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INFRARED LASER DIAGNOSTICS FOR ITER

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ABSTRACT

Two infrared laser-based diagnostics are under development at the Oak Ridge National Laboratory (ORNL) for measurements on burning plasmas such as ITER. Our primary effort is the development of a CO_2 laser Thomson scattering diagnostic for the measurement of the velocity distribution of confined fusion-product alpha particles. This diagnostic utilizes small-angle collective scattering of infrared light from the electron cloud surrounding the alpha particles. Key components of the system include a high-power, single-mode CO_2 pulsed laser, an efficient optics system for beam transport and a multichannel low-noise infrared heterodyne receiver. A successful proof-of-principle experiment has been performed on the Advanced Toroidal Facility (ATF) stellerator at ORNL utilizing scattering from electron plasma frequency satellites. The diagnostic system is currently being installed on Alcator C-Mod at MIT for measurements of the fast ion tail produced by ICRH heating. A second diagnostic under development at ORNL is an infrared polarimeter for Faraday rotation measurements in future fusion experiments. A preliminary feasibility study of a CO_2 laser tangential viewing polarimeter for measuring electron density profiles in ITER has been completed. For ITER plasma parameters and a polarimeter wavelength of 10.6 μm, a Faraday rotation of up to 26° is predicted. An electro-optic polarization modulation technique has been developed at ORNL. Laboratory tests of this polarimeter demonstrated a sensitivity of ≤0.01°. Because of the similarity in the expected Faraday rotation in ITER and Alcator C-Mod, a collaboration between ORNL and the MIT Plasma Fusion Center has been undertaken to test this polarimeter system on Alcator C-Mod. A 10.6 μm polarimeter for this measurement has been constructed and integrated into the existing C-Mod multichannel two-color interferometer. With present experimental parameters for C-Mod, the predicted Faraday rotation was on the order of 0.1°. Significant output signals were observed during preliminary tests. Further experiment and detailed analyses are under way.

COLLECTIVE THOMSON SCATTERING

Our primary effort is in the development of a CO_2 laser Thomson scattering diagnostic for the measurement of the velocity distribution of confined fusion-product alpha particles.[1] Collective Thomson scattering measurements at the CO_2 laser wavelength generally requires operation at small scattering angles. For fusion relevant plasma conditions, this scattering angle between the source and receiver is typically around one degree or less. Such small angles present problems with beam alignment and stray light rejection. A proof-of-principle test of the diagnostic system has been performed on ATF with a measurement of an electron resonance feature,[2] which examined these problems and successfully demonstrated the capability of this diagnostic. As an application for this diagnostic, the equipment used in the proof-of-principle test has been upgraded and moved to the Alcator C-Mod tokamak for the measurement of an ICRH-produced ion tail.

The receiver system makes use of heterodyne detection for reduction of stray light and improvement in the signal-to-noise ratio. The post heterodyne signal-to-noise ratio, S/N, is given by:

$$S/N = \frac{P_S}{P_s+P_N}\sqrt{1+B\tau} \tag{1}$$

where B is the receiver bandwidth, τ is the integration time, P_S is the scattered signal power, and P_N is the system noise. A large signal-to-noise ratio requires a large product of bandwidth time integration time. The bandwidth is set by the Doppler broadening of the ions to be measured and the integration time is limited to the laser pulse length. For the alpha particles in ITER the full spectral width is expected to be around 10 GHz, which will limit the bandwidth of a spectral channel used in measuring the spectral shape to around 1 GHz. According to Eq. (1) with a laser pulse length of 1 microsecond (as used in the proof-of-principle test), the signal-to-noise ratio will have a maximum value of 32. For the experiment at Alcator C-Mod (which also has a 1 GHz bandwidth), the pulse length has been extended to 5 microseconds to permit a signal-to-noise ratio of up to 71. For ITER, the laser pulse length must be further increased to permit larger signal-to-noise ratios.

The source laser is a modified Lumonics TEA-103. It consists of four cells, unstable resonator optics, and is controlled by a low power cw injector laser which sets the wavelength, polarization, and lengthens the pulsewidth. A small quantity of tripropylamine is added to the gas mix which allows the discharge to remain stable with increased nitrogen levels, which produces longer pulse lengths.

For this experiment, the velocity is determined by measuring the scattering amplitude in k space (i.e., in scattering angle) rather than conventional frequency space. For ITER the system will be expanded to include measurements of scattering in frequency and time.

INTERFEROMETER/POLARIMETER

The second diagnostic under development at ORNL is an interferometer/polarimeter system for phase shift and Faraday rotation measurements in future fusion experiments. The feasibility of the system for ITER has been investigated both theoretically and experimentally. Theoretical analyses have been carried out to study the wave propagation in ITER for both vertical and tangential viewing systems. Computer codes have been developed and have been used to calculate the phase shift, ϕ, Faraday rotation angle, θ_f, ellipticity, ε, and the angle of beam refraction. The results are summarized in Table I. The values corresponding to Alcator C-Mod plasma are also given for comparison.

