Two dimensional phase contrast imaging of micro-turbulence in LHD

C.A. Michael, K. Tanaka, L. Vyacheslavov[1], A. Sanin[1],
K. Kawahata, S. Okajima, N. Tamura, S. Inagaki and LHD experimental group

National Institute for Fusion Science, Toki, Japan

[1] Budker institute for nuclear physics, Novosibirsk, Russia

Abstract

2D PCI is an excellent method to measure core and edge turbulence with good spatial resolution ($\Delta\rho$~0.1). Recent progress in 2D PCI is presented, focusing on signal interpretation and cross-beam correlation techniques.

A new means (for us) to interpret the line-integrated fluctuation signals is presented. Fluctuations with any component propagating along the line of sight are not detected. The ramifications of this constraint are discussed, including how radial streamers and zonal flows may appear in the detected signal. Some examples of measurements are given.

A cross-beam correlation technique is used to provide an alternate means of spatial resolution in the plasma edge. Results from this technique, presented, show the strong presence of low frequency coherent modes, in addition to a broadband component, and provide a more clear picture than with just 2D PCI alone

Outline

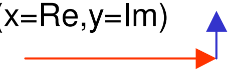
- Principles and signal interpretation
  - Measurement principles
  - Interpretation of line-integrated fluctuations
  - how to interpret asymmetry
  - Image processing using Maximum entropy power spectrum
- Typical Spatial profiles from 2D system
  - Comparison of phase velocity with rotation velocity
  - fluctuation profile change during non-local transport
  - spectrogram features
- Cross-beam technique
  - Geometry
  - Results (broadband & coherent mode)

Phase contrast imaging

Small phase (density) fluctuation ϕ Incident beam electric field A_0, intensity I_0

Phase shifted electric field: $A_0 e^{i\phi} \approx A_0 + A_0 i\phi$

complex phasor diagram (x=Re,y=Im)



intensity = I_0

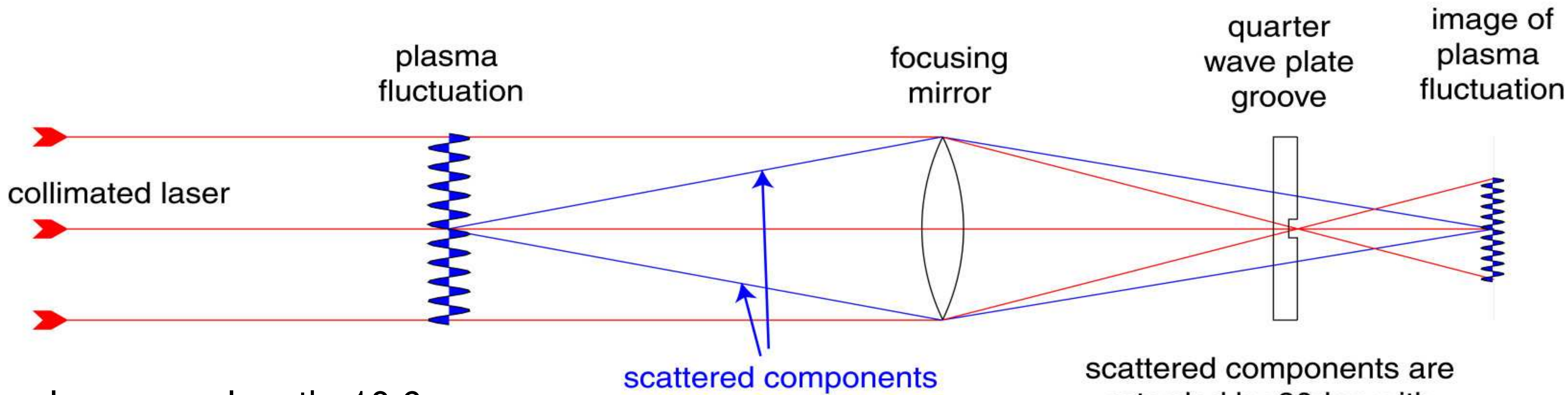
spatially separated at phase plate

Undiffracted component (A_0) Diffracted component ($A_0 i\phi$)

phase/amplitude converstion: interferometer with "internal" reference

After quarter wave plate: $iA_0 + A_0 i\phi$

intensity = $I_0(1+2\phi)$

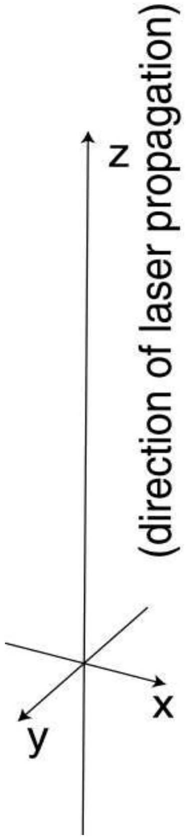


laser wavelength: 10.6μm
Fluctuation scale: ~1cm
scattering angle: ~0.06deg

scattered components are retarded by 90deg with respect to unscattered components

Spatial localization using magnetic shear principle

- Because scattering angle is small, cannot directly resolve position along line of sight



<u>Fluctuation 3-d wavevector k is perpendicular to local field line:</u>

For all fluctuations: $$k \cdot B = k_x B_x + k_y B_y + k_z B_z = 0$$

For measured fluctuations: $$k_z = 0$$ because of line-integration effect! (next slide)

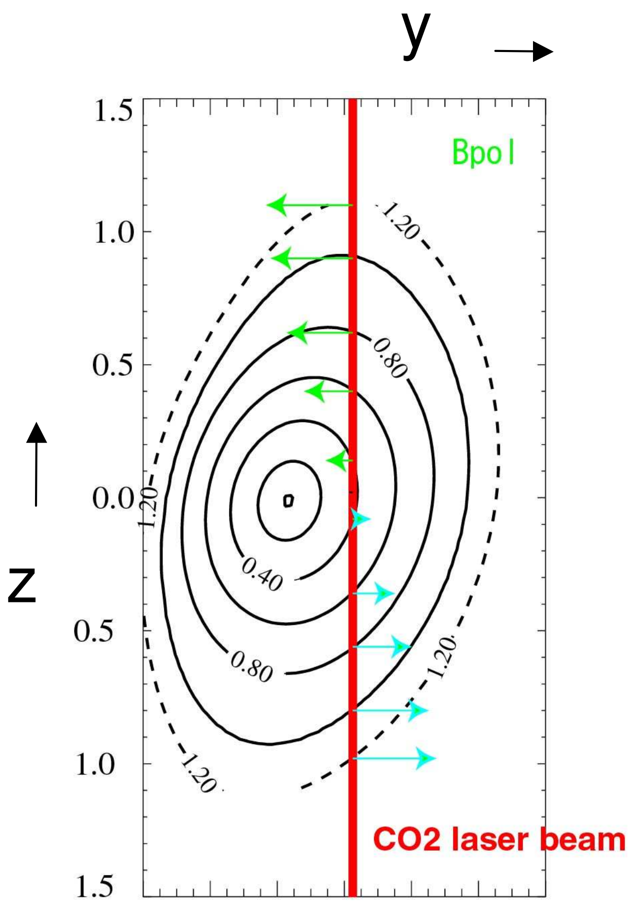
For fluctuations in image plane: $$k_x B_x + k_y B_y = 0$$

i.e. <u>projection of fluctuation</u> is perpendicular to <u>projection of local field line</u>

Motivation: use a **2d detector** to obtain **spatial resolution**

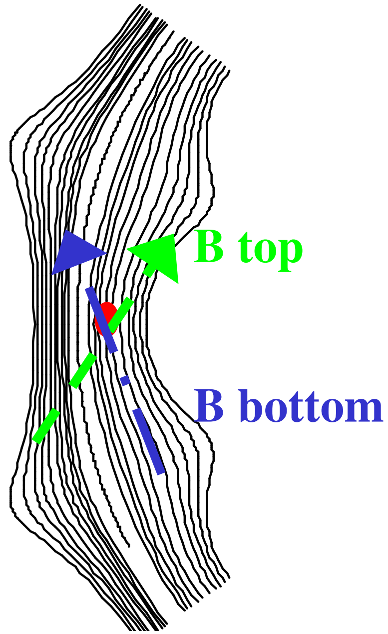
2D imaging on LHD

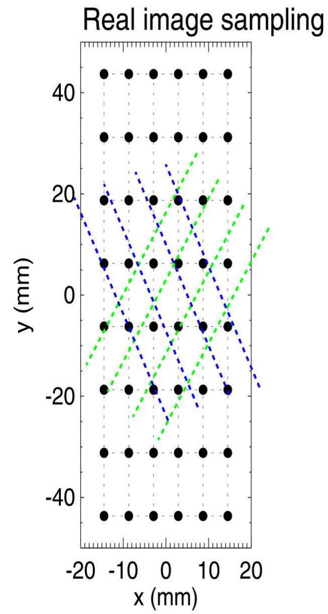
Side View



Rax=3.6m,beta=0%

Top View

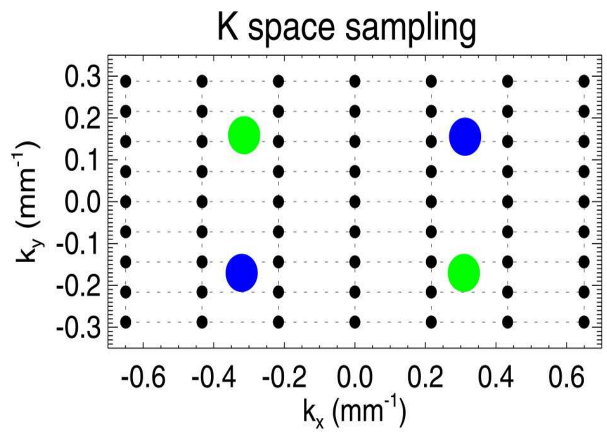


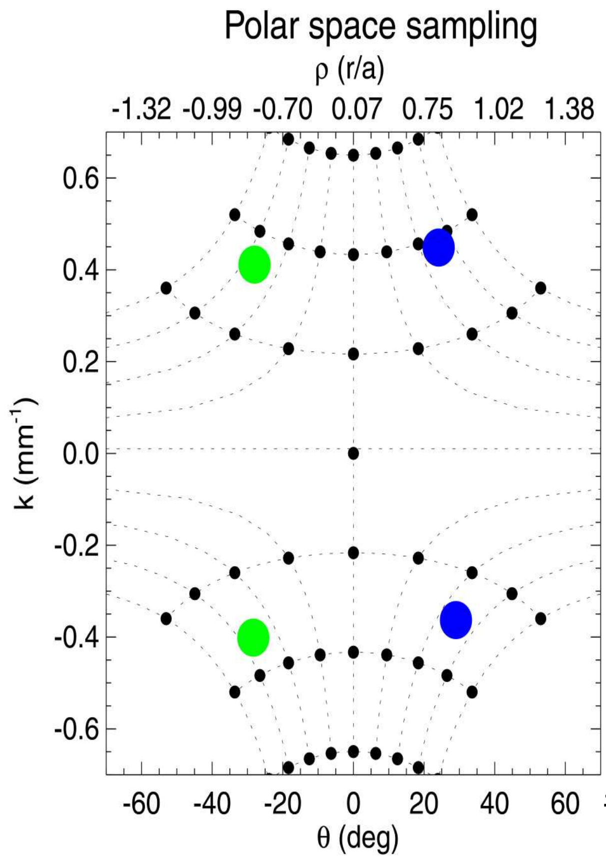


Polar conversion:

$$k = \sqrt{k_x^{\ 2} + k_y^{\ 2}}$$

$$\theta = \tan^{-1}(k_y / k_x)$$





Interpretation of Line-integrated fluctuations

Results:

Local to line-integrated fluctuations:

$$\bar{\Gamma}(x, y, \Delta x, \Delta y) = \iint \Gamma(x, y, z, \Delta x, \Delta y, \Delta z)\, d\Delta z\, dz$$

