Instrumental Capabilities and Limitations of Two-Dimensional Phase Contrast Imaging on LHD

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A novel phase contrast imaging is employed for diagnostics of plasma density fluctuations on LHD. With the use of two dimensional 48 ch (6×8) detector array and CO_2 laser probe beam this technique permits observation of radial profiles of density fluctuation during a single discharge either within the entire plasma diameter in overview mode or within some fraction of the diameter in zoom mode. The velocity of density fluctuations in laboratory frame can be determined simultaneously with fluctuations of velocities. Analysis of system performance was made with the use of numerical calculations. The targets for the analysis include wave number and spatial resolution of the method, contrast of instrumental function, which is determined by low k signal leakage into the high k spectral region, and focal depth of the optical system for different fluctuation wave numbers. The role of shortcomings of optical system like distortion of the optical front by diffraction is studied. Suggestions for future upgrade of the diagnostics are advanced.

Keywords: LHD, two-dimensional, phase contrast, microfluctuation

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1. Introduction

Phase contrast imaging (PCI) [1] is widely employed for diagnostics of plasma density fluctuations in fusion devices. The PCI method was invented in 1935 by F. Zernike to improve microscopy of thin highly transparent objects and whereas it holds high sensitivity it lacks spatial resolution along the line of sight when applied to plasma of thickness up to several meters. The Abel inversion procedure commonly used in interferometry to convert data of chordal measurements to radial plasma density profiles is unsuitable for small scale fluctuations because of strong line integration effect and generally lack of symmetry for fluctuations. The partial solutions used up to now are either location of probe chord near the plasma edge to exclude plasma core [2] or the use of magnetic shear technique. The latter method initially was utilized for collective scattering on Tore Supra [3] and then applied for PCI on Heliotron E [4]. The method is based on filamentary structure of low frequency microfluctuations, which are oriented along magnetic field lines ($k_{\parallel} << k_{\perp}$). When direction of magnetic lines varies significantly along the line of view, an experiment can be set in such a way that only fluctuations aligned in certain direction can be detected. If the direction of the magnetic field in the plasma is known this gives localization of observations along the viewing line. The drawback of this method is that only fluctuations at a single location can be detected in a particular geometry and variation of diagnostic configuration mechanically to change selected localization is too slow to follow dynamics in fluctuations distribution along the whole plasma diameter. A novel approach here is the use of a two-dimensional detector array, which records fluctuations with all orientations simultaneously [5, 6]. Fluctuations associated with different directions (therefore with different localizations) can be separated from the integral 2-D pattern with the use of 2-D spatial Fourier transform or with 2-D high resolution spectral estimation techniques. The Large Helical Device (LHD) has the additional advantage for implementation of magnetic shear technique because of large (~90° variation of $\tan^{-1}(B_r/B_\phi)$ when the beam is traveling vertically through the LHD plasma from bottom to top.

2. Capabilities

The two-dimensional PCI was installed on LHD and shows good capabilities [6,7]. The geometry of experiment is shown in figure 1 where vertical plasma cross-section and probe PCI beam A marked in red are plotted. The unique feature of 2-D PCI enables studying of global behavior of plasma microturbulence across the entire plasma diameter with time resolution determined only by detector bandwidth and sampling rate. This technique provides momentary profiles of plasma density microfluctuations data ($\tilde{n}(\rho, k)$, $\tilde{n}(\rho, v_{pol})$) through the entire plasma diameter for

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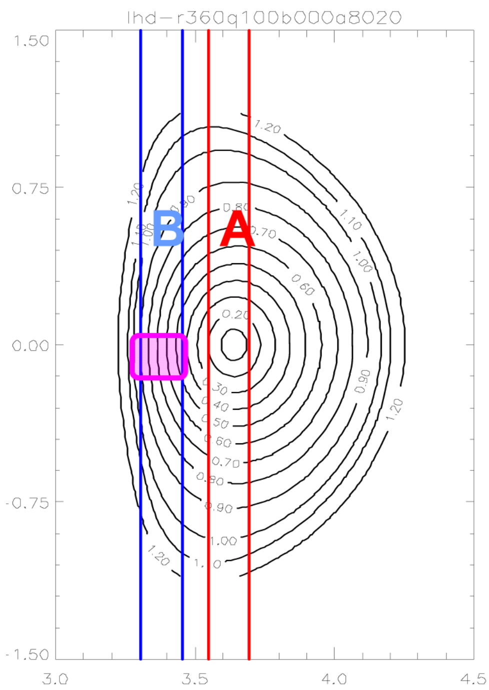

Fig. 1 Geometry of present PCI probe beam (A, red) shown for magnetic configuration with axis position Rax=3.6 m and $\beta = 0$.