Table I. Summary of plasma effects on phase shift, Faraday rotation angle, ellipticity, and angle of refractions for various wavelengths using parabolic electron and current distributions.

	C-Mod	ITER							
		Viewing vertically				Viewing tangentially			
Wavelength (microns)	10.6	1.0	3.39	10.6	119	1.0	3.39	10.6	119
Major radius (m)	0.65	8.06							
Minor radius (m)	0.2	3.01							
Central density ($10^{20}/m^3$)	10	1.27							
Plasma current (ma)	3	25.0							
Toroidal field (t)	9	5.7							
Faraday rotation (deg)	1.4	0.018	0.2	2	248	0.23	2.7	26	3277
Ellipticity (e)	$7.6 \cdot 10^{-6}$	$9.6 \cdot 10^{-11}$	$4.3 \cdot 10^{-8}$	$1.3 \cdot 10^{-5}$	$0 \le \varepsilon \le 1$	$1.3 \cdot 10^{-10}$	$5.7 \cdot 10^{-8}$	$1.7 \cdot 10^{-5}$	$0 \le \varepsilon \le 1$
Phase shift (fringes)	2.5	0.46	1.6	4.8	55	1.4	4.6	14.4	162
Angle of refractions (deg)	$3 \cdot 10^{-3}$	$6.5 \cdot 10^{-6}$	$7.5 \cdot 10^{-5}$	$7.3 \cdot 10^{-4}$	$9.2 \cdot 10^{-2}$	$9.6 \cdot 10^{-6}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.4 \cdot 10^{-1}$

An electro-optic polarization modulation technique has been successfully developed at ORNL to achieve the high sensitivity and time resolution required for the measurement of the Faraday rotation. The polarimeter is a modification of a previous system developed for CIT.[3] Because of similarities in the expected phase shift and Faraday rotation between ITER and Alcator C-Mod (Table I), a collaboration between ORNL and the MIT Plasma Fusion Center has been undertaken to test this polarimeter system on Alcator C-Mod. A 10.6 μm polarimeter for this measurement has been constructed and integrated into the existing C-Mod multichannel two-color interferometer. Detailed analyses and experiments of the previous systems have been reported.[4] Only a brief description of the modified system is therefore presented in the following.

The two-color heterodyne interferometer consists of ten CO_2 laser (10.6 μm) channels and three HeNe laser (0.6328 μm) channels viewing the plasma vertically with a Michelson geometry. The main components are: a CO_2 laser, a germanium Bragg cell, and a HgCdTe thermoelectrically cooled detector array. The acoustic optic Bragg cell diffracts ~50% of the CO_2 laser power into a reference beam. This cell also introduces a frequency shift of 40 MHZ in the diffracted beam. The undiffracted probing beam is passed through a CdS quarterwave plate, a CdTe electro-optic modulator and a mechanical polarization rotator. Emerging from the polarization modulator, the Gaussian beam is expanded to an elliptical beam with a profile of 1×20 cm via cylindrical mirrors in order to view the plasma cross section accessible by the viewing ports. The return beam in the two-pass system is decollimated and is passed through an analyzer. The reference beam is also expanded and is guided to the signal detector array to mix with the probing beam.

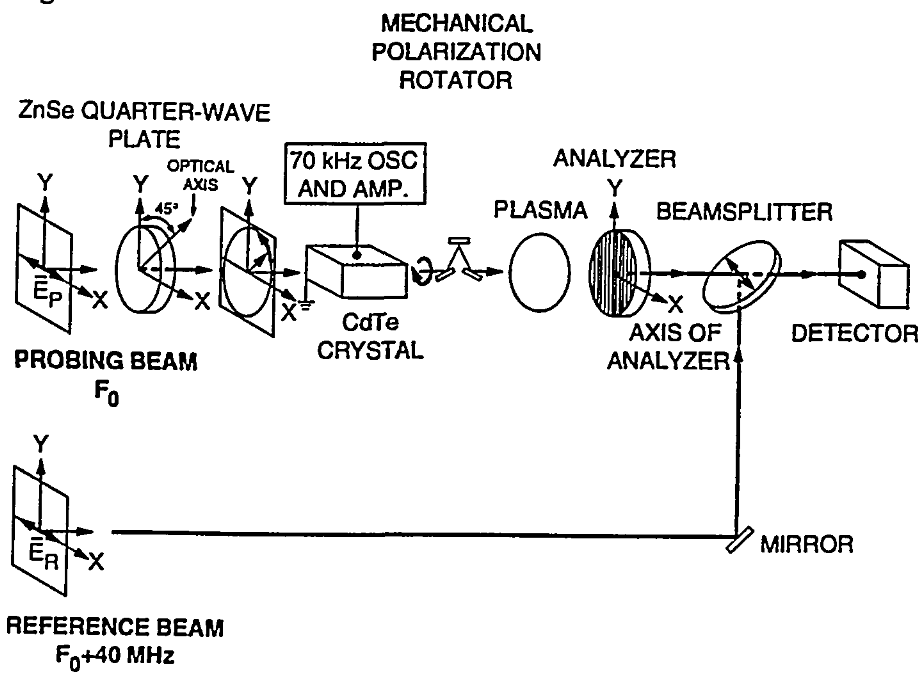

Figure 1. Illustration of the electro-optic polarization-modulation technique used in the CO_2 laser polarimeter on Alcator C-Mod.

