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A PHASE CONTRAST INTERFEROMETER ON DIII-D

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ABSTRACT

A novel imaging diagnostic has recently become operational on the DIII-D tokamak for the study of density fluctuations at the outer edge of the plasma. The phase contrast imaging approach overcomes the limitations of conventional scattering techniques in the spectral range of interest for transport-related phenomena, by allowing detection of long wavelength modes (up to 7.6 cm) with excellent spatial resolution (5 mm) in the radial direction. Additional motivation for the diagnostic is provided by wave-plasma interactions during heating and current drive experiments in the Ion Cyclotron range of frequencies. Density perturbations of $4 \times 10^7 \text{ cm}^{-3}$ with a 1 MHz bandwidth can be resolved. The diagnostic employs a 7.6 cm diameter CO₂ laser beam launched vertically across the plasma edge. An image of the plasma is then created on a 16-element detector array: the detector signals are directly proportional to the density fluctuations integrated along each chord. Wavelengths and correlation lengths can be inferred from the spatial mapping. The phase contrast method and its application to DIII-D are described and tests and first plasma data are presented.

INTRODUCTION

Recent experimental¹ and theoretical² work have indicated that turbulent density fluctuations at the edge of tokamak plasmas may be dominated by low wavenumber modes, with wavelengths of the order of a few to tens of ion Larmor radii, and that these modes are chiefly responsible for anomalous transport.³ Conventional and widely used diagnostics for the measurement of density fluctuations, such as CO₂⁴ or far infrared⁵ scattering, suffer from lack of spatial resolution at such wavelengths; microwave reflectometry measurements thus far have lacked wavenumber resolution.⁶ The direct spatial representation provided by imaging methods is more attractive at the low wavenumbers, where the scale lengths of the modes become comparable to the characteristic gradient lengths. An imaging diagnostic is also an ideal tool for studying the physics of plasma interaction with rf waves during ICH or lower hybrid experiments: our goal during the fast wave current drive experiments⁷ will be to investigate primary waves as well as parametric decay activity.⁸

The phase contrast method is an ideal choice among imaging techniques, since it uniquely combines high sensitivity with a response function which is approximately independent of wavenumber above a given cutoff k_c . To our knowledge, this technique which is well known in the microscopy field⁹ has been applied previously only to two high-density plasma experiments.^{10,11} In our experiment, we use a CO₂ laser beam ($\lambda_0 = 10.6 \mu\text{m}$) with a diameter of 7.6 cm, which is launched vertically through the outer edge of the DIII-D plasma (see Fig. 1). The detector is a 16-element, LN₂-cooled, HgMnTe linear photovoltaic array, with a bandwidth of 100 MHz. Low intrinsic detector noise insures that a phase sensitivity of $\simeq 10^{-6}$ radians can be attained, corresponding to a minimum detectable density of approximately $4 \times 10^7 \text{ cm}^{-3}$.

I. TRANSMISSION TECHNIQUES AND PHASE CONTRAST

The laser beam experiences a phase shift upon traversing the plasma equal to¹² (neglecting any toroidal dependence)

$$\Delta\Phi(R, t) \simeq r_e \lambda_0 \int n_e(R, z, t) dz \quad , \quad (1)$$

Fig. 1. Location of diagnostic on DIII-D.

where $\lambda_0 = 10.6 \mu\text{m}$, $r_e = 2.8 \times 10^{-13} \text{ cm}$ (classical electron radius), z is the vertical direction of propagation and R is the major radius. It can be shown that the radial fluctuation wavenumber must not exceed a given k_{max} in order for Eq. (1) to be valid. In our apparatus, a low-pass filter limits the spectrum to $k \leq 15 \text{ cm}^{-1}$.

The plasma acts as a phase object, and no amplitude variation will be recorded by an image-forming instrument. Non-imaging techniques, such as scintillation¹³ and far-forward scattering,¹⁴ have been employed to measure plasma density fluctuations;

these methods offer the advantage of simplicity but display an undesirably non-uniform response in k -space which renders data interpretation difficult. Far-field measurements such as conventional scattering^{4,5} resolve the individual k components from scattering volumes which increase in size for decreasing wavenumbers, thereby losing spatial resolution.

Imaging techniques which involve manipulation of the beam to transform the phase shift into a measurable intensity variation offer in general a more regular k -space response. Of these methods, those involving interference with an external reference beam are vulnerable to mechanical vibrations and subsequent loss of sensitivity. Techniques that rely on an internal reference have the inherent limitation of not being able to resolve fluctuation wavelengths longer than the beam width. Among the several such methods available (including Schlieren and dark ground) phase contrast is the only one that offers true "phase imaging," *i.e.*, the signal at the image plane is proportional to the phase at the corresponding point in the plasma (this is true in the approximation $|\Delta\Phi| \ll 1$, which is generally a very good one in the case of fluctuations above 1 kHz). The asymmetry between positive and negative orders in all the Schlieren techniques has the effect of summing different wavenumber components with different weights, thus rendering image formation impossible.

