Instrumental capabilities and limitations of two-dimensional phase contrast imaging on LHD

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1.Basic ideas and hardware

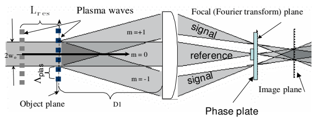
•Phase contrast imaging (PCI) is a type of imaging interferometry with “internal” reference beam, which is undiffracted (zero order) beam)

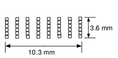
• Phase plate makes fringe visibility maximal by setting phase delay between interfering beams 0 or π

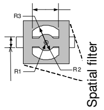
•Resultant signal at the image plane is $I_{SIG} \sim I_0 + 2\sqrt{I_0 I_{diffr}} = I_0(1+2\varphi)$, where $\varphi << 1$ is phase shift due to plasma density fluctuations $\tilde{n}_e$

•As all interferometry PCI is line integrating so for homogeneous plasma $\tilde{\varphi} = r_e \lambda_0 \tilde{n}_e \sqrt{L_{corr} L_{res}}$ where Λ_{fluct}<L_{corr}<L_{res} , Λ_{fluc}-fluctuations scale, L_{res}-integration length or resolution length

•Longitudinal correlation length L_{corr} is a major uncertainty in determination of $\tilde{n}_e$. Improvements requires decreasing L_{res}/Λ_{fluc} and additional estimation of L_{corr} in different geometry







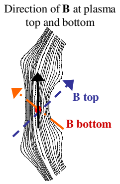
Magnetic shear technique

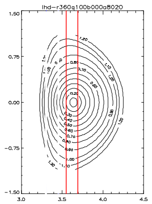
•Waves from different regions along the line of view can be distinguished by their traveling directions and this can make L_{res}<<L_{plas}, where L_{plas} is the plasma size along the viewing line

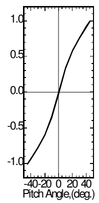
•The basis for this is :

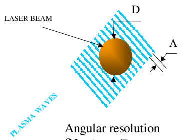
•1-D filamentary structure of low frequency density fluctuations ($k_{||} << k_{\perp}$) as it follows from theory and experiments

• large (~90°) variation of atan(Br/Bϕ) when beam traveling through the LHD plasma from bottom to top









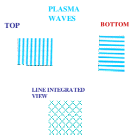
Angular resolution
$\delta\theta \sim \Lambda_{plas}/D$,

Radial resolution
$\delta\rho/\rho \sim \delta\theta/\theta_{shear}$

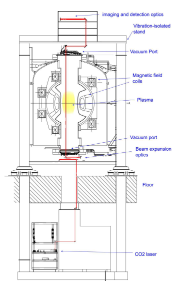
2-D PCI approach

Elementary 1-D fluctuation pictures can be resolved from integral 2-D image by the use of 2-D spatial Fourier transform or high resolution spectral estimation techniques

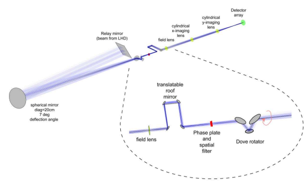
$$n(x,y) \xrightarrow{\text{Power spectrum}} S(k_x,k_y) \xrightarrow{\text{Cartesian to Polar conversion}} S(k,\theta(\rho))$$



Position of PCI optical system



Imaging and detection optics in zoom mode



Laser: 10W cw CO_2 (λ_0=10.6 μm)

Detector: 6x8 LN cooled MCT photoconductors array of 1MHz bandwidth

Configurable detection optics permits variation of detector array image size and aspect ratio in a plasma

2.Capabilities

•Provides momentary profiles of plasma density microfluctuations data $(\tilde{n}(\rho,k), \tilde{n}(\rho, v_{pol}))$ through the entire plasma diameter with 1cm^{-1}< k< 10cm^{-1}. This unique feature of 2-D phase contrast enables studying global behavior of plasma microturbulence.

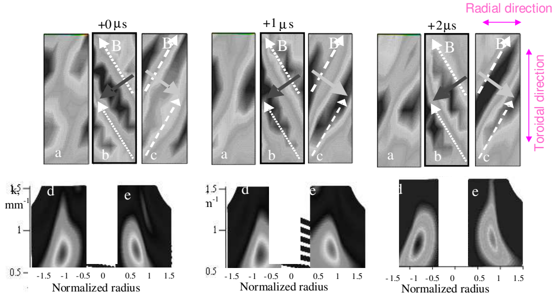
•Fast temporal sampling (up to several MHz) enables observation of fast phenomena in behavior of density fluctuations

•In zoom mode large k (op to 30cm^{-1}) fluctuation profiles can be studied in limited region (0.2-.3ρ) ether in the plasma core or at edges. Position of the region can be varied trough the whole plasma diameter.