Figure 1 shows a simplified sketch of the arrangement of the polarimeter. Both the probing beam and the reference beam are initially linearly polarized with their electric fields in the x direction. The quarter-wave plate is placed with its optical axis at 45° to the y-axis, thereby changing the probing beam into a circularly polarized wave. The modulator is driven by a 70 kHz oscillator-amplifier system with the electric field applied in the y direction. The mechanical polarization rotator consists of three mirrors mounted on a rotatable frame such that the polarization of the probing beam changes by twice the angle of the frame rotation. Emerging from the plasma, the probing beam is passed through an analyzer. The analyzer is oriented with its axis in the x direction, so that only the x component of the probing beam is mixed with the reference beam at the detector. The output of the signal detector V_s can be expressed by the following relation:

$$V_s = RP_pJ_1(\theta_m)\sin(2\theta)\sin(\omega_m t) + R(P_pP_r)^{1/2}[\cos(\theta)\cos(\Delta\omega t + \phi) + \sin(\theta)\sin(\Delta\omega t + \phi + \phi_m)] + \textit{terms of dc and other frequencies}, \quad (2)$$

where R is the responsitivity of the detector; θ is the sum of the polarization rotation angle due to the mechanical rotator θ_b, and the Faraday rotation in plasma θ_f; ω_m is the modulation frequency; $\Delta\omega = 40$ MHz; $J_1(\theta_m)$ is the Bessel function of the first kind with order 1; and P_p and P_r are the power of the probing and reference beam at the detector, respectively. The modulation of the phase shift between x component and y component of the electric field ϕ_m is sinusoidal and can be written as: $\phi_m = \theta_m \sin(\omega_m t)$, where θ_m is the amplitude of the modulation angle in degrees and is related to the modulation voltage V_m and the half-wave voltage of the CdTe crystal V_π by: $\theta_m = 180\ V_m/V_\pi$. The detector signal at the modulation frequency is synchronously detected by a lock-in amplifier. For small θ_f and by setting the mechanical polarization rotator at 0° position ($\theta_b = 0°$), the output voltage of the amplifier is then $V_{out} = ARP_pJ_1(\theta_m)\sin(2\theta_f)$, where A is the voltage gain of the amplifier. The values of the individual components in this equation may be lumped into a single calibration constant V_0 so that the equation becomes

$$V_{out} = V_0 \sin(2\theta_f), \quad (3)$$

where $V_0 = ARP_pJ_1(\theta_m)$. The value of V_0 can be obtained by setting the mechanical polarization rotator at a calibration angle θ_c of a few degrees (≤2°) away from its original 0° position and measuring a calibration voltage V_c at the output of the lock-in amplifier before the beginning of the plasma discharge. The voltage V_0 is related to V_c and θ_c by: $V_0 = V_c/\sin(4\theta_c)$. The V_0 as determined by this technique calibrates the polarimeter in a manner that does not require the absolute knowledge of the laser power, the detector responsivity, the modulation angle, or the gain of the amplifier. For small rotation angles, $(\theta_f + 2\theta_c) \leq 5°$, V_{out} is a direct measure of θ_f, since $\sin[2(\theta_f + 2\theta_c)] \simeq 2(\theta_f + 2\theta_c)$, and the above equations are reduced to the form

$$\theta_f = 2\theta_c(V_{out}/V_c - 1). \quad (4)$$

The outputs of the lock-in amplifiers are digitized for computer storage and processing. The values of the Faraday rotation angles along the ten vertical chords are calculated according to Eq. (4).

A test bench of the polarimeter system was set up at ORNL to determine the sensitivity of the polarimeter. The calibration experiment was carried out with the mechanical polarization rotator oriented at 1° position. Under this condition, a Faraday rotation of 2° was simulated. The output voltage of the lock-in amplifier was measured to be about 350 mV. With both beams blocked, an output voltage in the range of 1-2 mV was observed, thus a polarimeter sensitivity better than 0.01° was achieved. The polarimeter has been added in the existing two-color interferometer system on Alcator C-Mod. With present experimental parameters for C-Mod, the predicted Faraday rotation was on the order of 0.1°. Significant output signals were observed during preliminary tests. Further experiment and detailed analyses are under way.

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