A Dual Far-Infrared Laser Diagnostic of Magnetized Plasmas

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A dual far-infrared laser has been constructed and its properties have been exploited to probe tokamak-like discharges in the CDX toroidal device. Thermal variation of the difference frequency between the two far-infrared cavities is slow, though the cavities lack thermal stabilization, simply because their assembly on the same chassis exposes them to virtually identical temperature changes. The optical arrangement beyond the laser permits conversion within minutes between interferometry and density fluctuation observation, and within an hour between different operating wavelengths. Line-average densities of $2 \times 10^{13} \text{ cm}^{-3}$ and coherent fluctuations in the neighborhood of 20 kHz have been measured with this diagnostic.

MASTER

I. Introduction

The CDX (Current Drive Experiment) is a device dedicated to the study of tokamak plasma current maintenance by helicity injection.¹ Typical experiments include the formation of a tokamak plasma with $\bar{n}_e = 2 \times 10^{13} \text{ cm}^{-3}$, $T_e = 20 \text{ eV}$, $B_T = 4.5 \text{ kG}$, $a = 3 \text{ cm}$, and $R = 59 \text{ cm}$. In preparing for this experiment, it was thought valuable to have diagnostics of the total electron density and the electron density fluctuation spectrum. The dual far-infrared laser system serves both these needs.

Electron density interferometry is simply a measurement of the phase shift of radiation passed through the plasma with respect to that propagated through vacuum.² The frequency of the radiation used must be sufficiently high that cutoffs are avoided and so that density gradients do not substantially alter the direction of beam propagation. Typically this requires a probe beam whose frequency is several times the peak electron plasma frequency of the discharge observed. For CDX plasmas, this requires $f > 96 \text{ GHz}$, or $\lambda < 3.1 \text{ mm}$. At the same time, because the phase shift is proportional to the wavelength, a long wavelength is desired to keep the phase shift measurable above the noise induced by random phase fluctuations. For the densities quoted above, radiation in the far-infrared region of the spectrum (roughly $100 \mu\text{m}$ to $1000 \mu\text{m}$) will propagate with suitably small deflections, yet will also have a measurable phase shift.

For observation of electron density fluctuations, one desires resolution in position and in wave number, plus a good signal-to-noise ratio. Millimeter waves tend to diffract too rapidly and are cut off in the densest CDX plasmas, making them a poor choice for scattering applications. Infrared radiation, of wavelength $10 \mu\text{m}$ or less, demands complicated set-ups in order to observe global fluctuations with $k_{\perp} \rho_i \ll 1$. The intervening regime, the far-infrared, provides a satisfactory compromise with reasonable resolution in space ($\Delta x = 1 \text{ cm}$), in $k_{\perp}$ ($k_{\perp} \rho_i$ from 0.2 to 2.8), and good signal-to-noise ratio.³ Previous work in this field by Semet⁴ and others⁵ has verified the suitability of far-infrared laser systems for this type of diagnostic. Recent work by Brower and others^{6,7} on the Texas Experimental Tokamak (TEXT) has confirmed the utility of a dual cavity laser in such systems.

II. The Dual Far-Infrared Laser

A schematic of the dual far-infrared (FIR) laser is shown in Figure 1. Both cavities are mounted on a single supporting rail; they share a common vacuum system, and neither cavity is thermally stabilized.⁸ The cavities are of the dielectric-waveguide type, consisting of Pyrex tubes 2 m in length with 38 mm inner diameters and 2 mm thick walls. The input couplers are gold-coated copper disks with 3 mm diameter center holes for the admission of the CO₂ laser pumping beam. At the output end, the couplers consist of 0.5 mm thick quartz disks, coated with ZnSe to reflect the CO₂ beam. A nickel mesh, mounted parallel to the disk, acts as a partial reflector for the far-infrared radiation within the cavity. Operation of the laser has shown that at 394 μm , with formic acid as the lasing gas, the quartz disk is best placed behind the mesh. At 1222 μm , with ¹³CH₃F as the lasing medium, the disk is best placed in front of the mesh to avoid thermal distortion of the mesh by the CO₂ beam. The FIR radiation leaves the evacuated volume through windows of TPX.

Both far-infrared cavities are pumped by a single CO₂ laser which has a 2 m long cavity of 10 mm inner diameter. The grating-tunable laser can, with its present power supply, provide about 55 W cw output on 9P32. The CO₂ beam, after passing through a focussing lens, enters the far-infrared vacuum chamber through a ZnSe Brewster window. The beam is split approximately 50/50 in power by a 45° beamsplitter within the vacuum chamber, and the two beams are then directed into the cavities, where they are absorbed by the lasing gas.