•PCI technique advantages:

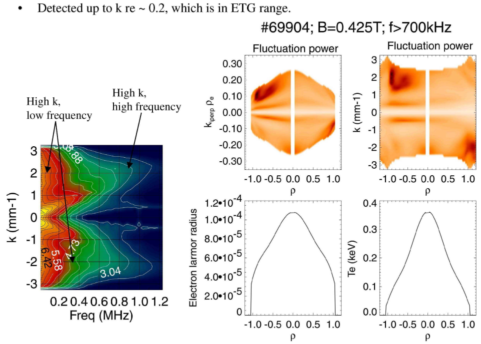
- •uses small ports, relative to mw or FIR scattering (scattering angles less that 10^{-2});
- •works good at medium and high plasma densities and tolerant to density gradients;
- •irrelevant to method of plasma heating,
- •sensitive to broad range of fluctuations wavenumbers

Dynamics of plasma density fluctuations spatial profiles



Detection of ETG scale turbulence

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



Evidence of capability of the system to detection of ETG scale fluctuations is clear here in spite of strong instrumental effect (L_{plas}>>L_{Talb}/4)

3. Limitations

•Limitation to region in k-space that can be observed

•Low k limits

•PCI by its physical principle is insensitive to Λ_{fluc}>D (k_{min}>2π/D) (D-diameter of laser beam in plasma)

•In the case the image of the detector array in plasma L_{array} is small (L_{array}<<D) fluctuations with L_{array}<Λ_{fluc}<D (2π/L_{array}>k> 2π/D) can be detected without localization due to poor angular resolution $\delta\theta=\Lambda_{fluc}/L_{aray}$

•High k limits

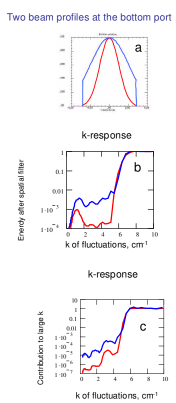
•Nyquist limit sets maximal k without aliasing k<π(N)$^{1/2}$/L_{array} , where N=48 is number of detectors in the array. The dynamic range of spatially resolved fluctuations k_{max}/k_{min}=0.5(N)$^{1/2}$

•Thin phase grating approximation used in signal interpretations holds for $L_{plas} << \frac{2\pi}{\lambda_0 k^2}$ (Klein & Cook, 1967) however phase grating image keeps its shape within a longer distance L_{Talbot}/4 where Talbot length is $L_{Talbot} << \frac{8\pi^2}{\lambda_0 k^2}$. In case L_{plas}>> L_{Talbot}/4 analog spatial filter has to be used to select plasma region for observation. For example for k=30cm^{-1} the length along the viewing line of plasma region to observe is L_{Talbot}/4=20cm.

•More weak restriction is maximal scattering angle determined by port size. Here $\theta_{max}=10^{-2}$, which defines k_{max}=60cm^{-1}

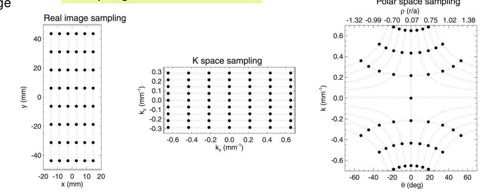
•Low k leakage can distort large k region. Typically high-pass time-frequency filter is employed for large k selection in addition to selection by spatial filter.

Apertures effect on small k signal leakage

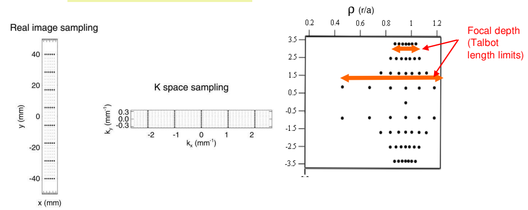


Contribution of leakage through the spatial filter of signal produced by low k fluctuations can be significant especially in zoom mode because of larger fluctuation power (S(k) ~ k^{-a}) and lower spatial resolution (L_{res}~k^{-1}). The leakage increases also by about one order for beam distorted by diffraction on apertures (fig. a,b). However most of leaked signal concentrates near the low edge of filtered spectrum (fig. c) relieving the leakage problem. Calculations with GLAD

Sampling in overview mode



Sampling in zoom mode



Additional probe beam B might be installed in future or 1-D PCI can be adjusted to region near plane z=0. This way not only information on L_{corr} will be obtained but also radial transport $\Gamma = \langle \tilde{n}_e \tilde{v}_r \rangle$ can be measured directly