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EDGE FLUCTUATION MEASUREMENTS BY PHASE CONTRAST IMAGING ON DIII-D

by
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ABSTRACT

A novel CO₂ laser phase contrast imaging diagnostic has been developed for the DIII-D tokamak, where it is being employed to investigate density fluctuations at the outer edge of the plasma. This system generates 16-point, 1-D images of a 7.6 cm wide region in the radial direction, and is characterized by long wavelength (7.6 cm) and high frequency (100 MHz) capability, as well as excellent sensitivity ($\tilde{n} \gtrsim 10^9 \text{ cm}^{-3}$). The effects of vertical line integration have been studied in detail, both analytically and numerically with actual flux surface geometries generated by the EFITD magnetic equilibrium code. It is shown that in the present configuration the measurement is mostly sensitive to radial wave vectors. Experimental results on fluctuation suppression at the L- to H-mode transition and on the L-mode wave number spectrum are discussed briefly. Finally, future plans for extending the measurement to the core of the plasma and for investigating externally launched fast waves are presented.

I. INTRODUCTION

Plasma turbulence and its effect on anomalous transport in tokamaks remain poorly understood¹ in spite of intensive investigation. Laser-based fluctuation imaging techniques offer significant advantages over other diagnostics in terms of increased sensitivity, excellent temporal and spatial resolution, and unlimited access to the core of fusion grade plasmas. The latter aspect is especially relevant to future large devices, such as ITER, where neutral beam attenuation poses serious limitations on the applicability of beam emission spectroscopy.²

The CO₂ laser phase contrast imaging (PCI) method has been demonstrated successfully on DIII-D.^{3,4} Plasma edge measurements, particularly in the context of the L- to H-mode transition, are discussed in this paper. The large bandwidth (100 MHz) and excellent sensitivity ($\tilde{n} \geq 10^9 \text{ cm}^{-3}$ on a 1 MHz bandwidth) of this technique make it also a leading candidate for detecting launched rf waves in the plasma core,⁵ in a proposed future configuration on DIII-D.

An important limitation of this type of technique is the inherent lack of spatial resolution along the direction of propagation, since the measurement is line-integrated. An investigation of the consequences of this averaging effect in different physical scenarios has been carried out, both analytically and numerically, and is discussed in this paper. It is shown that the DIII-D PCI system in its present configuration is mostly sensitive to radial wave vectors. Crossed beam correlation techniques can be used to provide highly localized measurements. Such a configuration has been proposed for the DIII-D interior (normalized minor radius $r/a \sim 0.8$).

II. TECHNIQUE AND HARDWARE

The phase contrast technique has been described in detail elsewhere.^{3,6} Here we merely recall its main features. The fluctuating component of the density, averaged along the line of sight (vertical in our case), is imaged onto a linear detector array, with a one-to-one correspondence between major radius and detector element position. The wave number response function is essentially constant down to a cutoff value k_c which is approximately equal to 2π divided by the beam width. The lack of an external reference beam with its associated vibrational phase shifts results in excellent density sensitivity.

The DIII-D PCI apparatus has also been described elsewhere.^{3,4} Here we provide a brief overview of the system with emphasis on considerations of mechanical stability and on recent upgrades. The light source is a 20 W CO₂ laser, telescopically expanded to a width of 7.6 cm. The beam, which propagates vertically through the outer plasma edge ($0.9 < r/a < 1.15$) (Fig. 1), is then focused on the appropriate phase mirror, and is finally imaged onto a 16-element, LN₂-cooled, photovoltaic HgMnTe array.

Accurate focusing is essential to the success of the technique. A dual-axis rotating mirror set, located 50 cm from the focal plane, compensates for the strong mechanical vibrations experienced by the optics. The mirror set is driven by a feedback network, which uses as input the focal position measured by a position sensor (Fig. 2). The successful development and excellent performance of this network have been an important element in the proof of principle of PCI. Owing to the late addition of this diagnostic to the DIII-D device, severe space limitations have

Fig. 1. Geometry of phase contrast imaging on DIII-D

dictated an overlong optical path and support structures prone to vibrations. The beam oscillation amplitude is approximately ± 1 mrad at a dominant frequency of 20 Hz. These rather unfavorable conditions should adequately simulate the vibration scenario of a larger device such as ITER, if a careful optical design is included in the early planning stages. Our well-proven feedback control design could then be applied to that system.

The original homodyne data acquisition configuration performed poorly at frequencies in the 100–1000 kHz range, owing to broadband noise appearing in the long cables (≈ 50 m) connecting the detector to the CAMAC digitizers. A new

Fig. 2. Schematics of imaging optics and feedback stabilization system

superheterodyne system is now in place. The signals are mixed with an rf (20–60 MHz) reference near the detector and are downshifted again before digitization. The high frequency carrier is unaffected by cable noise and the performance is now limited by detector noise at all frequencies of interest ($\tilde{n} \gtrsim 10^9 \text{ cm}^{-3}$ from 1 to 1000 kHz). A sensitivity of $\approx 5 \times 10^7 \text{ cm}^{-3}$ could be attained by altering the detector bias and reducing the bandwidth from 100 to 20 MHz.

III. INTERPRETATION OF THE MEASUREMENTS

This section summarizes the results of a study that will appear in full in a future publication. We shall focus on the correlation properties of the plasma turbulence. One can calculate the correlation function between any two PCI chord signals. Integral inversion techniques can be used in principle to derive the two-point density correlation function, if the dimensionality of the problem is reduced through the assumption of either homogeneity or isotropy.

