

Search for New Capabilities of Imaging Interferometry on LHD

L.N. Vyacheslavov^{a)}, K. Tanaka^{b)}, T. Akiyama^{c)}, K. Kawahata^{b)},
S. Okajima^{d)}, A.L. Sanin^{a)}, S. Iio^{c)}

a) Budker Institute of Nuclear Physics, Novosibirsk, 630090, Russia

b) National Institute for Fusion Science, Toki, 509-5952, Japan

c) Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8550, Japan

d) Department of Applied Physics, Chubu University, Kasugai 487, Japan

A CO₂ laser imaging interferometer is developing on Large Helical Device (LHD) [1]. It is designed for high spatial resolution measurements of both density profile and fluctuations especially at large density regimes. Three vertical slab probe beams cover almost entire plasma cross-section. As the first step one probe beam interferometer was installed and examined during the fifth LHD experimental campaign (Sept., 2001-Febr., 2002). Results obtained with heterodyne interferometer (HI) show fine resolution in the plasma boundary and no fringe jump during pellet injection [2]. The phase contrast interferometer mode (PCI) detected plasma density fluctuations [3]. The arrangement of the imaging part of the interferometer is chosen flexible to test several modifications of imaging interferometry in experiments. Two of the modifications use diffraction effects and are intended to obtain spatial resolution along the viewing line and to increase the sensitivity for detection of small-scale plasma density inhomogeneities in both PCI and HI. In this article, we report new schema of imaging interferometry that uses diffraction. By using new schema, more sensitive and spatially resolved measurements along beam axis become possible.

When collimated coherent radiation passes through small-scale phase object, which is the interferometry case, all information about this phase object is contained in the wave diffracted by the object. The amplitude of the diffracted wave is proportional to phase modulation produced by the phase object $\tilde{\varphi}$ ($\tilde{\varphi} \ll 1$ for typical microturbulence) and diffracted wave phase at the detector plane is generally determined by position of phase object (plasma density inhomogeneities) along the viewing line. In the case of imaging of a thin phase object the phase difference between diffracted and zero order wave is exactly 90° at the image plane that results in true phase image of the object (Eq.1). The first term in the right side of Eq.1 corresponds to the zero order wave and the second term to diffracted wave.

$$E = E_0 \cos(\varphi_0 + \tilde{\varphi}) \approx E_0 (\cos \varphi_0 - \tilde{\varphi} \sin \varphi_0) \quad (1)$$

When detector is placed not exactly in the image plane the phase difference departs from 90°. The combination of weak diffracted wave with not diffracted (zero order) wave produces simultaneous phase and amplitude modulation of the probe wave. The amplitude

component in the image can be directly recorded by ordinary intensity sensitive detector. This out-of-focus contrast of thin phase object is routinely employed in electron microscopy [4]. The similar effect with periodic phase object is well known in classical optics. The phase grating with pitch Λ illuminated with coherent collimated light produces a pure amplitude self-image at a quarter of Talbot distance $L_T = \frac{2 \cdot \Lambda^2}{\lambda}$ [5], where λ is the wavelength of light. An initial pure phase grating becomes pure amplitude after light passes $L_T/4$ distance and again phase at the distance $L_T/2$. Typically only phase component of the probe beam, which passes plasma inhomogeneity, is recorded both in the HI and the PCI techniques, so the information about axial position lies idle. The idea of spatial resolution along the viewing line using imaging interferometry is to measure both amplitude and phase components of wave modulation either in HI or PCI. The possible geometry for such measurements in the case of imaging HI is shown in Fig.1. Here the phase of 1-MHz beating signal is employed for measurement of phase image while the homodyne signal due to interference of zero order