Local to line-integrated power spectrum:

$$\bar{S}(k_x, k_y) = \int S(k_x, k_y, 0, z)\, dz$$

i.e only sensitive to $k_z = 0$

Local to line-integrated fluctuation rms:

$$\tilde{N}^2 = \tilde{n}^2 l_c L$$

where:

L is extent in z dimension of fluctuation

$$l_z = \frac{S(k_z = 0)}{\int S(k_z)\, dk_z} \sim \frac{1}{k_{zc}}$$

but! dependent highly on $S(k_z)$ and projection angle

Definitions:

z axis along beam.
x and y axes perpendicular to beam

local density fluctuation: $\tilde{n}(x, y, z)$

line-integrated density fluctuation:

$$\tilde{N}(x, y) = \int \tilde{n}(x, y, z)\, dz$$

Local correlation function:

$$\Gamma(x, y, z, \Delta x, \Delta y, \Delta z) = \left\langle \tilde{n}(x, y, z)\tilde{n}(x + \Delta x, y + \Delta y, z + \Delta z) \right\rangle$$

Correlation of line-integrated fluctuations:

$$\bar{\Gamma}(x, y, \Delta x, \Delta y) = \left\langle \tilde{N}(x, y)\tilde{N}(x + \Delta x, y + \Delta y) \right\rangle$$

Line-integrated power spectrum:

$$\bar{S}(k_x, k_y) = \int \bar{\Gamma}(\Delta x, \Delta y) e^{ik_x \Delta x} e^{ik_y \Delta y}\, d\Delta x\, d\Delta y$$

Local power spectrum:

$$S(k_x, k_y, k_z, z) = \int \Gamma(\Delta x, \Delta y, \Delta z, z) e^{ik_x \Delta x} e^{ik_y \Delta y} e^{ik_z \Delta z}\, d\Delta x\, d\Delta y\, d\Delta z$$

(assuming correlation function is homogeneous in x and y directions)

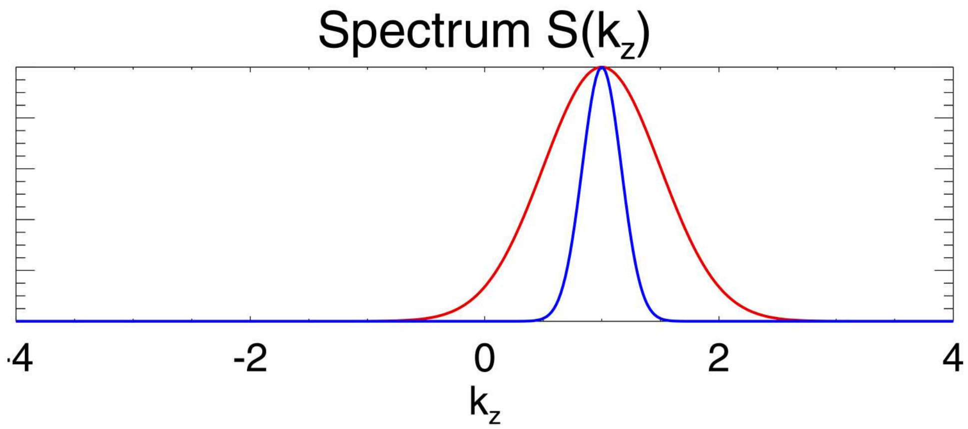
What does k_z=0 really mean?

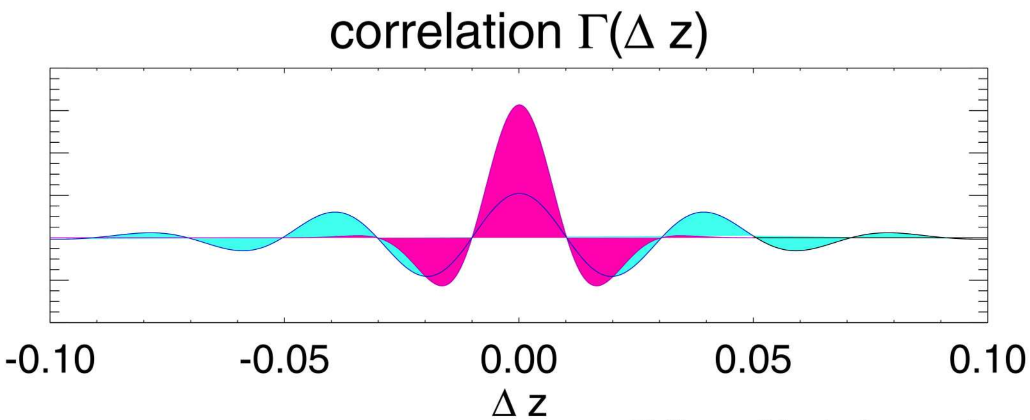
- Q: The notion of a fluctuation with **k_z=0 is counter intuitive?**
- ANSWER: The k_z=0 component is that from the integral of the correlation function. The correlation function "wavepacket" does go to zero because of the presence of components with k_z not equal to zero

$$\Gamma(\Delta z) = \int S(k_z) e^{ik_z \Delta z} dk_z$$

$$S(k_z = 0) = \int \Gamma(\Delta z) d\Delta z$$

- Example:
  - Gaussian spectrum, change width
  - Narrower spectrum: integral of correlation function is close to zero
  - Wider spectrum: integral of correlation function is more non-zero





S(kz=0)=integral under curve

k_r, k_θ spectrum

- Suppose a given radial,poloidal spectrum.
- Projected spectrum calculated as follows:
- Understand what we are measuring
- k_z=0 constraint defines a slice in k space which is measured.

$$k_z = k_r \hat{r}_z + k_\theta \hat{\theta}_z = 0$$

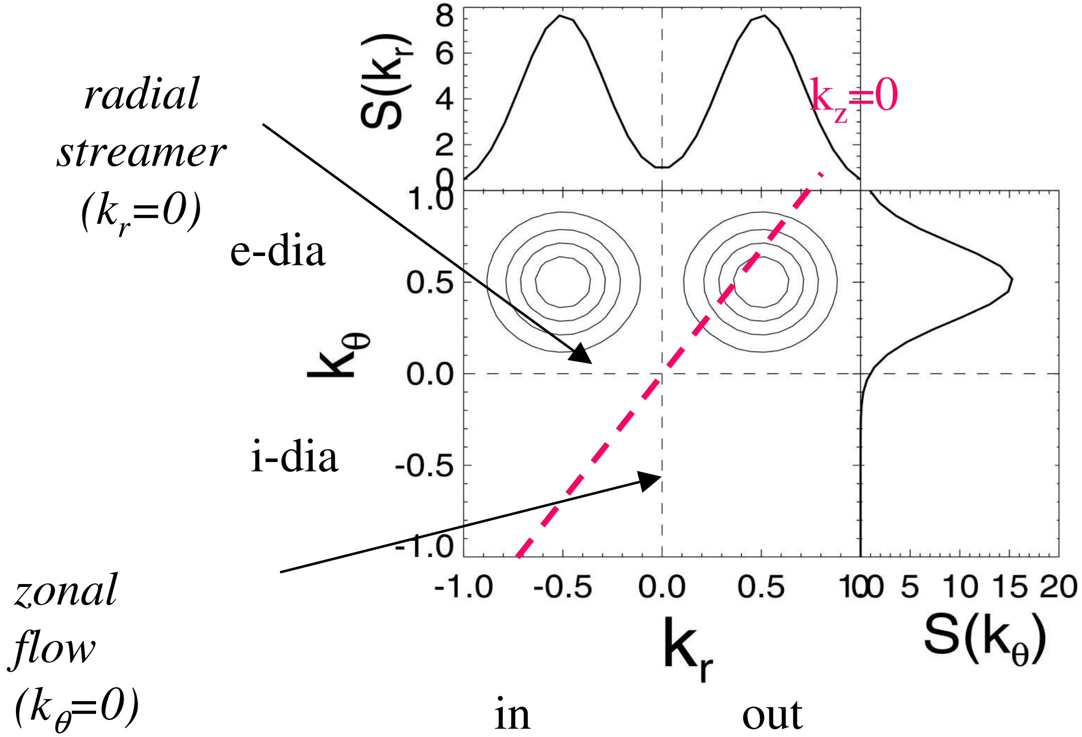
$$\hat{p} = \hat{B} \times \hat{z} / |\hat{B} \times \hat{z}|$$

$$\begin{pmatrix} k_p \\ k_z \end{pmatrix} = \begin{pmatrix} \hat{r}_p & \hat{\theta}_p \\ \hat{r}_z & \hat{\theta}_z \end{pmatrix} \cdot \begin{pmatrix} k_r \\ k_\theta \end{pmatrix}$$

$$S(k_p, k_z) = S(k_r, k_\theta)$$

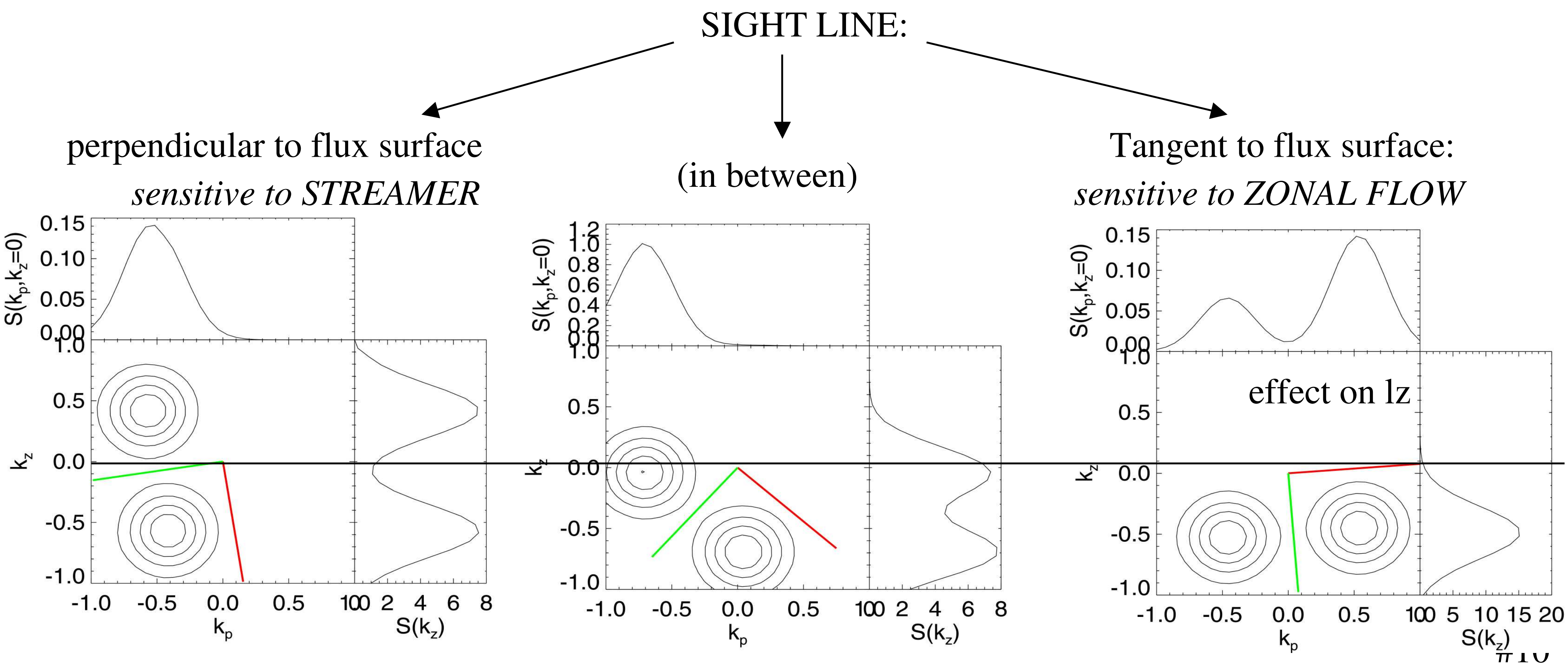
(caveat: linear projection only valid down to scales comparable with the flux surface curvature

- Fluctuation power typically follows a power law, e.g. $S(k) \sim k^{-\alpha}$. However, spectrum should have a peak at a particular k, e.g. $k_{peak} \sim 0.1\rho_i$
- Fluctuation power at k_r=0 or k_θ=0 *should be small* except for the action of phenomena such as zonal flows, GAMS and large scale low m, radially localized MHD modes.



