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Far-infrared laser scattering in the ACT-I toroidal device

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A far-infrared laser scattering diagnostic has been built for the ACT-I toroidal device. The optical system uses a passively stabilized 447-μm CH_3I laser. A polyethylene etalon is the beam splitter. The vacuum windows are plastic (TPX), which we found has the vacuum property Q 6.5×10^{-9} Torr l/s/cm^2. Using paraboloidal and ellipsoidal mirrors for detection optics improves the signal strength and allows a better rf enclosure design for the detector. The diagnostic was tested by scattering from an ion Bernstein wave, a technique which can be used for ion temperature diagnostics.

I. INTRODUCTION

Laser light scattering has long been a versatile tool for nonintrusive measurements of plasma density fluctuations associated with waves in plasmas.[1] We built a far-infrared (FIR) laser scattering diagnostic for the ACT-I toroidal device[2] to detect radio frequency waves. This complements probe diagnostics because it resolves the perpendicular wave number $k_\perp$ of the wave and does not interfere with the plasma. The purpose of this paper is to provide practical information for designing FIR diagnostics, including far-infrared laser scattering diagnostics of larger plasma devices. We will explain how we used different types of optical components to obtain higher signal levels and conclude by showing data produced by the diagnostic in scattering from the ion Bernstein wave.

II. APPARATUS

A focused laser beam enters and exits the ACT-I vacuum vessel from the side, passing vertically through the plasma where it is scattered (Fig. 1). All optics are mounted on a table which moves, for scanning the laser beam through the plasma radially. The optical system is shown in Fig. 2. A 50 W, cw CO_2 laser, operating on the 10P18 line, optically pumps the FIR laser, which is a glass tube filled with CH_3I gas. A polarizer P1 and a CdS quarter wave plate QWP1 eliminate optical feedback from the FIR laser to the CO_2 laser[3]; this passive stabilization method increases the FIR laser power by about 25% to 15 mW. Increased power improves the heterodyne detection signal strength, which is[4]

$$P_D = (P_s P_{\rm LO})^{1/2} = \tfrac{1}{2}\tilde{n} r_0 \lambda_0 L\,(P_0 P_{\rm LO})^{1/2}. \qquad (1)$$

Here $\tilde{n}$ is the wave electron density fluctuation, r_0 is the classical electron radius, λ_0 is the wavelength of the laser light, L is the length of the effective scattering volume, P_0 is the laser power incident on the plasma, and $P_{\rm LO}$ is the local oscillator beam power.

The CO_2 laser cavity length is lock-in stabilized by modulating its length at 520 Hz with a PZT (piezoelectric translator) and detecting a 520 Hz sound wave with a microphone in the FIR laser cavity.

A polyethylene film beam splitter BS1 divides the FIR laser beam into a local oscillator beam and the incident beam. The film is an etalon, a fact we exploit to obtain an optimal reflecting fraction of 1/3 by selecting the etalon thickness and by orienting the incident FIR polarization with a quartz quarter wave plate QWP2. The laser beam begins circularly polarized[3] and QWP2 converts it to linearly polarized. Polyethylene lens L2 focuses the beam in the plasma.

The vacuum windows on ACT-I are made of the plastic TPX, a material commonly used in the FIR.[5] We mention here, incidentally, that no outgassing specifications for vacu-

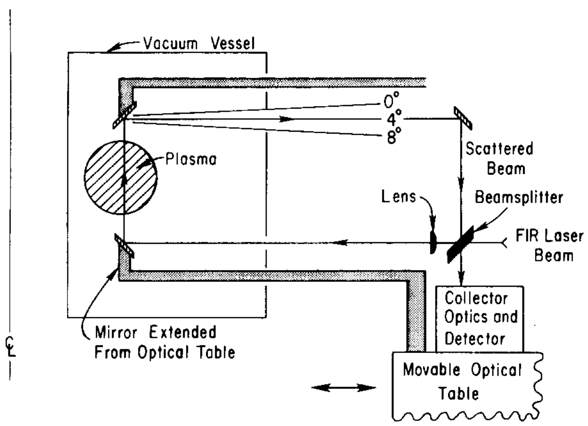

FIG. 1. Side view of the vacuum vessel showing the scattering geometry.

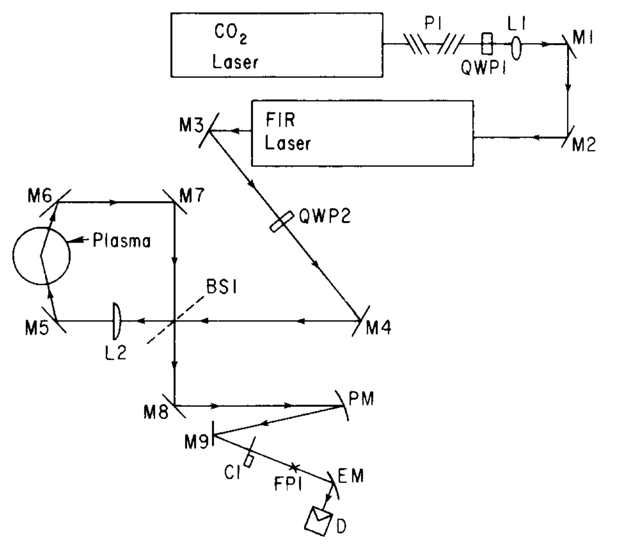

FIG. 2. Schematic of the optical system, which is described in the text. The symbols are: M, mirror; P, polarizer; QWP, quarter wave plate; L, lens; BS, beam splitter; PM, paraboloidal mirror; EM, ellipsoidal mirror; C1, chopper; and D, detector.