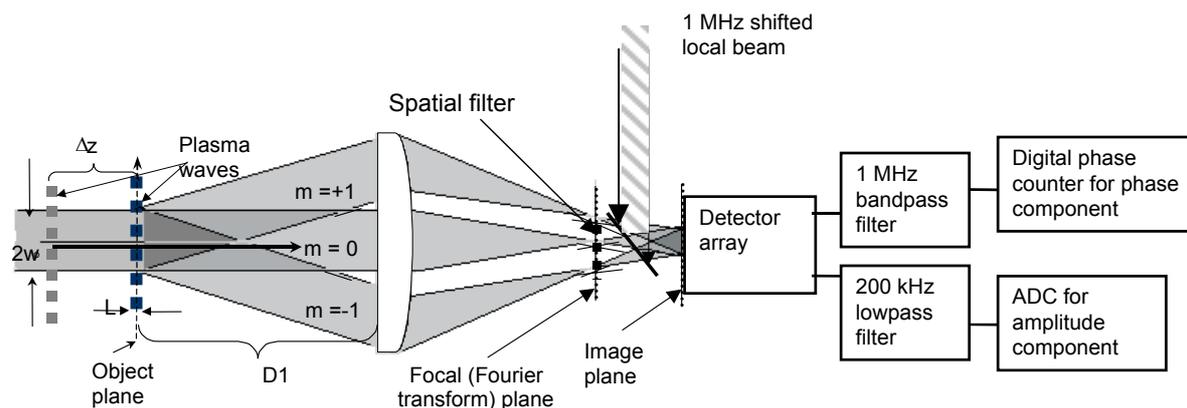


Fig.1. Version of simultaneous phase and amplitude measurements with a single linear array of detectors in the case of heterodyne imaging interferometer.

wave with diffracted wave is used for detection of amplitude image. Another modification in both HI and PCI aims at increase in sensitivity to plasma fluctuations. The point is to raise intensity of diffracted wave relative to zero order wave. If we simultaneously increase, say, B times the amplitude of the incident probe beam and decrease zero order amplitude at the Fourier plane also B times it results in B -fold gain in the phase shift of wave in the image plane ($B\tilde{\varphi} \ll 1$).

$$E = B \cdot E_0 \left(\frac{1}{B} \cos \varphi_0 - \tilde{\varphi} \sin \varphi_0 \right) = E_0 \cdot (\cos \varphi_0 - B\tilde{\varphi} \sin \varphi_0) \approx E_0 \cdot \cos(\varphi_0 + B\tilde{\varphi}) \quad (2)$$

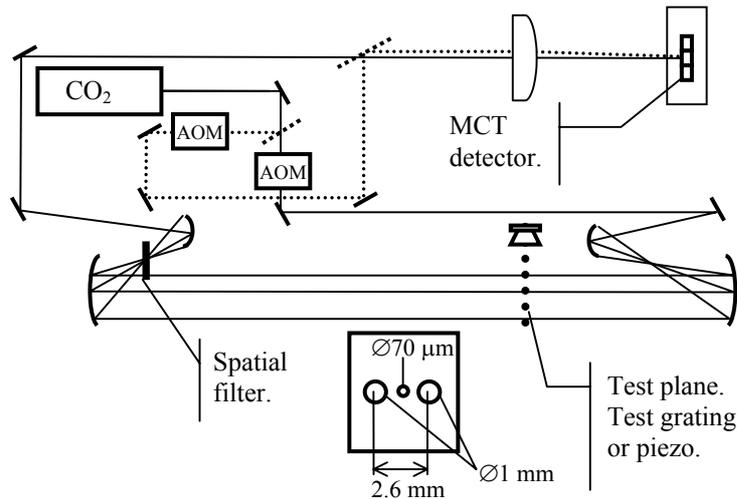


Fig.2. Test bench experiment layout

For experimental verification of both above mentioned conceptions a test bench experiment is performed (Fig.2). Standard HI arrangement with cw CO₂ laser employs two afocal parabolic mirror systems and a ZnSe lens to image a phase object in the LN₂ cooled MCT detector array. To attenuate the zero order wave a

spatial filter with 70μm pinhole is used. As a thin phase object a 1cm-pitch linear phase grating made from 5 μm thick Teflon strips is used in order to check spatial resolution. The phase shift produced by Teflon grating is about 1.5 radians. For test of optical gain of phase signal we use a piezo plate as source of ultrasonic (US) waves with frequency of 33.5 kHz. The peak-to-peak amplitude of the phase shift produced by US is $3 \cdot 10^{-4}$ radians for 10μm CO₂ laser radiation. This phase shift corresponds to the shift produced by plasma fluctuations with wavelength 1cm, amplitude $\delta N_e \approx 4 \cdot 10^{17} \text{ m}^{-3}$ and extension of the fluctuation region along the viewing line of 10 cm. The results of experiments with

