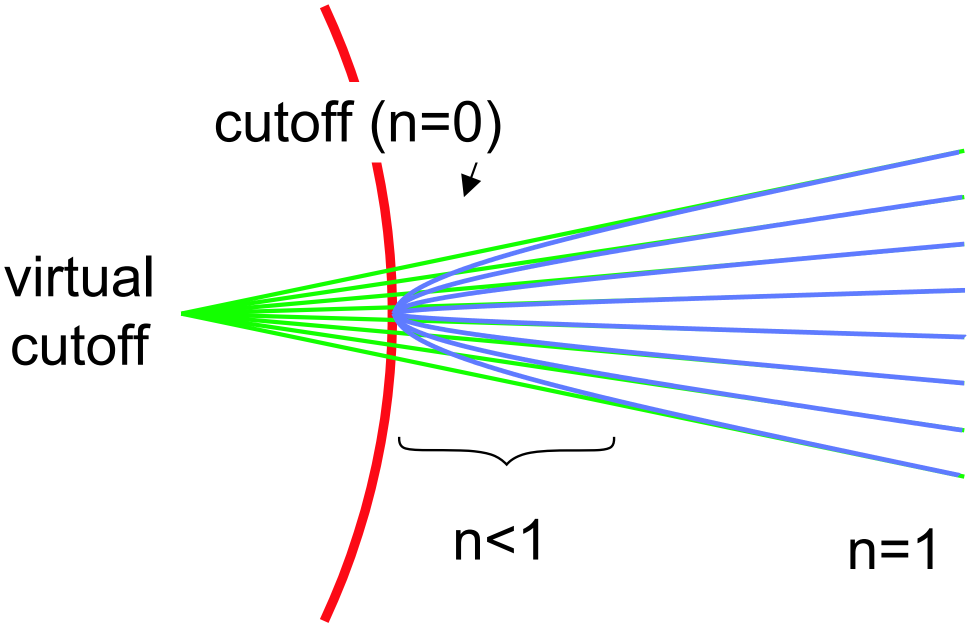
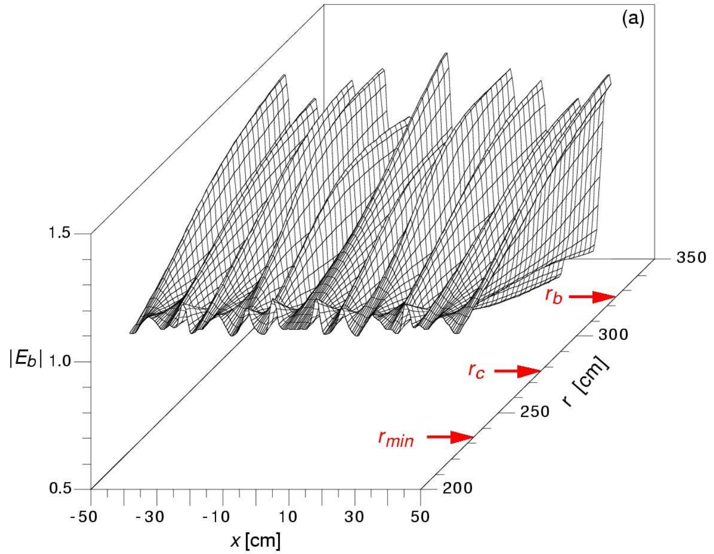
Existence of Virtual Cutoff Layer Allows Optical Focusing

- Problem: Refraction by plasma deviates beam paths
- Solution: There exists a “virtual cutoff” layer, located behind actual cutoff, where ray asymptotes arrive at common focal plane, *enabling optical imaging of rays*





E. Mazzucato, Nucl. Fusion **41**, p.203 (2001)