Although the FIR cavities are not thermally stabilized, they require only infrequent tuning, perhaps once in an hour after operating temperature is reached. The beat frequency between the two outputs, typically 1 MHz, may vary only ± 300 kHz during the same period because the proximity of the cavities subjects them to nearly identical temperature changes and hence nearly equal changes in length. Only when the two cavities have different rates of change in length will the beat frequency drift. At a fill pressure of 50 mTorr of ¹³CH₃F, with about 25 W of CO₂ laser power entering each cavity, the 1222 μm output is roughly 1 mW from each cavity. With 165 mTorr of HCOOH and the same input powers, each cavity emits about 5 mW at 394 μm .

III. Optical Arrangement

The optical configuration is depicted in Figures 2a and 2b. The mirrors are front-surface optical-quality mirrors which permit a HeNe laser beam used for alignments to pass through the system without undue distortion. The beamsplitters are composed of electroformed nickel mesh⁹ stretched flat on aluminum frames. Specifications of the beamsplitters appear in Table 1.

The polyethylene focusing lenses present in the system were employed because of their simplicity and availability from previous experiments. Lens L1 focuses the scene beam to a waist at the plasma midplane—the waist is 1.1 cm in diameter for a 394 μm beam and 2.7 cm in diameter for a 1222 μm beam. During 1222 μm operation, the focusing mirror assembly M7, M8, and M9 is replaced with an $f/0.5$ polyethylene lens and the detector is repositioned. The focusing mirrors are preferred for 394 μm operation because they transmit more power than the polyethylene lens would, but at 1222 μm the lens is substantially less lossy and provides a needed larger aperture. All optical components within the system provide apertures large enough to pass at least 95% of the incident power, except the above-mentioned focusing mirror assembly, which loses 12% of the incident power due to an undersize aperture.

The optical system include two mirrors, M4 and M5, which are inside the CDX vacuum vessel. These mirrors are mounted on shafts which are securely fixed to the optical table on which the rest of the apparatus sits. The shafts are free to slide through Wilson seals, so that the entire optical table may be translated to probe plasma from -0.4 cm to $+10.9$ cm from the vessel centerline.

The detectors used are of the Schottky diode variety. A corner-cube-mounted reference detector^{10,11} has been used both at 394 μm and at 1222 μm since its sensitivity is adequate to provide the desired signal at either wavelength. A corner-cube-mounted scene detector is also used for 394 μm operation, but a biconical-mount detector¹² is used at 1222 μm due to its greater sensitivity.

Homodyne operation is depicted in Figure 3a. In this configuration, only one far-infrared cavity is used. A moveable mirror intercepts beams that have been scattered from the incident beam by an angle θ . The choice of θ

determines the $k_{\perp}$ that is observed through the relationship

$$k_{\perp} = 2k_0 \sin \frac{1}{2} \theta$$

where $k_{\perp}$ is the wave number of the fluctuation, k_0 is the wave number of the FIR laser beam, and θ is the angle of scattering. In practice, a range of $k_{\perp}$ s is detected for any particular θ because the detection optics accept beams scattered within $\pm 2^\circ$ of the selected θ . The $k_{\perp}$ selected for each angle of scattering is listed in Table 2.

In homodyne mode, data analysis is straightforward: the detector output at each time is proportional to the amplitude of fluctuations of the selected $k_{\perp}$ at that time. Hence, a Fourier transform of the detector voltage versus time gives directly the frequency spectrum of the fluctuations.

Heterodyne operation is depicted in Figure 3b. This configuration is most often used for density interferometry, with the two cavities detuned by 1 MHz. In this case, the beam which passes undeflected through the plasma is observed, and the phase shift induced by the plasma is impressed upon the scene detector 1 MHz output. Electronic comparison of the phases of the scene and reference detector outputs produces a voltage proportional to the integral of the electron density along the path of the beam. Scattering measurements can be conducted in the heterodyne mode by observing at non-zero scattering angles.

Data analysis is complicated in heterodyne scattering by the fact that all fluctuations are seen as an offset in frequency from the 1 MHz beat frequency. This requires a second mixing of the detected signal to remove the 1 MHz offset or more rapid sampling of the signal if that offset is to be removed digitally. Heterodyne scattering does have an advantage over homodyne scattering in that the sign of the fluctuation's frequency may be determined by noting whether it appears above or below 1 MHz. Knowledge of the sign of the frequency then tells the direction of propagation of the disturbance. Contrast this with homodyne scattering in which the beat frequency is zero, so that $+\omega$ and $-\omega$ cannot be distinguished. (In fact, homodyne scattering systems can determine the direction of wave propagation, but the technique still requires two detectors.^{13,15}) Heterodyne scattering would also be advantageous for the study of launched waves (*not* a part of the CDX research program at present) in that rf pickup in the detector electronics would ap-

pear at ω_{rf} , distinctly different from power scattered from rf waves in the plasma, which would appear at $\omega_{rf} \pm 1$ MHz.