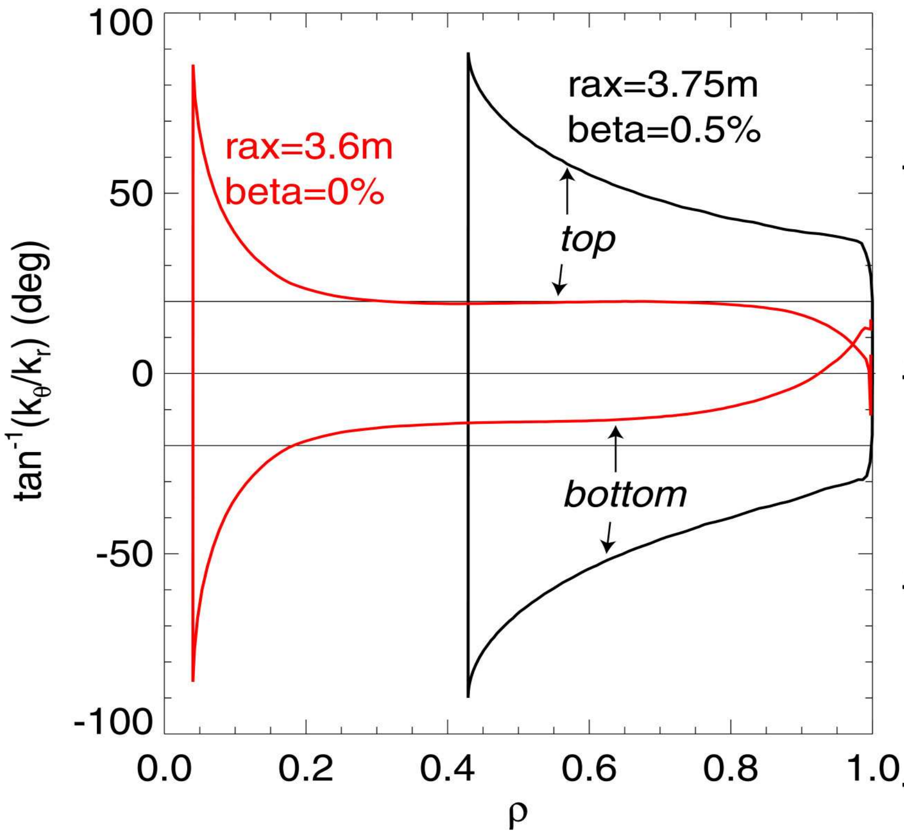
Projection of spectrum in k-space

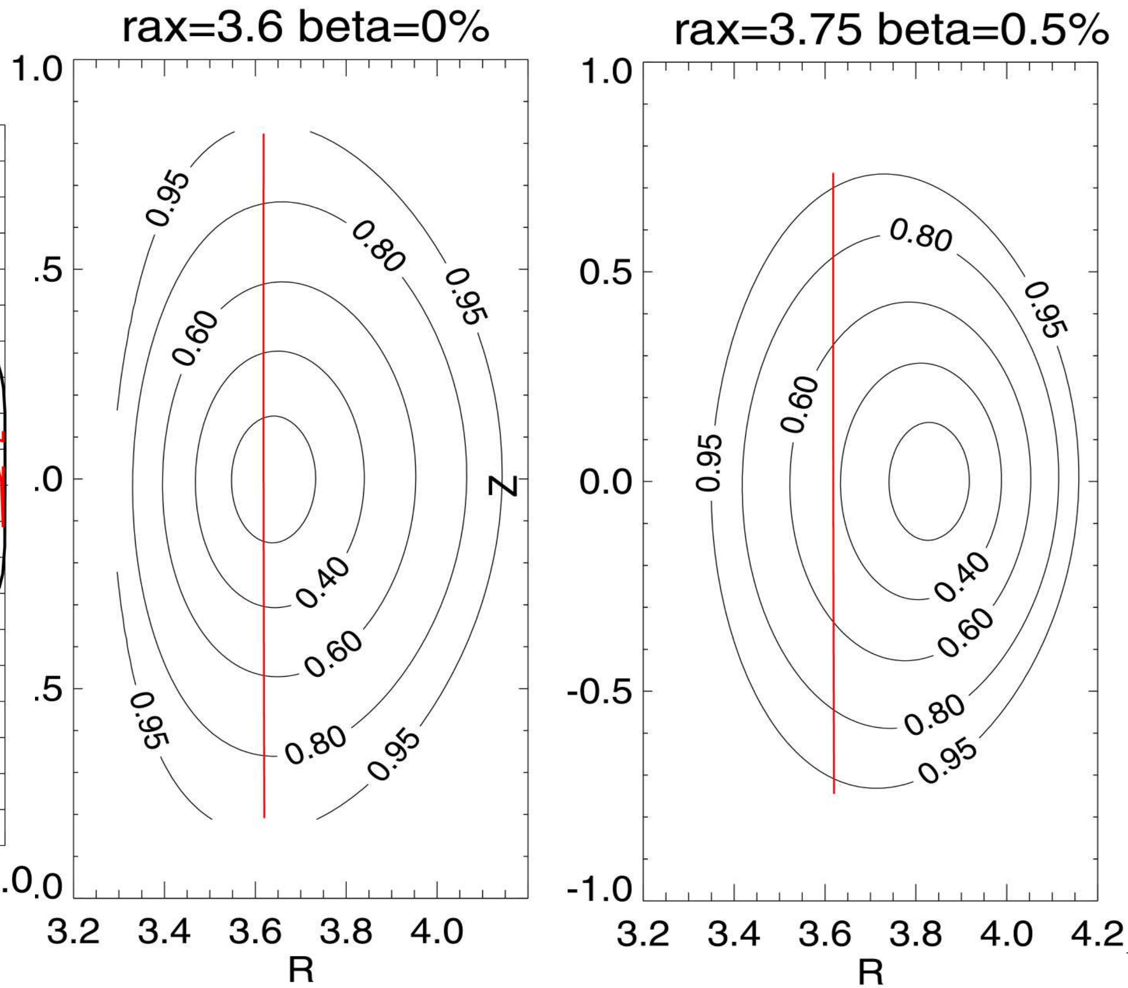
- At points perpendicular and tangent to the flux surface, the signal intensity is expected to be smaller. *(except, the limit k_θ=0 breaks projection assumption)*
- The effect of line integration, given by l_z may vary in a complicated manner near the tangent and perpendicular positions (assuming power in $k_r=0$ and $k_\theta=0$ components is zero)
- Upper and lower projections are *asymmetric* in k-space.



Sight lines in different configurations

- Compare sight lines in physical space in in k-space for standard and outward shifted configurations
- Sampling of upper and lower parts of the plasma cover significantly different parts of k-space.
  - Even at R_{ax}=3.6m, 3D effects of B vector result in approx. 20deg projection to the line of sight
  - Asymmetry expected

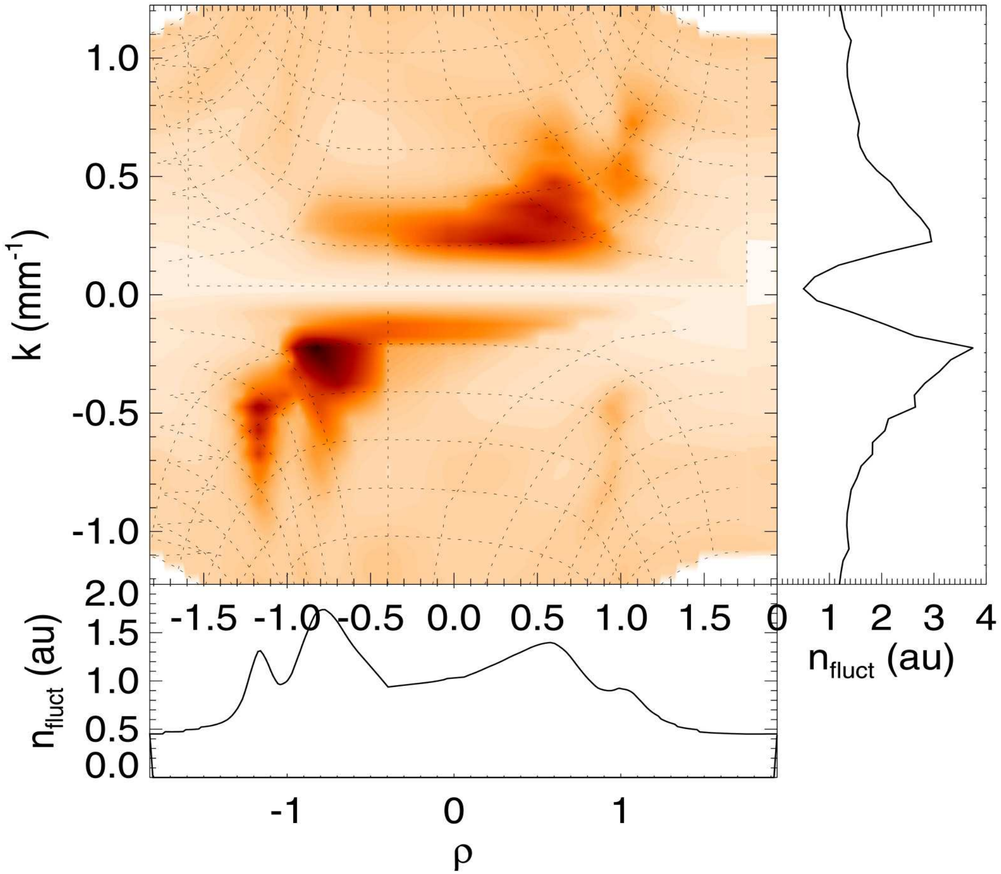




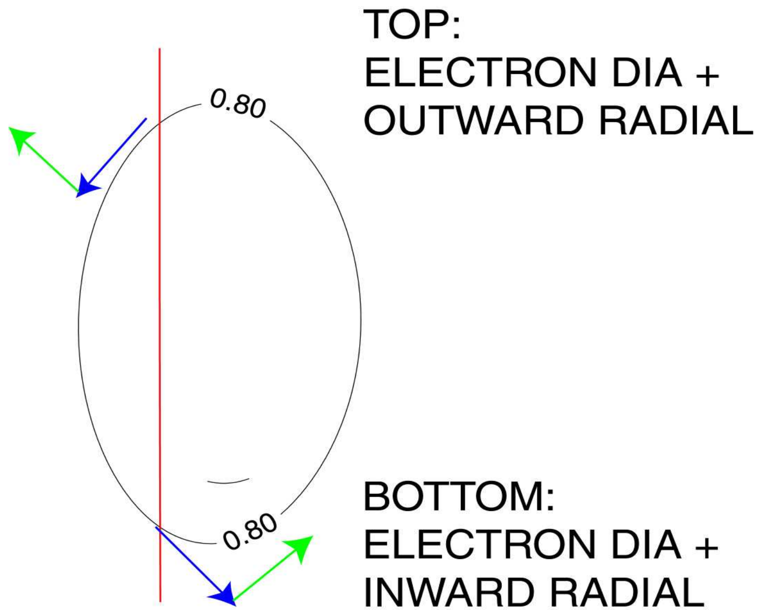
Up/Down asymmetry: difference in k-space

- Up and down may not be symmetric, because different parts of k space are measured
- Data generally shows some up/down (equivalent to in/out) asymmetry of fluctuation behavior.
- At edge of plasma, non-closed flux surfaces may also cause asymmetry.
- Instrumental (TALBOT) effects for $k>1mm^{-1}$.

#69615 (Rax=3.65m)



k_z=0 condition requires:



out/in asymmetry may be related to radial flux?