Without such assumptions, an unambiguous inversion is not possible in general. The equal-time PCI autocorrelation function can be approximated by the expression $\int \tilde{n}_e^2 L_{cz} dz$, where L_{cz} is an effective vertical correlation length:

$$\frac{1}{L_{cz}^2} \simeq \frac{\sin^2 \theta}{L_{c\rho}^2} + \frac{\cos^2 \theta}{L_{c\theta}^2}, \quad (1)$$

where $L_{c\rho}$ and $L_{c\theta}$ are the radial and poloidal correlation lengths, respectively, and θ is the poloidal angle ($=0$ on the outboard midplane), which is a function of the integration variable z (Fig. 1).

We postulate gaussian wave number spectra in the radial and poloidal directions, centered respectively at $k_{\rho 0}$ and $k_{\theta 0}$. We also assume that fluctuations are symmetrically distributed above and below the midplane, but the actual spatial distribution is not otherwise specified *a priori*. The two-chord PCI correlation function, as a function of the displacement along the major radius, will be characterized by an apparent correlation length

$$L_{cR} \simeq \sqrt{L_{c\rho}^2 \cos^2 \bar{\theta} + L_{c\theta}^2 \sin^2 \bar{\theta}}, \quad (2)$$

where $\bar{\theta}$ should be interpreted as an amplitude-weighted rms chord average. The apparent wave number spectral density will be bi-gaussian, with the two peaks located at

$$k_R \simeq \frac{1}{L_{cR}^2} (k_{\rho 0} L_{c\rho}^2 \cos \bar{\theta} \pm k_{\theta 0} L_{c\theta}^2 \sin \bar{\theta}). \quad (3)$$

The $\pm$ sign reflects the fact that the projection of k_θ on a horizontal plane has opposite signs above and below the midplane. Since generally $L_{c\rho} \sim L_{c\theta}$, the peak k_R values can be written as $k_{\rho 0} \cos \bar{\theta} \pm k_{\theta 0} \sin \bar{\theta}$, which bear an obvious interpretation as the horizontal projections of the peak wave number from either side of the midplane.

In our present geometry, $|\theta| < 0.25$ rad always, and $|\bar{\theta}| \ll 1$ rad in most cases. Therefore $L_{cz} \simeq L_{c\theta}$, $L_{cR} \simeq L_{c\rho}$, and $k_R \simeq k_{\rho 0}$; thus the PCI cross-phase and coherence functions reflect the *radial* fluctuation structure. Significant departures from this conclusion could only occur for large $L_{c\theta}/L_{c\rho}$ or $|k_{\theta 0}|/|k_{\rho 0}|$ ratios. Such cases would be identified in general by a double-peaked spectrum as indicated by Eq. (3). In addition, up-down asymmetries in the fluctuation level could alter this picture significantly. Fluctuations localized to one side of the midplane would select only one sign in Eq. (3) and could produce a single non-zero peak even with $k_{\rho 0} = 0$.

The approximations implicit in the foregoing analysis can be incorporated in the single quantity $\bar{\theta}$, which was not rigorously defined. Although a consistent definition of $\bar{\theta}$ is possible, a numerical simulation is more illuminating at this stage. The PCI correlation function and the corresponding apparent k_R spectrum have been derived by using realistic field line geometries, inferred from the EFITD⁷ magnetic equilibrium code for specific DIII-D discharges. Figure 3 shows the k_R spectrum

for one particular set of parameters. The results confirm the basic validity of the analytical calculations, while adding more complex details such as the asymmetry between the two peaks due to up-down flux surface asymmetries.

Fig. 3. Apparent k_R spectral density of PCI chord integrals from gaussian fluctuation spectra, calculated numerically for a lower single-null diverted DIII-D discharge ($k_{\rho 0} = 2 \text{ cm}^{-1}$, $k_{\theta 0} = 8 \text{ cm}^{-1}$, $L_{c\rho} = L_{c\theta} = 2 \text{ cm}$).

IV. EXPERIMENTAL RESULTS AND FUTURE PLANS

The PCI system has been used primarily in the context of L- to H-mode transition experiments. It is well documented that the onset of the H-mode in diverted plasmas is accompanied by a reduction of the amplitude of fluctuations near the separatrix.⁸ Our measurements have added new details to this picture: the L-mode exhibits a broad spectral feature which peaks at ≈ 50 kHz and is strongly suppressed, as well as broadened, in the transition to H-mode (Fig. 4). Moreover, the L-mode cross-phase function increases monotonically with radial separation (Fig. 5). The sign convention is such that this pattern corresponds to inward propagation. The conclusions of Section III lead us to interpret the measurements as either a) an inward propagating radial wave structure with phase velocities of the order of $(1.7-2.0) \times 10^5$ cm/s, or b) a poloidally propagating structure localized to one side of the midplane. Either observation lacks a theoretical explanation at present. More studies and comparisons with other diagnostics will hopefully provide clues for selecting the proper interpretation.

An extension of this system to a second radial location is planned for the future. This would access the core region of the plasma ($r/a \sim 0.4-0.6$) and permit direct detection of externally launched fast waves during current drive experiments.⁵ In addition, we plan to implement a crossed beam configuration and carry out a highly localized study of fluctuations in the midplane region at $r/a \sim 0.8$ through the application of correlation techniques.⁹

Fig. 4. L-mode (solid line) and H-mode (dashed line) PCI power spectral density functions. The chord is 2.5 cm inward from the one tangent to the separatrix.

Fig. 5. Coherence (solid line) and cross-phase (dashed line) at 50 kHz as functions of radial separation in L-mode (a positive phase derivative corresponds to inward propagation). Estimates were evaluated on 200 realizations.

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