The phase contrast technique is based on the observation that to first order in $\Delta\Phi$, the transmitted wave consists of the original incident plane wave plus a small localized disturbance which carries all the information about the plasma structure, and which lags in phase by 90° . This can be seen mathematically by expanding the wave field $E(R, t) = E_0 e^{-i\omega_0 t + i\Delta\Phi(R, t)}$ into

$$E(R, t) \simeq E_0 e^{-i\omega_0 t} [1 + i\Delta\Phi(R, t)] \quad . \quad (2)$$

The first term in the square brackets is the direct beam, while the second term is the diffracted beam.¹⁵ The two components can be separated physically in the focal plane of a lens. If a spatial filter is introduced that can shift the phase of the direct beam by 90° , while also reducing its intensity by a factor ρ , the two beam components

will then interfere constructively or destructively in the image plane, with a resulting intensity

$$I(x, t) \simeq |E_0|^2 \left[\rho \pm 2 \sqrt{\rho} \Delta\Phi \left(\frac{x}{M}, t \right) \right] , \quad (3)$$

where x is the coordinate of the radial image, and M is the magnification. The time-dependent component of the signal is now proportional to the original phase shift, thus, according to Eq. (1), to the line integral of the density perturbation. The vertical integration implies that no spatial resolution can be achieved along the vertical direction (the effective integration length is typically 60 cm in our case).

The actual experiment is performed with a gaussian beam truncated by an aperture stop at the e^{-2} width (7.6 cm). A focal filter (*phase mirror*) is made by applying a $1.3 \mu\text{m}$ ($= \lambda_0/8$) thick reflective coating on a blank substrate with a surface reflectivity of ρ , except for a central band which is left uncoated. The width of the band is of the order of the focal spot size, and it corresponds to a given cutoff wavenumber k_c .

The wavenumber response function can be calculated analytically in the approximation of spatial invariance:

$$T(k) = \frac{2}{\pi} I_0 \sqrt{\rho} \int_{-1}^1 e^{-y^2} \frac{\sin(k_c w y)}{y} [1 - \cos(k w y)] dy , \quad (4)$$

where I_0 is the beam intensity and w is the gaussian half-width. This function is plotted in Fig. 2. For a sinusoidal phase shift $\Delta\phi(R, t) = \phi_0 \cos(kR - wt + \psi_0)$, the ac signal intensity at the detector will be $I_{ac}(x, t) = T(k) \Delta\phi(x/M, t)$.

The sensitivity of the measurement is determined by detector noise, which is predominantly shot noise in a photon detector. The signal to noise ratio is

$$S/N = \frac{2 A \eta I_0}{\hbar \omega_0} \frac{(\Delta\Phi)^2}{\Delta f} , \quad (5)$$

where A is the element area, η the quantum efficiency, and Δf the bandwidth. Although the S/N ratio does not depend directly on ρ , using a phase mirror with $\rho < 1$ allows larger values of I_0 to be attained without reaching saturation. In practice, it is desirable to operate at the highest possible power levels.

Fig. 2. Phase contrast response function (curve is calculated, circles represent experimental measurements from sound waves).

II. EXPERIMENTAL APPARATUS

The light source is a 20 W CO₂ laser. A continuously variable ZnSe attenuator is available to reduce the power below detector saturation. The gaussian beam is expanded to a width of 7.6 cm by a telescope composed of a ZnSe lens and an off-axis parabolic mirror. All these components are mounted on an optical table as are the imaging optics. Eight large mirrors relay the beam to and from the DIII-D vessel, which is accessed through two ZnSe windows. At the focus of a second off-axis parabolic mirror ($F = 203$ cm) is the phase mirror. An image of the plasma is created on the plane of the detector by the parabolic mirror combined with two additional ZnSe lenses. The setup is flexible and allows variable magnification (to reduce the range and increase the spatial resolution) as well as image orientation.

The long optical path, the lack of isolation of the several mirrors mounted on, and around the vessel, and mechanical vibrations during plasma discharges cause large movements in the focal spot position. In order to keep the focal spot centered on the phase-shifting groove, a fast, high-gain, dual-axis feedback stabilization system is used, including two small rotating mirrors located before the phase mirror. The position of the spot is measured by a quadrant, LN₂ cooled, HgCdTe detector.

Phase mirrors of different sizes and materials were employed in the testing phase. The width that optimized the response function was found to be 480 μm . The data described in the present work were collected with a mirror of that size, made of Al-coated steel, lent to us by the TCA team. More recently, we started testing three new mirrors with grooves of the same size, with Ge, ZnSe, and BaF₂ substrates ($\rho = 0.36$, 0.17, and 0.03, respectively).