Signal/Image analysis

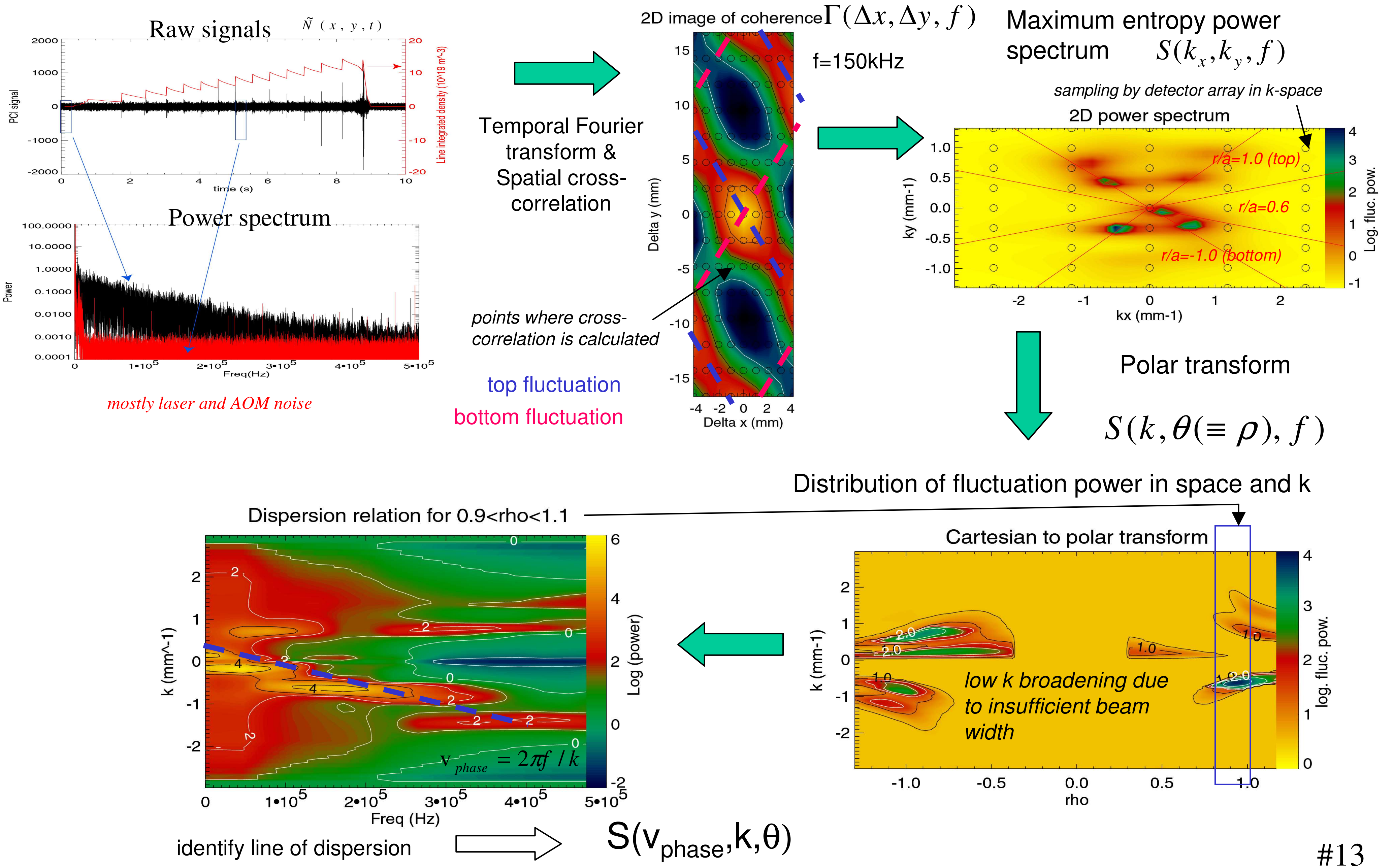
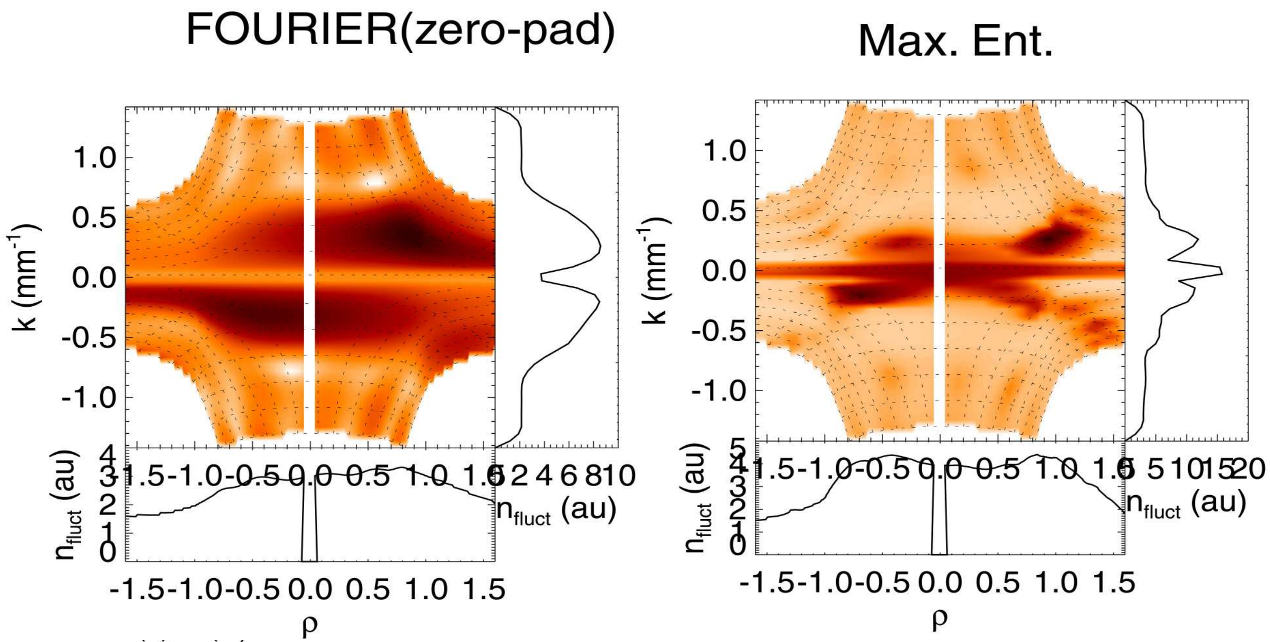
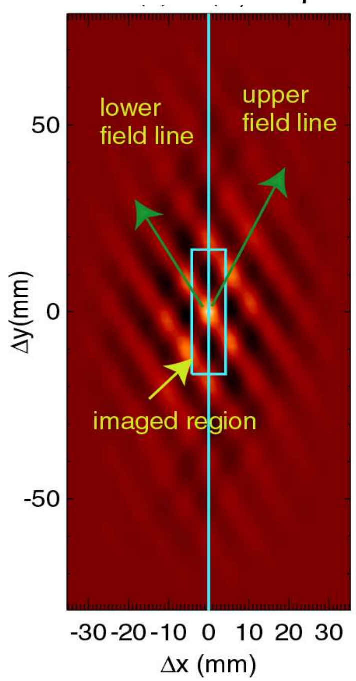


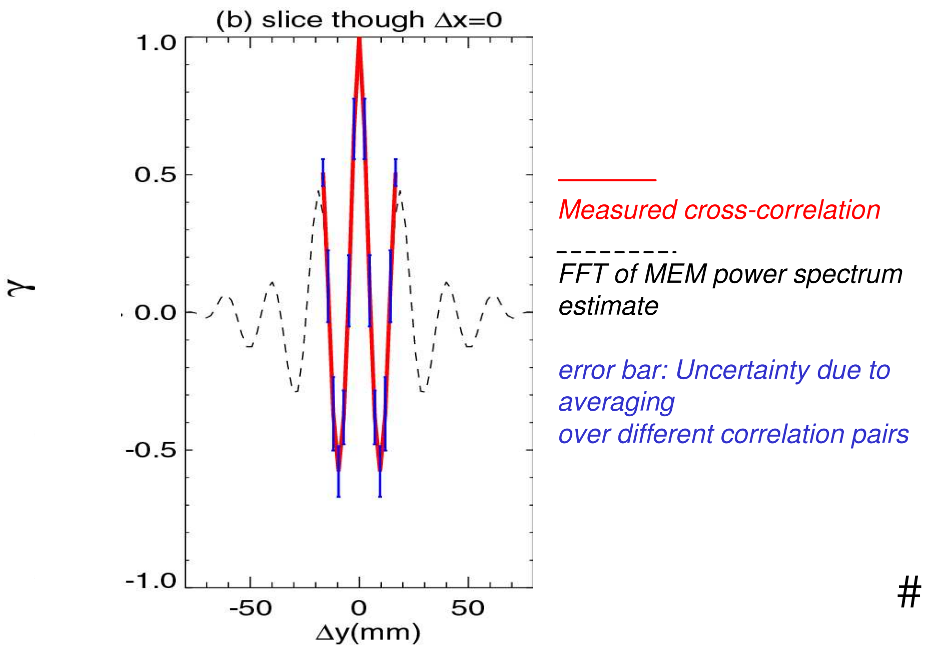
Image processing using Maximum Entropy power spectrum

- Correlation function does not go to zero over image
- With conventional Fourier analysis, spectral broadening severely compromised spatial and spectral resolution
- Image is effectively extrapolated using high resolution the maximum entropy power spectrum
- Maximum entropy method provides much superior resolution. Peak broadening depends on incoherent noise



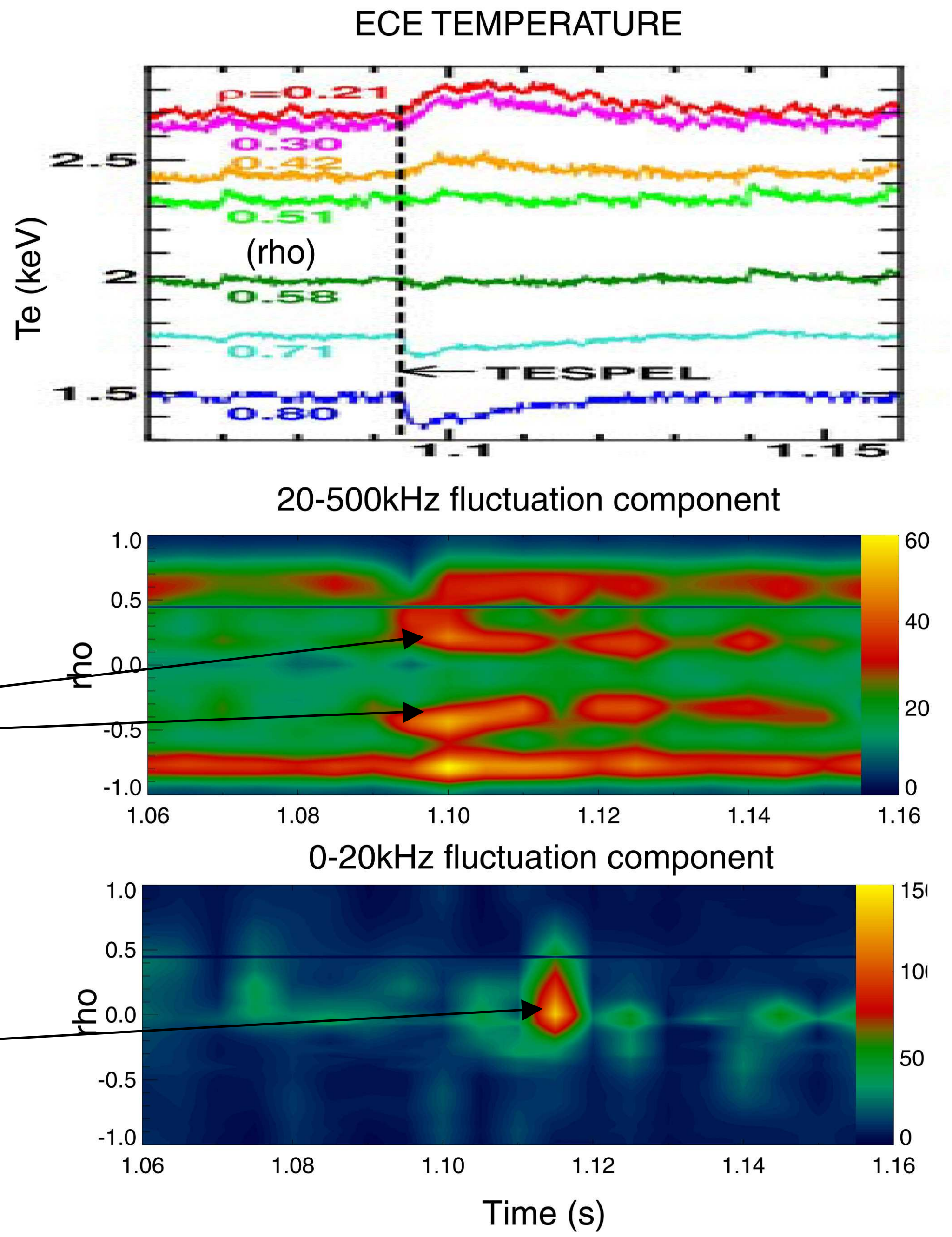


Extension of cross-correlation function using MEM



Fluctuations change when transport becomes non-local

- When TESPEL pellet is injected, the edge temperature decreases while the core temperature increases.
- Unexplainable by local, diffusive transport theory
- This NON-LOCAL transport phenomena has been observed and classified in detail [N. Tamura et al,IAEA ‘06].
- Fluctuations are indeed observed to change during non-local transport



