1. Basic ideas and hardware

- Phase contrast imaging (PCI) is a type of imaging interferometry with an "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 \( I_\text{PCI} = 1 + 2 \sum (1 \pm 2) \), where \( 1 \pm 2 \) is phase shift due to plasma density fluctuations \( \Delta n \).
- As all interference PCI line is integrated is for homogeneous plasma \( \rho = 0 \) following equation holds:

\[ \Delta n_{\text{PCI}} = \Delta n_{\text{norm}} \cdot \Delta \rho / \rho \]

where \( \Delta n_{\text{norm}}/\rho \) - fluctuations scale, integration length or resolution length.
- Longitudinal correlation length \( \lambda_{\text{ PCI}} \) is a major uncertainty in determination of \( \Delta n \). Improvements require decreasing \( \lambda_{\text{ PCI}}/\rho \), and additional estimation of \( \lambda_{\text{ PCI}} \) in different geometry.

- Waves from different regions along the line of view can be distinguished by their traveling directions and this can make \( \lambda_{\text{ PCI}}/\rho \) smaller, where \( \rho \) is the plasma size along the viewing line.
- The basis for this is:
  - 1-D elementary structure of low frequency density fluctuations \( \Delta n_{\text{ PCI}} \approx k \Delta \rho \) as it follows from theory and experiment.
  - Large (~50%) variation of \( \lambda_{\text{ PCI}}/\rho \) for beam traveling through the LHD plasma from bottom to top.

2. Capabilities

- Provides momentary profiles of plasma density microfluctuations data \( \Delta \rho(k) \), \( \Delta n(k, \nu) \) through the entire plasma diameter with \( \Delta n \sim 1 \times 10^{-2} \) cm. 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 \( k \) (up to \( 30 \mathrm{cm}^{-1} \)) fluctuations profiles can be studied in limited region (0.2-0.3D) either in the plasma core or at edges. Position of the region can be varied through the whole plasma diameter.
- PCI technique advantages:
  - Uses small ports, relative to MW or FIR scattering (scattering angles less that 10°).
  - Works well at medium and high plasma densities and tolerant to density gradients.
  - Relevant to method of plasma heating.
  - Sensitive to broad range of fluctuations wave numbers.

Dynamics of plasma density fluctuations spatial profiles

- 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 \( \Delta n_{\text{PCI}} \approx k \Delta \rho \) and lower spatial resolution \( \lambda_{\text{PCI}}/\rho \). The leakage increases also by 50% due to diffraction on aperture \( \beta_D \). However most of leaked signal concentrates near the low edge of filtered spectrum \( \Delta k \), relencing the leakage problem. Calculations with GLAD.

3. Limitations

- Limitation to region in k-space that can be observed.
  - Low \( k \) limits:
    - PCI theory principle is invalid when \( k < k_{\text{max}} \) (D-diameter of laser beam in plasma). In the case the image of the detector array in plasma \( \Delta n_{\text{max}} \) is small \( k_{\text{max}} \approx 0.5 \mathrm{D} \), fluctuations with \( k > k_{\text{max}} \approx 0.5 \mathrm{D} \) can be detected without localization due to poor angular resolution.
  - High \( k \) limits:
    - Angular limit sets maximum \( k \) without aliasing \( k_{\text{max}} \Delta \rho \), \( k_{\text{max}} \approx N \delta \rho \), where \( N \delta \rho \) is number of detectors in the array. The dynamic range of spatially resolved fluctuations \( \Delta n \approx 0.5 \mathrm{D} \) is limited.
-钎Phase grating approach used in signal interpretations holds for \( k_{\text{min}} \lesssim 2 \pi / \lambda \) (Klein & Cook, 1983). However phase grating image keeps its shape within a larger distance than \( \lambda_{\text{PCI}}/\rho \) of which Talbot length

\[ L_{\text{Talbot}} = \frac{D^2}{\lambda} \]

is. In case \( L_{\text{Talbot}} \ll \lambda_{\text{PCI}}/\rho \) angular spatial filter has to be used to select plasma region for observation. For example for \( k=30 \mathrm{cm}^{-1} \) the length along the viewing line of plasma region to observe is \( L_{\text{Talbot}} = 10 \mathrm{D} \).

> 0.5

More weak restriction is maximum scattering angle determined by port size. Here \( k_{\text{min}} \approx 0.1 \mathrm{D}^{-1} \), which defines \( \lambda_{\text{PCI}}/\rho \approx 0.1 \mathrm{D}^{-1} \).

< 0.1

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.

Detection of ETG scale turbulence