The detector is a 16-element, LN₂-cooled, photovoltaic HgMnTe linear array, followed by 16 low-noise preamplifiers, operating in the bandwidth 1 kHz – 100 MHz. The signals can either be digitized directly (after a series of filtering and amplification stages) at a 2 MHz sampling rate for investigating broad-band turbulence, or they can be heterodyned with an rf reference signal during ICRF studies.

III. TESTS AND FIRST PLASMA DATA

The Phase Contrast Interferometer can be tested on acoustic and ultrasonic waves propagating in air in a direction perpendicular to the laser beam. The index of refraction of air depends linearly on the pressure perturbation. A simple test apparatus, consisting of a loudspeaker and a calibrated microphone, was assembled to measure the wavenumber response and to absolutely calibrate the diagnostic. Figure 2 shows the measured response function along with the theoretical function.

The diagnostic has been used only recently to study broadband density turbulence on the DIII-D tokamak ($R = 1.67$ m, $a = 67$ cm) in both L-mode and H-mode plasmas. The most direct way to explore the spatial structure of dominant modes is to measure the two-point correlation function. Figure 3 shows the real part of the correlation function for a highly coherent mode observed at 96 kHz during H-mode. The eight points shown correspond to the innermost half of the beam, with the separatrix being approximately in the middle. The spatial Fourier transform peaks at $k_R = 1.4$ cm⁻¹, corresponding to the sinusoidal waveform shown in

Fig. 3. Two-point correlation function of density fluctuations, at given frequency and at given time during H-mode ($I_p = 1$ MA, $B_T = 2.1$ T). The wave shown corresponds to the peak of the spatial Fourier transform.

the figure. Figure 4 shows the time evolution of the auto-correlation spectrum for the same discharge.

Although correlation methods can provide valuable information, the diagnostic can also resolve rapidly moving structures unrevealed by correlation functions. This powerful capability is unique to the phase contrast technique, owing to its property of preserving the temporal and spatial form of the density fluctuations. We plan to use this technique in the coming year to carry out detailed measurements on low frequency turbulence in the plasma edge in DIII-D.

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Fig. 4. Time evolution of auto-correlation spectrum of fluctuations at given spatial location.

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REFERENCES

- ¹ R.J. Fonck, R. Durst, Y.J. Kim, S.F. Paul, N. Bretz, R. Nazikian, Bull. Am. Phys. Soc. **36**, 2445 (1991).
- ² H. Biglari, P.H. Diamond, M.N. Rosenbluth, Phys. Fluids B **1**, 109 (1989).
- ³ V.S. Chan, D.M. Meade, APS News, Vol. 1, **3**, 64 (1992).
- ⁴ R.E. Slusher, C.M. Surko, Phys. Fluids **23**, 472 (1980).

- ⁵ R. Philipona, E.J. Doyle, N.C. Luhmann, Jr., W.A. Peebles, C. Rettig, K.H. Burrell, R.J. Groebner, H. Matsumoto, and the DIII-D Group, *Rev. Sci. Instrum.* **61**, 3007 (1990).
- ⁶ A.E. Costley, P. Cripwell, R. Prentice, A.C.C. Sips, *Rev. Sci. Instrum.* **61**, 2823 (1990).
- ⁷ M.J. Mayberry, S.C. Chiu, M. Porkolab, V. Chan, R. Freeman, R. Harvey, R. Pinsker, "60 MHz Fast Wave Current Drive Experiment for DIII-D," in *Radio-Frequency Power in Plasmas* (Proc. 8th Top. Conf. Irvine, 1989) No. 190, AIP, New York (1989) 298.
- ⁸ M. Porkolab, "Parametric Instabilities in the Tokamak Edge Plasma in the Ion Cyclotron Heating Regimes," *Fusion Engineering and Design* **12**, 93 (1990).
- ⁹ F. Zernicke, *Physica* **9**, 686, 974 (1942).
- ¹⁰ H.M. Presby, D. Finkelstein, *Rev. Sci. Instrum.* **38**, 1563 (1967).
- ¹¹ H. Weisen, *Rev. Sci. Instrum.* **59**, 1544 (1988).
- ¹² F.F. Chen, *Introduction to Plasma Physics and Controlled Fusion*, Plenum Press, New York, 1984.
- ¹³ L.E. Sharp, *Plasma Phys.* **25**, 781 (1983).
- ¹⁴ D.E. Evans, E.J. Doyle, D. Frigione, M. von Hellermann, A. Murdoch, *Plasma Phys.* **25**, 617 (1983).
- ¹⁵ E. Hecht, *Optics*, Addison-Wesley, Reading, 1987.

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