modes excited at mid radius

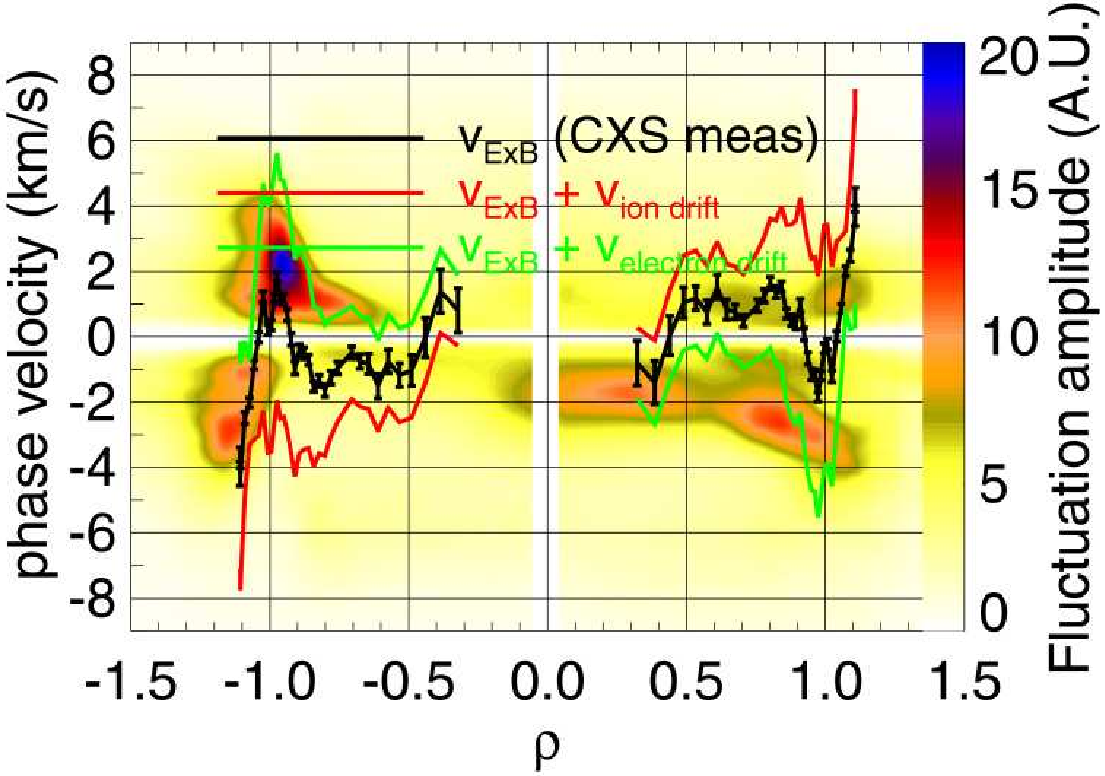
core mode at low frequency observed. ***Such modes at the tangent point must have low*** k_θ *Given they are at low frequency, we may conjecture that these modes may be zonal flows.*

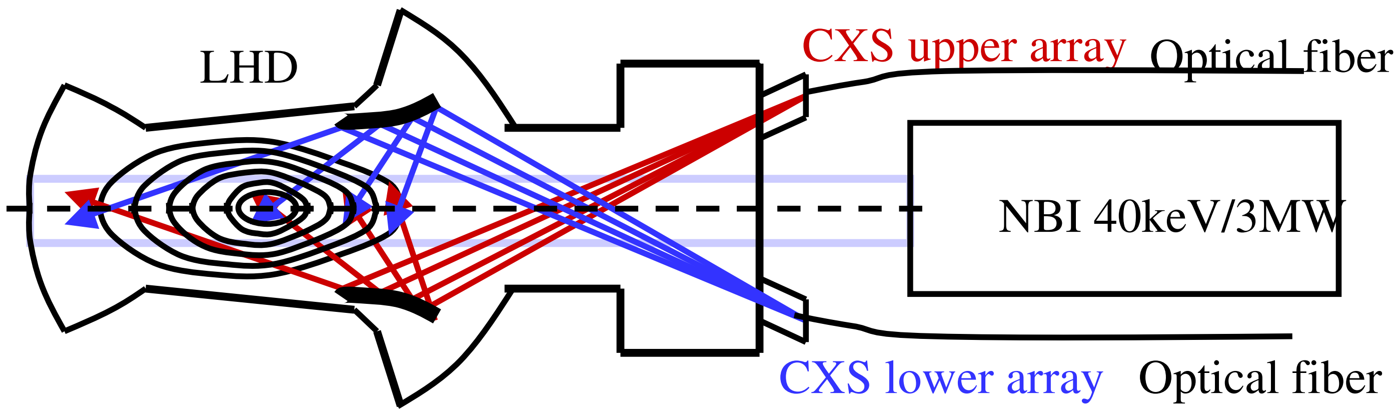
Comparison of fluctuation with rotation velocity

- Project from frequency to velocity (via k). Sum to compute a "distribution of phase velocity".
- Compare with CXRS rotation velocity (taking into account sight line geometry)
- Components identified propagating at electron diamagnetic velocity

$$v_{dr} = \left(E_r^* \pm T(L_{n*}^{-1} + L_{T*}^{-1})\right)\frac{\nabla\rho}{B}.(\hat{l} \bullet \hat{\theta})$$

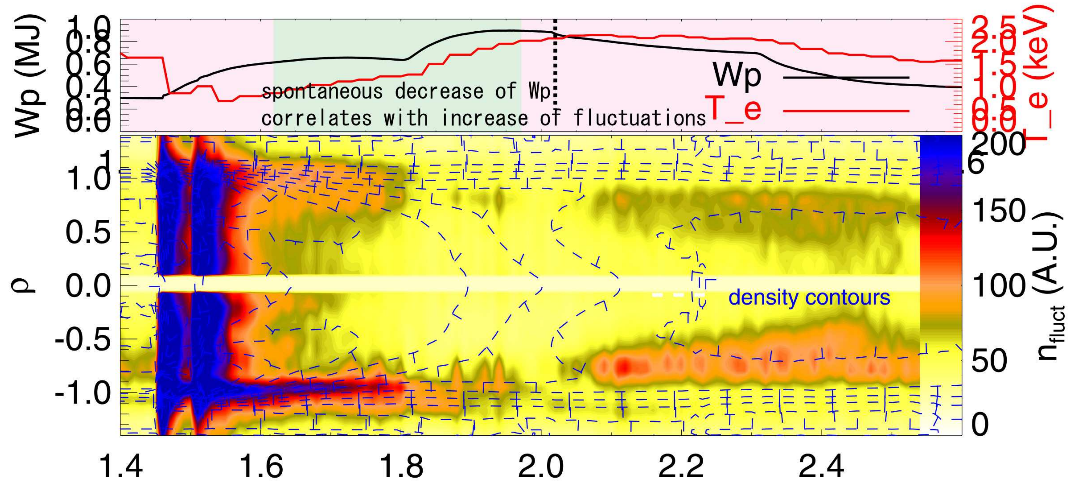
$$= \left(v_{CXS} \pm \frac{T}{aB}(L_{n*}^{-1} + L_{T*}^{-1})\right).(\hat{l} \bullet \hat{\theta})$$

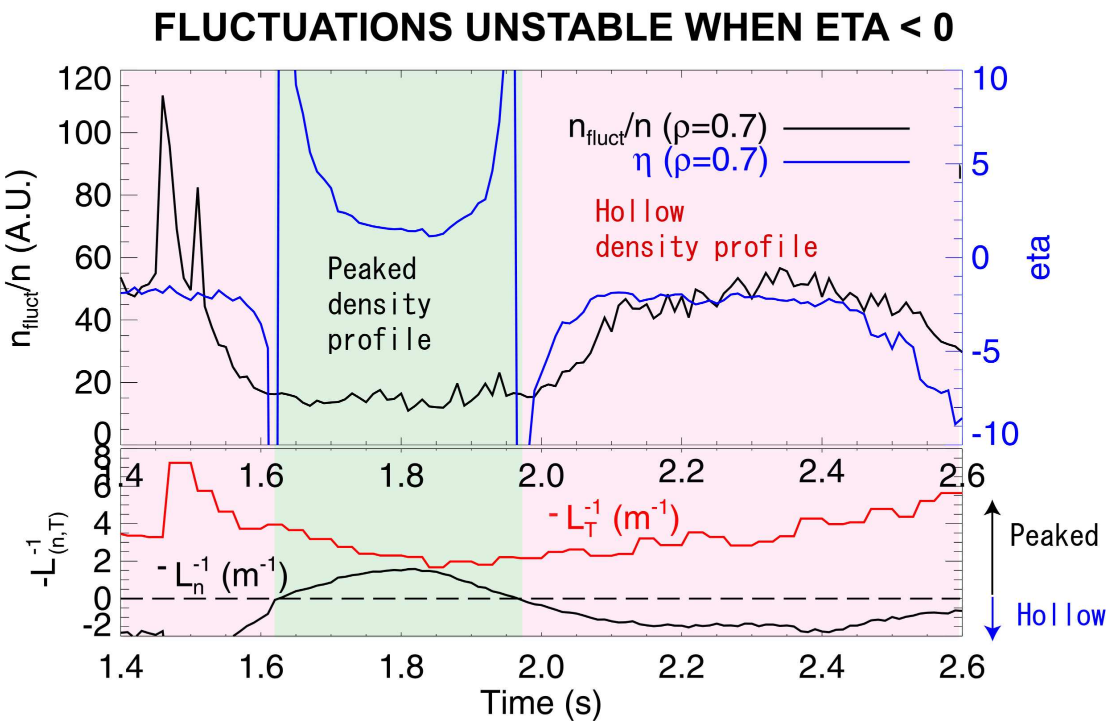




Study of driving terms for fluctuations

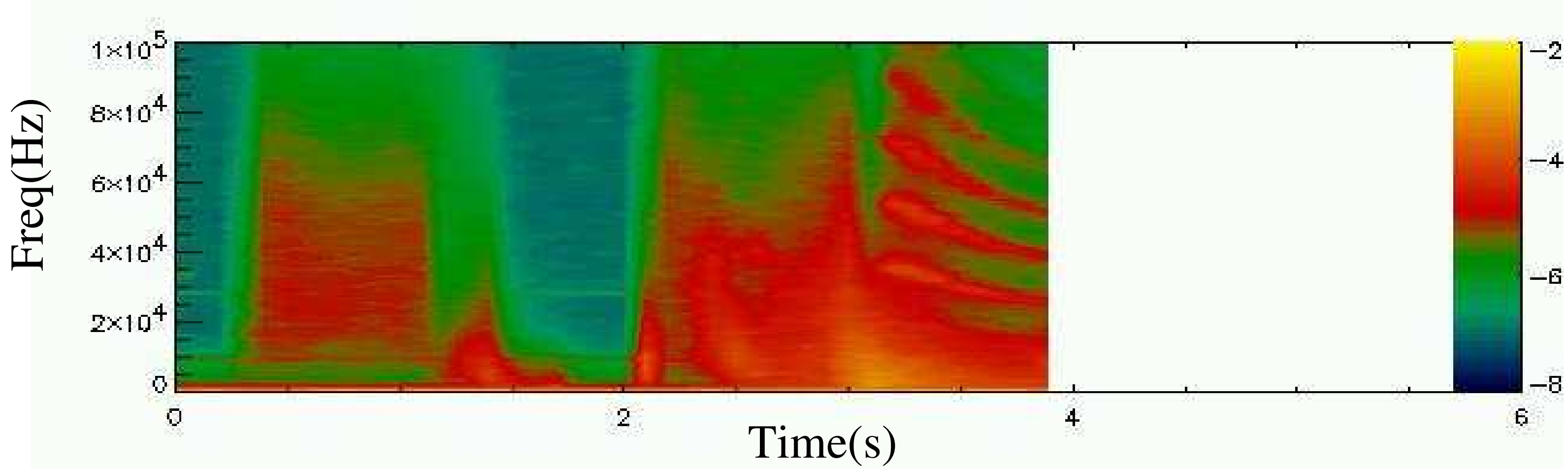
- Compare temperature and density gradients with density fluctuations.
- In this case, Hollow density profile drives fluctuations in the hollow part of the profile
- Ramifications for radial flux and causality of hollow density profile?