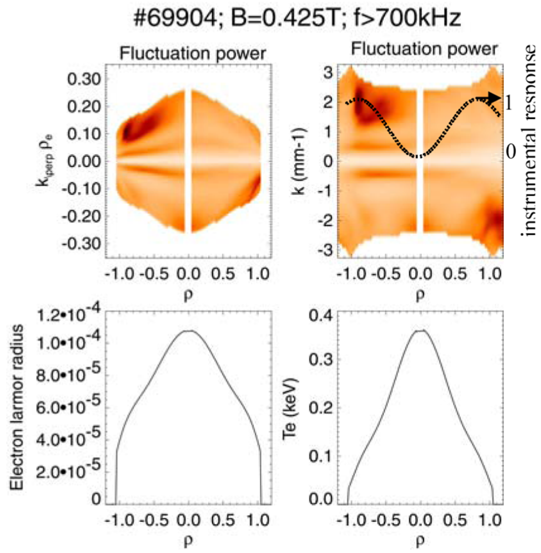

Fig. 2 Profile of density fluctuations with large k observed in discharge with low magnetic field. The dashed black curve shows instrumental response for $k = 2\,\mathrm{mm}^{-1}$, which has a minimum in the plasma center.

fluctuation scales in the range $1\,\mathrm{cm}^{-1} < k < 10\,\mathrm{cm}^{-1}$. Assembled in a movie such pictures present global dynamics of plasma density fluctuations at the frame rate of order of 1 MHz [8]. Spatial resolution depends on wavenumber of fluctuations and for observed high k region $5\,\mathrm{cm}^{-1} < k < 10\,\mathrm{cm}^{-1}$ resolution of 0.2-0.1ρ was obtained, where ρ is normalized minor radius. To reach maximal spatial resolution for array with limited number of detector elements a high resolution 2-D spectrum estimation technique is used instead of two-dimensional Fourier analysis. The obtained velocity profiles $\tilde{n}(\rho, v_{pol})$ exhibit different fluctuations modes resided at different locations across the plasma diameter [7]. Relation $\tilde{n}(\rho, v_{pol})$ with temperature and density profiles and with theoretical estimation of growth rates give means for identification of drift-wave turbulence modes [7,9]. The detection optics of the current PCI system is configurable so the image of the rectangular detector array in plasma can be varied in size and in aspect ratio. This feature enables realization of another advantage of 2-D PCI - its ability to sense small scale (up to $k = 30\,\mathrm{cm}^{-1}$) fluctuations at the edges of plasma and also in the plasma core. An example of the detection of ETG-scale fluctuations is shown in figure 2. Fluctuation profiles are convolved with instrumental function with strongly unequal response over the observation region. These fluctuation profiles are obtained in the overview mode [6] of the optical system that is not designed for observation of fluctuations with $k > 10\,\mathrm{cm}^{-1}$. The range $5\,\mathrm{cm}^{-1} < 30\,\mathrm{cm}^{-1}$ can be covered with zoom mode when only fraction of plasma cross-section is selected for spatially resolved measurements [6]. The limitation issues are addressed in the next section here we only list the general advantages of the PCI techniques that hold for 2-D modification as well:

- uses small ports, relative to mw or FIR scattering (scattering angles less that 10^{-2} rad);
- 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.