Conversion between heterodyne and homodyne modes may be performed within a few minutes simply by blocking beam ω_1 in Fig. 2(a) and inserting an additional beamsplitter at point B. The latter beamsplitter reflects part of beam ω_2 along the path of the local oscillator beam for subsequent mixing at the scene detector. Conversion to another operating wavelength requires the replacement of beamsplitters BS1 through BS4 and replacement of the mesh portion of the output couplers inside the far-infrared cavities. This can take as little as one hour, provided the appropriate meshes have been previously affixed to frames.

IV. Results

Figure 4 shows the time-evolution of the line-integral density in a tokamak-like discharge in CDX, as measured with the FIR laser system. The high density seen between $r = 0$ cm and $r = 4$ cm, about a factor of four larger than that observed in the densest open-field-line plasmas, shows improved particle confinement in these types of discharges. From this evidence, one might postulate that closed magnetic surfaces exist. Other diagnostics have verified this hypothesis.¹

Figure 5 shows the amplitude of the scattered beam as a function of frequency at various wave numbers. These spectra show a pronounced peak at about 20 kHz. The peak is most pronounced at small $k_{\perp}$ (long wavelength) and is thought to be a saturated instability driven by the high plasma pressure. The spectra also show a broad background of fluctuations extending to above 100 kHz, again strongest at small $k_{\perp}$'s. Other authors^{4,15} have suggested that this portion of the spectrum may be due to drift wave turbulence. Similar spectra have been derived from probe floating potential traces taken from the same plasmas.

V. Summary

A dual far-infrared laser system has been constructed on the CDX device for purposes of interferometry and scattering measurements of CDX plasmas.

The system has been found to be flexible in terms of both configuration and wavelength of operation. In addition, good stability of the beat signal between the two FIR beams has been observed, in spite of the lack of thermal stabilization. The close proximity of the two cavities keeps the differential changes in length nearly zero thereby steadying the beat frequency. Measurements of both plasma density and density fluctuation levels have been performed, revealing a number of physical effects important to CDX operation.

VI. Acknowledgments

C. Bennett, R. Chouinard, and Dr. W. A. Peebles are to be thanked for their suggestions during the design and construction of this instrument. Thanks are due also to Prof. N. C. Luhmann, Jr. and Dr. W. A. Peebles of UCLA for the loan of the biconical-mount Schottky diode detectors employed. Able technical assistance was provided by W. R. Kineyko and J. P. Taylor. This work was supported by U.S. Department of Energy Contract # DE-ACO2-76-CHO-3073.

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Figure 1 The dual far-infrared laser and its associated CO₂ pump laser.

Figure 2 The far-infrared optical system as seen (a) from above and (b) from the side, in the plane of A and A'. Here BS denotes beamsplitter, M denotes mirror, L denotes lens, D denotes Schottky diode detector, W denotes a window, and ω denotes the frequency of the beam.

Figure 3 The optical configuration for (a) homodyne scattering measurements and (b) heterodyne interferometry.

Figure 4 The line-integral electron density as a function of radius and time for a CDX tokamak-like discharge.

Figure 5 Homodyne fluctuation spectra at several values of $k_{\perp}$ from the CDX tokamak-like discharges. A strong, single-frequency mode is seen at 20 kHz, with a broadband background.

Wavelength	Beamsplitter	Material	Transmission
394 μm	BS1	70 lpi mesh	95%
	BS2, BS3, BS4	150 lpi mesh	50%
1222 μm	BS1	3 mil mylar	95%
	BS2	70 lpi mesh	20%
	BS3, BS4	45 lpi mesh	50%

Table 1: Beamsplitter characteristics for each operating wavelength. (Refer to Figure 2 for the location of each beamsplitter.)

θ	1222 μm $k_{\perp}$ (cm^{-1})	394 μm $k_{\perp}$ (cm^{-1})
0.0	0.00	0.00
1.0	0.90	2.78
2.0	1.79	5.57
3.0	2.69	8.35
4.0	3.59	11.13
5.0	4.49	13.91
6.0	5.38	16.69
7.0	6.28	19.47
8.0	7.17	22.24
9.0	8.07	25.02
10.0	8.96	27.80

Table 2: The observed $k_{\perp}$ at various scattering angles for each laser wavelength. At 1222 μm , the $\pm 2^{\circ}$ acceptance of the optics results in a detection of $k_{\perp}$'s up to $\pm 1.7 \text{ cm}^{-1}$ from the value listed. At 394 μm , the $k_{\perp}$ acceptance is $\pm 4.67 \text{ cm}^{-1}$.

DUAL FAR-INFRARED LASER

Fig. 1

Fig. 2(a)

SIDE VIEW
Vertical Section thru AA'

Fig. 2(b)

HOMODYNE FLUCTUATION SPECTRUM MEASUREMENT

Fig. 3(a)

ELECTRON DENSITY INTERFEROMETRY

Fig. 3(b)

#87X0893

Fig. 4

#87X0892

Fig. 5

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