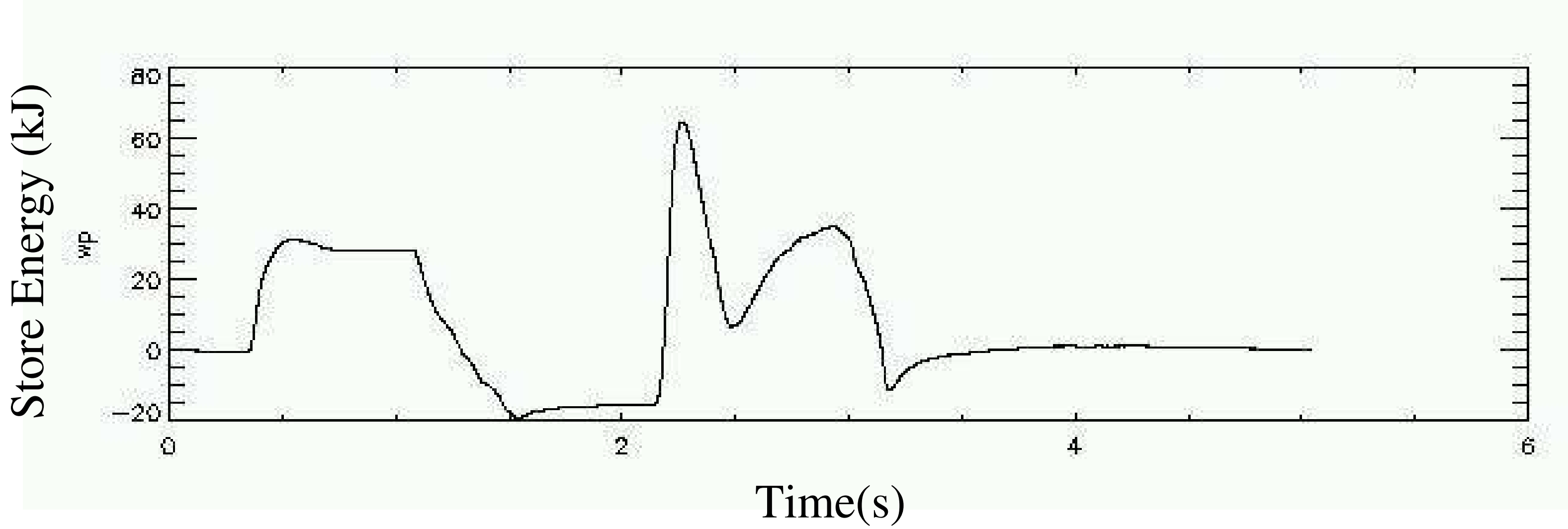




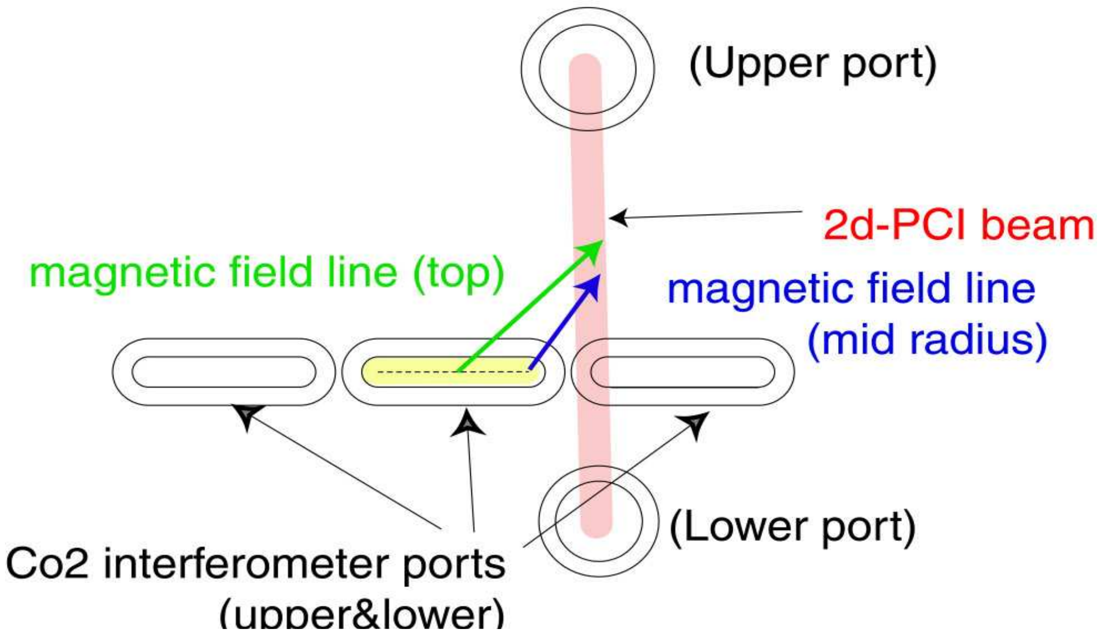
Spectrogram shows rich variety of behaviour

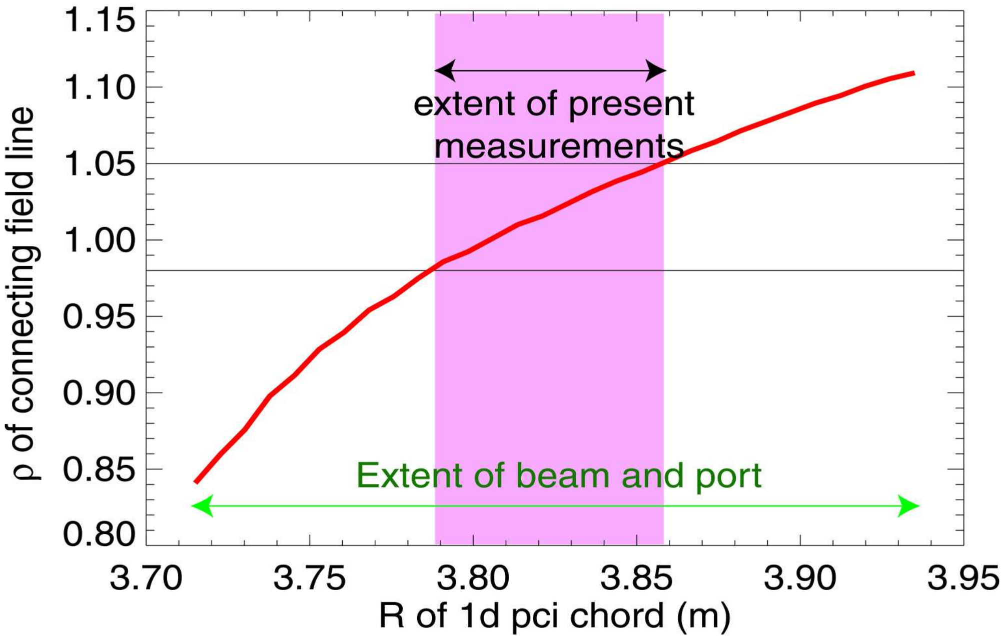
- Frequency of fluctuations depends strongly on plasma conditions. May relate to rotation velocity
- Broadband components are mostly observed. Occasionally, coherent modes are also observed.



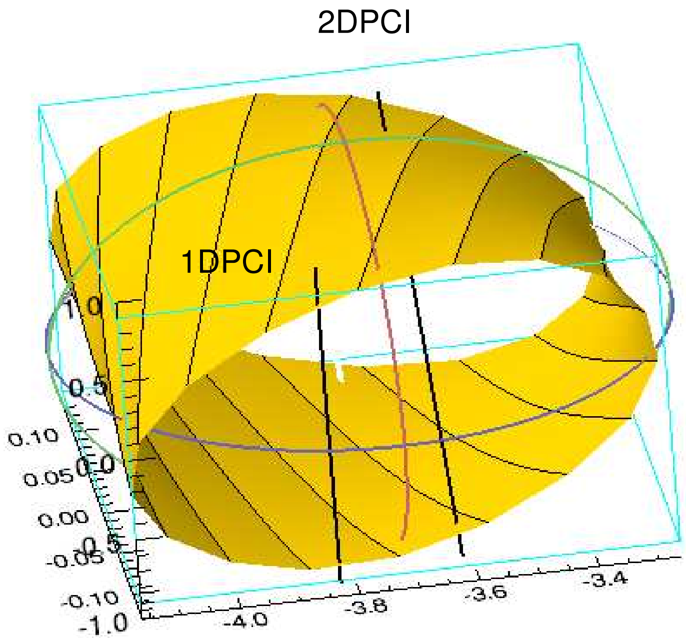


Spatial localization using cross-beam techniques





- Interferometer sight lines very close to PCI sight line, can be connected via field lines about 20cm.
- CO_2 interferometer in central port is converted to a 1-d PCI arrangement
- Cross-correlation of 2d PCI and 1-d PCI gives localization around the top edge of the plasma



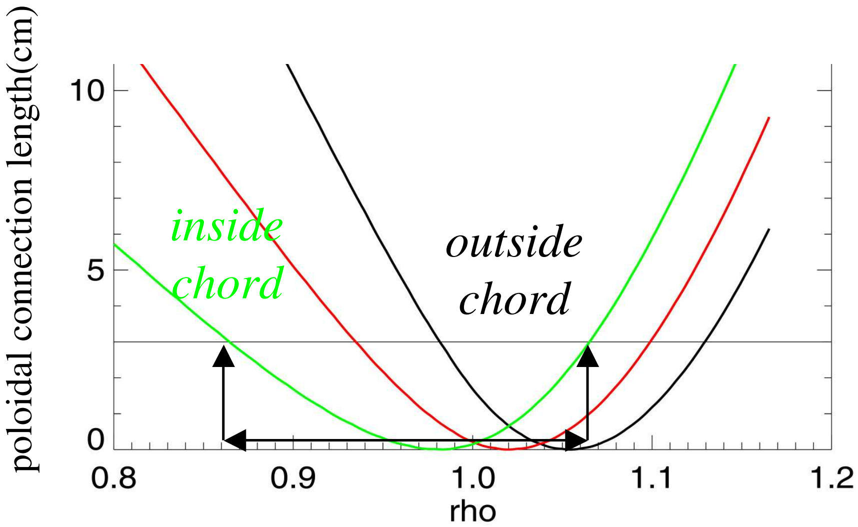
Cross beam: interpretation

$$\overline{\Gamma}(L_1,L_2)=\langle N_1N_2\rangle=\int_{L_1}\int_{L_2}\langle\tilde{n}(\rho_1,\theta_1)\tilde{n}(\rho_2,\theta_2)\rangle dl_1 dl_2$$