3. Limitations

For PCI as the collective forward light scattering technique the momentum conservation $\boldsymbol{k} = \boldsymbol{k}_s - \boldsymbol{k}_i$, where $\boldsymbol{k}$, $\boldsymbol{k}_s$ and $\boldsymbol{k}_i$ are the wavenumbers of plasma wave, scattered and incident light respectively, means that PCI is sensitive only to spectral components of plasma fluctuations with $\boldsymbol{k}$ almost normal to the probe beam direction. The Raman-Nath approximation, which is the basis for PCI, requires that the plasma wave size along the beam L_{R-N} should be relatively thin: $L_{R-N} = \frac{2\pi Q}{\lambda_0 k^2}$, where $Q << 1$ is the Klein-Cook parameter [10], and λ_0 is the laser wavelength. Calculation however shows that the approximate homogeneity along the beam direction of the PCI response is kept within much longer length: $L_{T/4} = \frac{2\pi^2}{\lambda_0 k^2}$. $L_{T/4} = 46\,\mathrm{cm}$ for $k = 20\,\mathrm{cm}^{-1}$ so adjusted for maximum sensitivity at the plasma edges ($|\rho| = 1$) the response is near to zero in the plasma center as is it is seen in figure 2. The length of plasma fraction covered in zoom mode along the viewing line should not exceed $L_{T/4}$ for respective wavenumber. The upper edge of the k-range covered by the present system $k = 30\,\mathrm{cm}^{-1}$ corresponds to $L_{T/4} = 20\,\mathrm{cm}$. This region along the beam should be selected by an additional spatial filter placed at the Fourier plane in front of zoom optical system [6]. For optimized magnification of the detection optics the maximal detectable $k_{\max} = 30\,\mathrm{cm}^{-1}$ should be near and bellow the Nyquist limit $k_{\mathrm{Nyq}} = \pi(N)^{1/2}/L_{\mathrm{array}}$, where $N = 48$ is number of detectors in the array and L_{array} is the size of image of the detector array in plasma. The minimal scale of angularly (and spatially) resolved fluctuations is $k_{\min} = 2\pi/\Delta$, where Δ is least of L_{array} or diameter of laser beam in plasma D. This means that dynamic range of detectable spatial scales is simply determined by number of detector elements $k_{\max}/k_{\min} = \pi/(4N)^{1/2}$. It should be noted that PCI method is insensitive to long scale fluctuations with $k < 2\pi/D$ by its physical principle. Capability of PCI to detection of small scale fluctuations may be deteriorated due finite contrast of input high pass spatial filter, which can not eliminate leakage of signal produced by scattering on large scale fluctuations. Contribution of this leakage increases especially in zoom mode because of larger fluctuation power ($S(k) \sim k^{-a}$) and lower spatial resolution ($L_{\mathrm{res}} \sim k^{-1}$) at small wavenumbers. The finite contrast of spatial filter is determined by focal spot wings of the probe beam. These wings, in their turn, are governed by distortion of probe beam wave front, in particular, by diffraction on apertures. Figure 3 shows results of calculated attenuation of PCI signal by high pass filter in dependence on wavenumber of wave in plasma. It is clear that for beam cut by aperture at the input port (3a) low k signal is rejected about one order of magnitude less effective than for narrower Gaussian beam (3b). However most energy of the leaked signal is concentrated at the low k edge of pass band so the contribution to the higher k is much less than total leaked power (3c). Angular resolution in two-dimensional PCI is $\delta\theta \sim 2\pi/Dk$ and spatial resolution $\delta z/z \sim \delta\theta/\Delta\theta$ here $\Delta\theta$ is difference in magnetic pitch angles between plasma edges and plasma center $\Delta\theta \sim 40^\circ$. The resolution length along the viewing line δz is the major uncertainty in determination of amplitude of density fluctuations $\tilde{n}_e$ because PCI signal intensity $\tilde{I} = 2I_0 r_e \lambda_0 \tilde{n}_e \sqrt{L_{\mathrm{corr}}\delta z}$, where L_{corr} is the correlation length of plasma density fluctuations along the line of sight and $2\pi/k < L_{\mathrm{corr}} < \delta z$. In present experimental configuration typically $\delta z k/2\pi$ ~10-20 so the uncertainty in $\tilde{n}_e$ is within a factor of 3-5. Additional beam B shown in figure 1 in blue can help to obtain information on radial correlation length L_{corr} if initially region near $z = 0$ (marked by magenta) is selected with spatial filter. It is possible with beam B even to gain direct information on radial flux $\Gamma = \langle \tilde{n}_e \tilde{v}_r \rangle$.

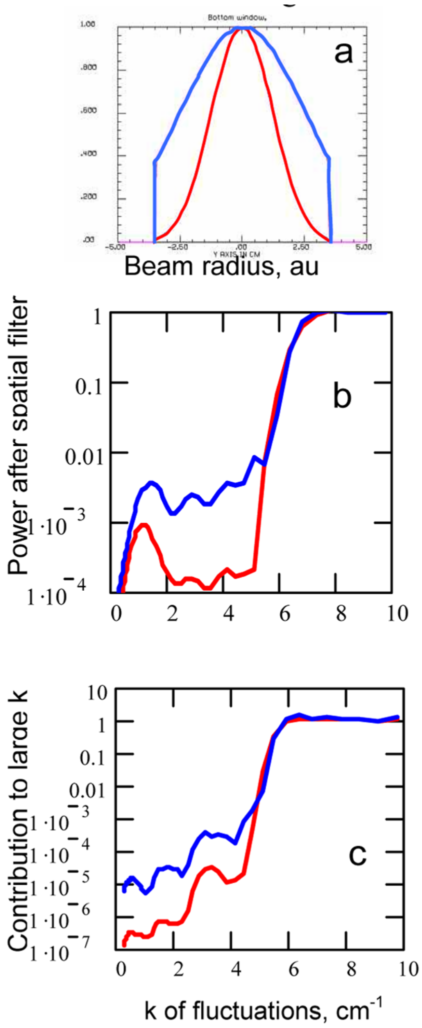

Fig. 3 Attenuation of PCI signal vs wavelength of the plasma wave. (a) Beams profiles at the input port; (b) total power of the PCI signal after spatial filter and phase plate; (c) high k contribution.

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