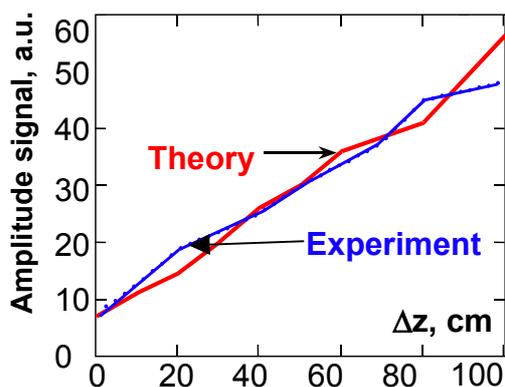


Fig.3 Amplitude component in the image of phase grating vs. displacement Δz from the object plane

resolution along z-axis (Fig.3) are compared with full diffractive simulations using commercial code GLAD. Amplitude signal increases more than 5 times while the test grating moves 100 cm along z-axis. It seems that 10 cm z-resolution is real for fluctuations with $\Lambda=1\text{cm}$. It is worth to note that the Talbot distance decreases as Λ^2 ($L_T/4=5\text{m}$ for $\Lambda=1\text{cm}$ and $L_T/4=1.25\text{m}$ for $\Lambda=0.5\text{cm}$). Consequently, the shorter wavelength of plasma wave the easier its localization by amplitude component. The result of test of optical

gain is shown in Fig.4, where phase signal produced by 33.5kHz ultrasonic wave in air is amplified almost 30 times by attenuation of the zero order wave.

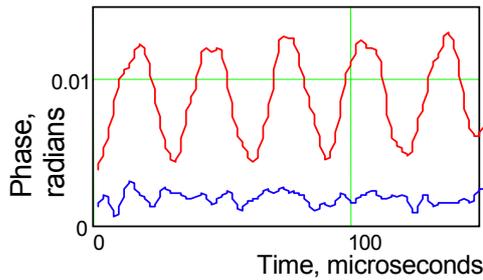


Fig.4. Optical gain of phase shift.

Red-with gain, Blue-without.
Initial phase shift from
ultrasonic wave is $3 \cdot 10^{-4}$

In real experiment spatial spectrum of fluctuation is broad and a spatial filter at the Fourier plane to select diffracted wave with particular k is necessary. When k is selected, spatially resolved fluctuation measurements are possible by using proposed schema.

Much more complicated than localization of a single plasma wave is the localization of particular one from a set of waves situated along z axis. It is possible indeed if there is a rotation velocity shear along the viewing line (Fig.5). This technique can be useful however when the dispersion of plasma fluctuations is

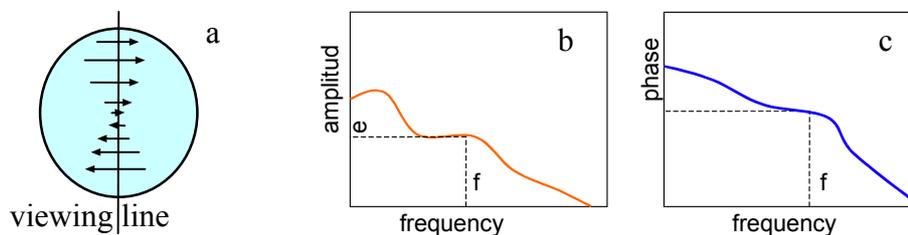


Fig.5 Use of shear of the rotation velocity along the viewing line (a) for localization both the rotation velocity and plasma fluctuations. Spectra of amplitude signal (b) and phase signal (c) for wave of particular k .

determined by plasma rotation. In this case the rotation velocity and radial electric field can be determined from comparison of the spectra of phase (Fig.5c) and amplitude (Fig.5b) signals as shown in Fig.5. Rotational velocity shear along the viewing line broads frequency spectrum for a particular k of fluctuations. To relate phase and amplitude signal with some frequency f it is possible to determine both the location and intensity of plasma wave. The frequency f permits to determine the phase velocity of the wave i.e. radial electric field at a particular location.

References

1. K. Tanaka, L. N. Vyacheslavov, K. Kawahata T. Tokuzawa, , S. Okajima, Rev. Sci Instrum., 72,1089,2001.
2. T. Akiyama, K. Tanaka, L. N. Vyacheslavov, T. Tokuzawa, Y. Ito, S. Tsuji-iiio, S. Okajima, K. Kawahata, CO₂ Laser Imaging Interferometer for High Spatial Resolution Electron Density Profile Measurements on LHD, submitted for 14th Topical Conference on High Temperature Plasma Diagnostics, July 8, 2002, Madison, WI,
3. K. Tanaka, L. N. Vyacheslavov, T. Akiyama, A. Sanin, K. Kawahata, T. Tokuzawa, Y. Ito, S. Tsuji-iiio, S. Okajima, Phase Contrast Imaging Interferometer for Edge Density Fluctuation Measurements on LHD, submitted for 14th Topical Conference on High Temperature Plasma Diagnostics, July 8, 2002, Madison, WI,
4. J.M. Cowley, Diffraction Physics, North Holland Publishing Comp.,1975.
5. H.F. Talbot, Philos. Mag., 9, 402, 1836.