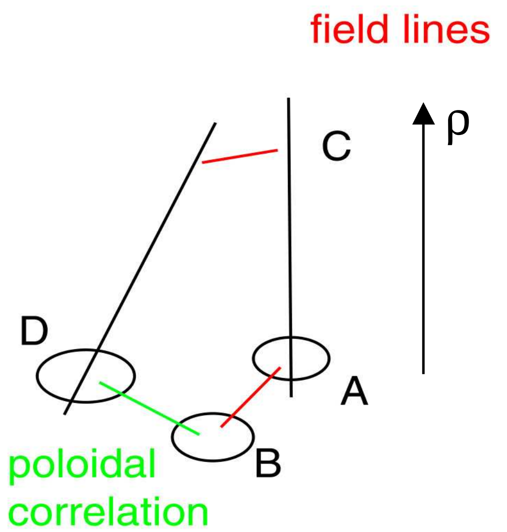
$$=\int_{L_1}\int_{L_2}\Gamma(\rho_1,\Delta\rho,\Delta\theta)dl_1 dl_2$$

$$=\int_{L_1}\int_{L_2}\exp(-\Delta\rho/\rho_c-\Delta\theta/\theta_c)dl_1 dl_2$$

where r_c,θ_c are radial,poloidal correlation scales



radial range of sensitivity to for given θ_c=3cm



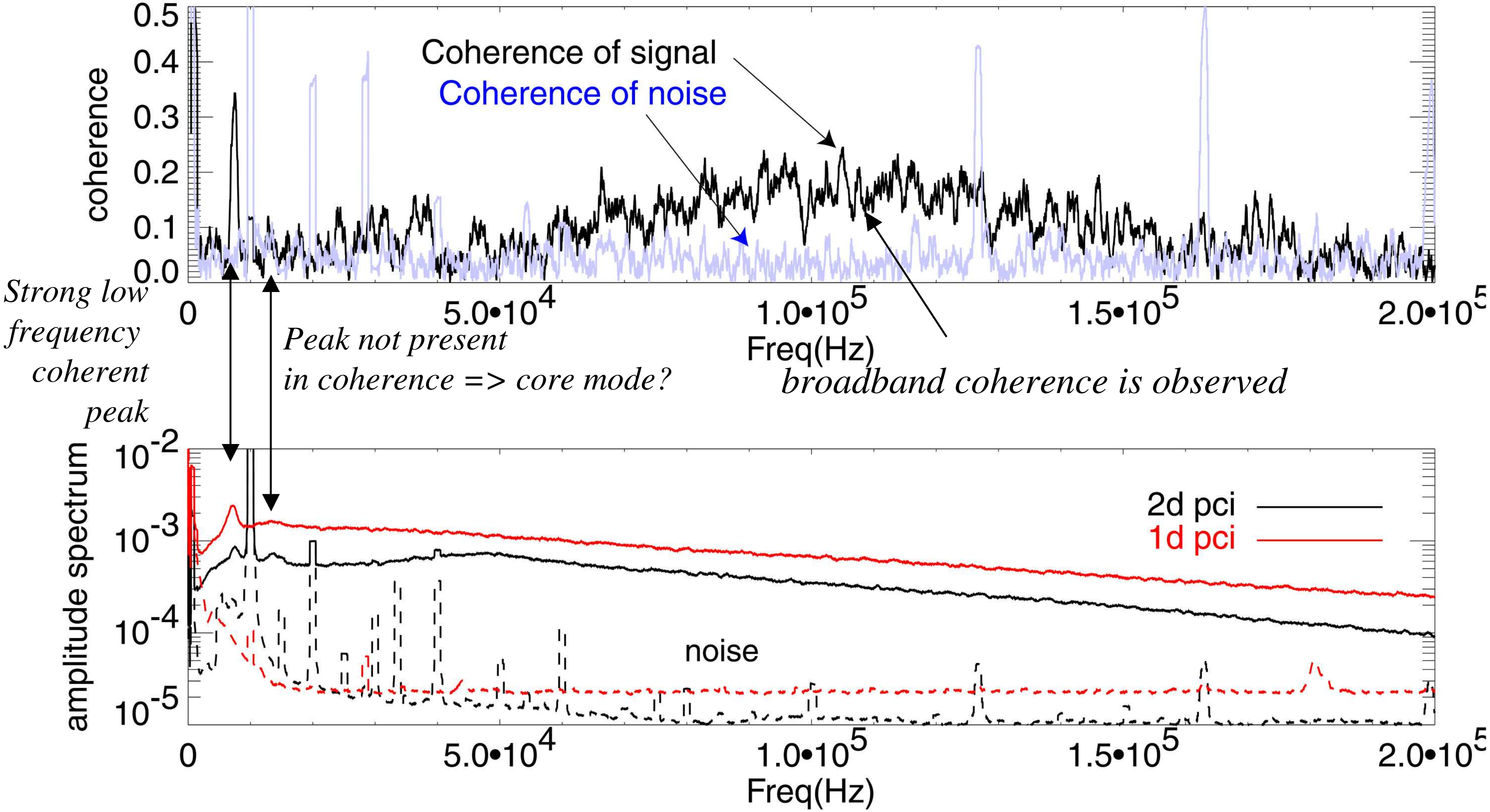
fluctuation is at a given ρ. A,B,D are all on the same flux surface

- Correlation via 2 paths:
  - ACD: (signal contains only k_z=0 the difference of chord directions makes this equivalent to ABD)
  - ABD: poloidal correlation
- For this sight line mostly normal to flux surfaces, Cross-correlation is sensitive to poloidal correlation length

- RESOLUTION: Δρ ~0.15
- As chords move inside, radial resolution **degrades**

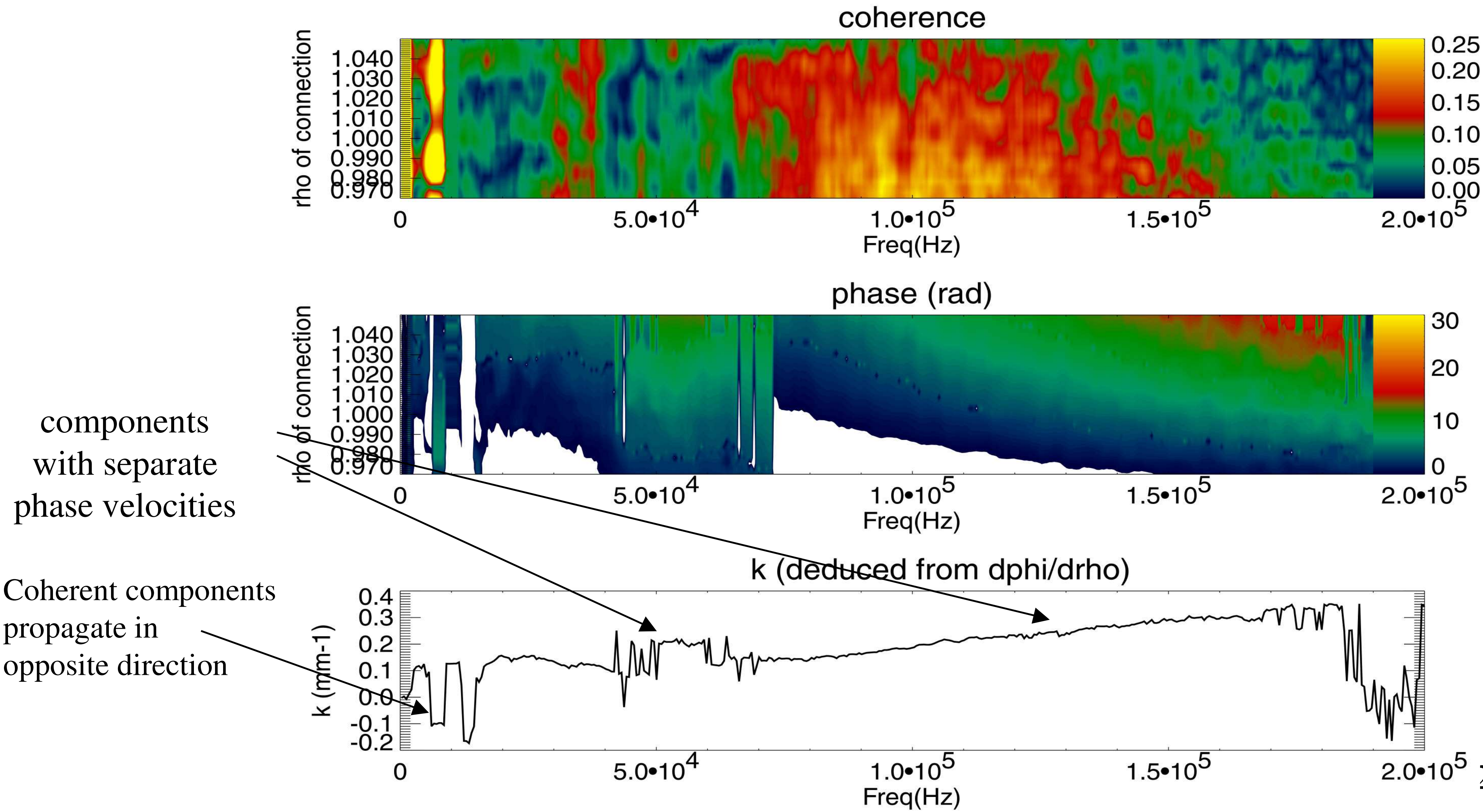
Cross-beam: rich correlation spectrum is detected

- Cross-correlation of chords with connecting field line at ρ=0.98
- Coherent low frequency peak (~7kHz) as well as broadband coherent component is observed

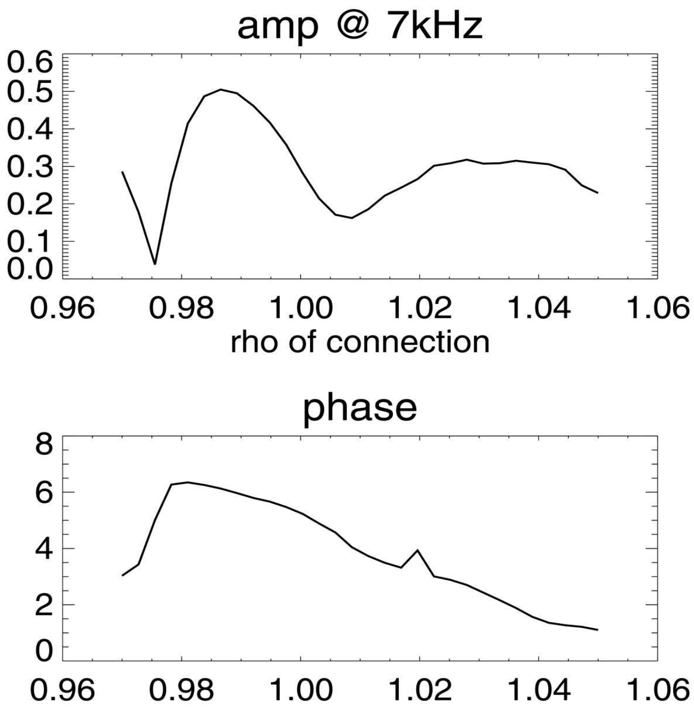


Cross-beam: spatial dependence of coherence

- Coherence is strongest on inside channel.
- Phase varies with channel. Can deduce wavenumber

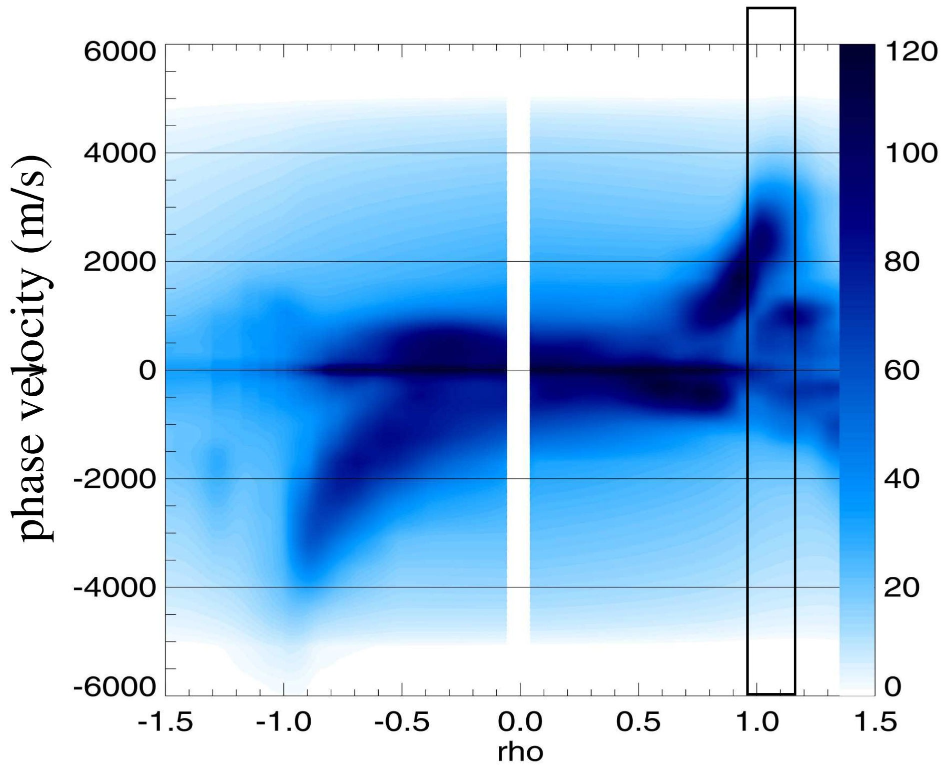


Coherent structure



- Double peaked coherence is observed.
- May result from a spatially coherent, spatially extended MHD structure

Comparison with 2D results

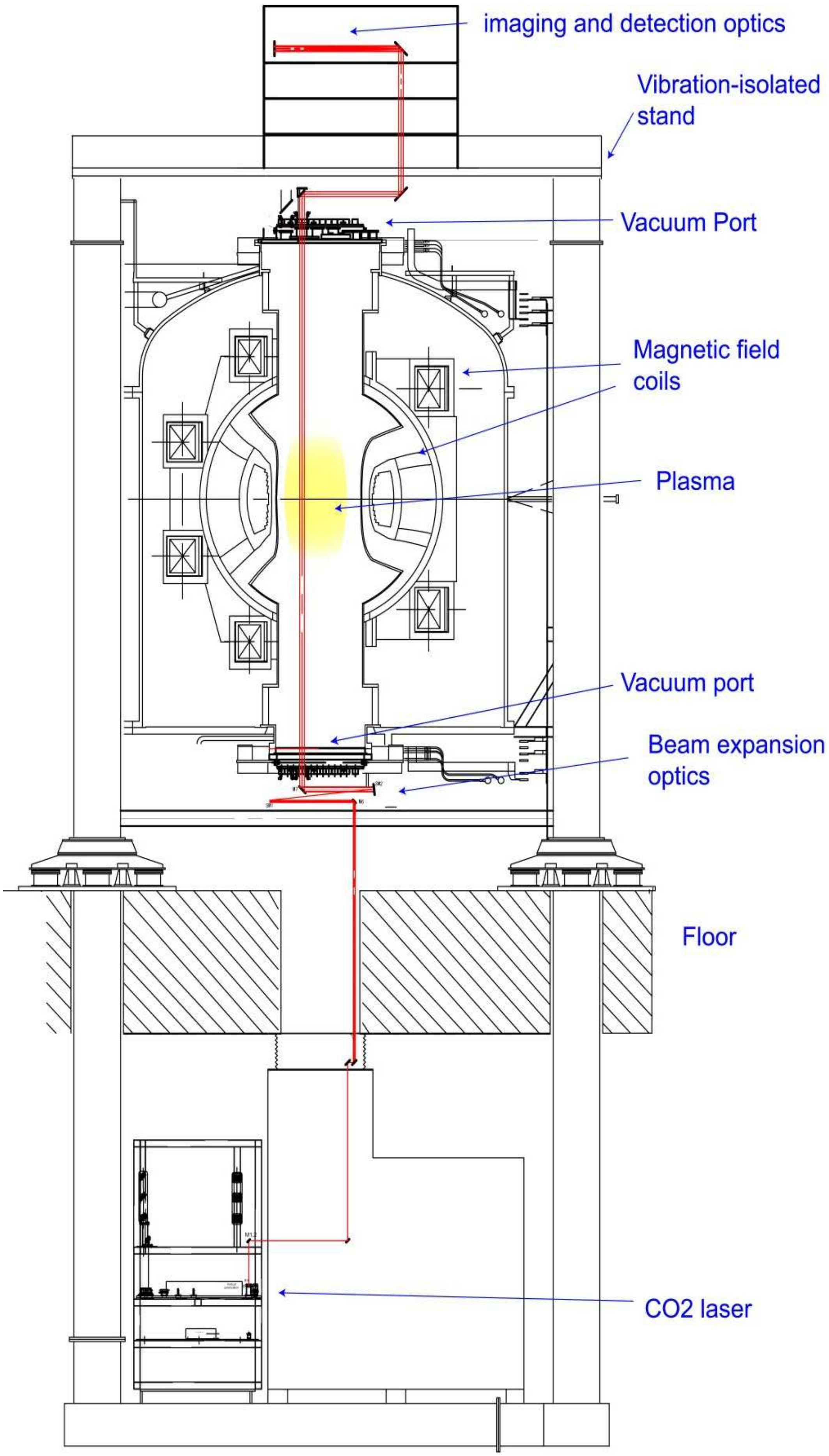


- 2D PCI exhibits a similar structure in the top edge as from correlation analysis, with low speed and high speed branches both observed.

Conclusions

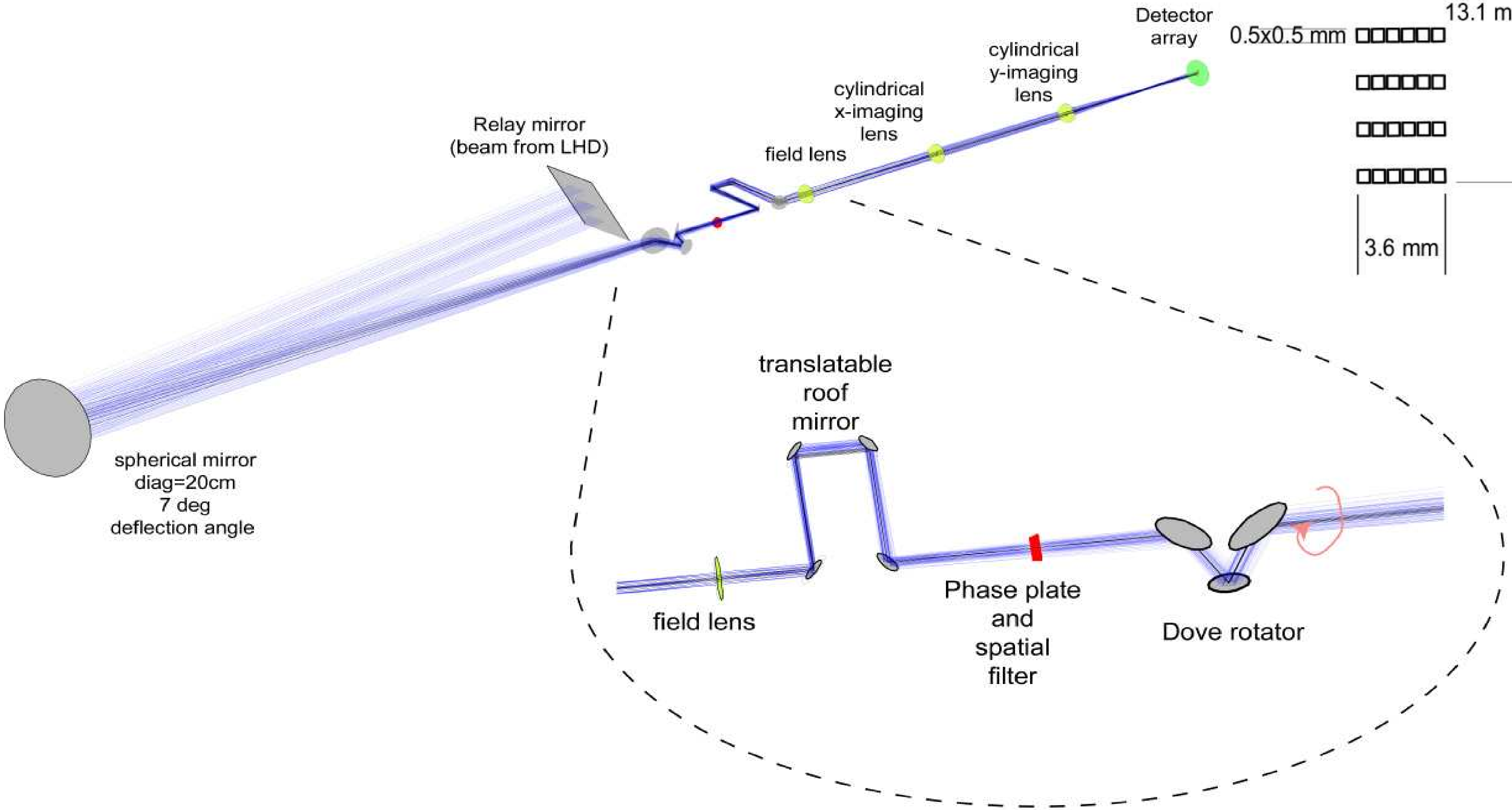
- PCI signal interpretation:
  - Constraint k_z=0 provides new means to interpret the fluctuation images.
  - May explain up/down asymmetry as in/out asymmetry in k-space
  - Asymmetry may relate to fluctuation driven flux?
- 2D PCI system:
  - Fluctuation amplitude profiles are measured with good spatial resolution, characteristic of the wavenumber targeted.
  - Phase velocity compares well with expected rotation+diamagnetic velocity
  - Fluctuation peaks detected at tangent point, where instrument is sensitive to zonal flows. Such peaks are detected during the action of non-local core temperature rise
- Cross-correlation between 1D and 2D PCI systems:
  - Sight lines are well suited to analyze fluctuations on the top edge using cross-correlation techniques
  - The structure of low frequency coherent modes is illucidated more clearly with the correlation technique. The broadband component is detected and its frequency/phase velocity structure agrees with analysis of the 2D system
  - In the future plans, the sight lines can be altered to measure closer towards the core, however spatial resolution will suffer

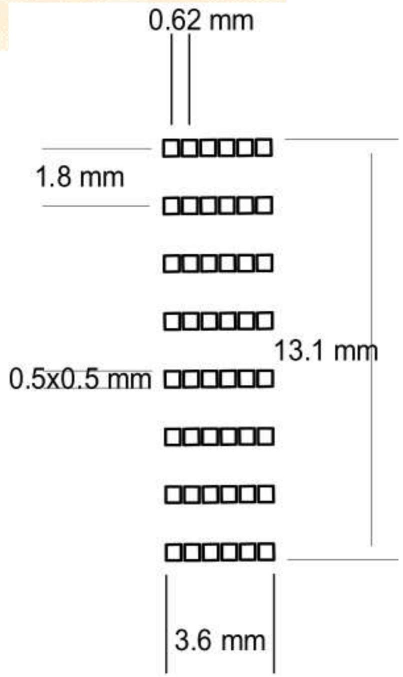
2D imaging system on LHD: schematic



Detection optics

- Flexible optical system allows for image rotation and change of the image plane.





Detection of ETG scale turbulence

- Detected up to k re ~ 0.2, which is in ETG range.