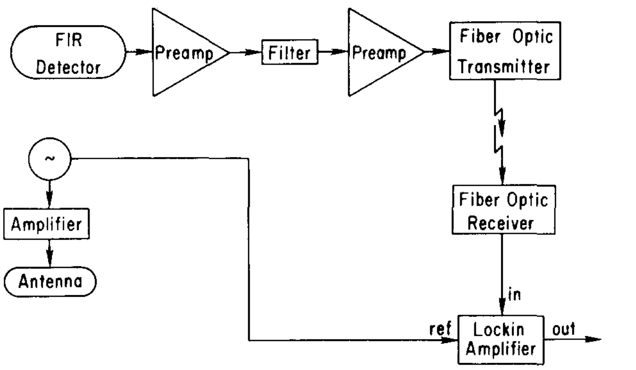

FIG. 3. Basic single lock-in detector instrumentation for detecting a wave driven by an oscillator, indicated by the circle. A fiber optic link is used to reduce rf pickup passively.

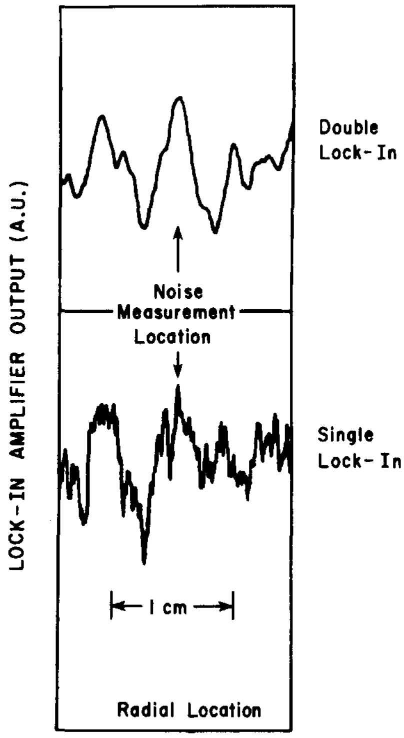

FIG. 4. Ion Bernstein wave interferometry trace. The signal is obtained using both the single lock-in method (bottom) and double lock-in method (top), which reduced noise. The optical table was translated to scan the radial positon of the laser beam in the plasma. The measurement was made in a region of the plasma 3 cm outside the magnetic axis, where the magnetic field is 4.3 kG. The 12.5 MHz wave was driven by an antenna inserted into the hydrogen plasma, and was detected with a 4° scattering angle.

um window use were available for it, so we measured it and found $Q = 6.5 \times 10^{-9}$ Torr l/s/cm^2. A useful feature of TPX is that it has the same low index of refraction, 1.43, in the visible and in the FIR,[5] and like polyethylene film it is transparent in both the visible and the FIR; this allows a HeNe laser to be used to align the optical system for zero angle scattering. Crystal quartz is usually used for FIR vacuum windows, but it has several disadvantages. Quartz has high absorption[6] which means that the window should be as thin as possible; but since it has a high index of refraction, 2.1, it reflects a great deal of power unless its thickness is carefully adjusted to make it an etalon. Etalons have the additional disadvantage of working for only one wavelength, yet it is common to vary the wavelength of the FIR laser, depending on the need. Quartz is also unavailable in large dimensions. Provided that its outgassing is tolerable for the plasma device, as it is for ACT-I, TPX is preferable because less laser power is lost using it.

A wave in the plasma, with wave number $k_\perp$, scatters laser light at an angle θ_s according to the Bragg relation

$$\theta_s = 2 \sin^{-1}(k_\perp / 2k_0), \tag{2}$$

where k_0 is the laser light wave number. Mirror M7 selects θ_s; M7 is translated and rotated by digitally controlled stepping motors to scan the scattering angle. The wave number is resolved with an accuracy[4] $\Delta k_\perp = 2/w_0$ which is 4.4 cm^{-1} for our diagnostic, where w_0 is the half-width of the beam in the plasma.

The combined local oscillator and scattered beams are focused by the off axis paraboloidal mirror PM through the focal point FP1. The ellipsoidal mirror EM has its two focal points at FP1 and D, the detector. Using this pair of curved mirrors PM and EM improves the signal-to-noise ratio in two ways. First, by using reflecting rather than the usual refracting optics, losses of light are eliminated. Secondly, having two focal points means that one of them, FP1, can be positioned at the entrance of the rf enclosure for the detector, and the entrance hole can be very small, improving the shielding. The detector D is a room temperature Schottky diode mixer.[7] A mechanical chopper C1 modulates the detector signal.

The basic signal processing instrumentation is shown in Fig. 3. A fiber optic cable carries the detector signal to an rf lock-in amplifier. The lock-in is synchronized with the rf oscillator which drives the wave in the plasma. Since lock-in detection is a powerful method of eliminating thermal detector noise and the Schottky diode detector has an extremely low noise level,[7] NEP$\simeq 2 \times 10^{-19}$ W/Hz, meaning that detector signals as small as 2×10^{-19} W may be detected using a 1-Hz bandwidth, if there is no rf pickup. Traditional passive methods of reducing rf pickup may not suffice. To reduce actively rf pickup to very low levels, we devised a new lock-in method which we call the double lock-in method. Since this method should be generally useful in any application where synchronous rf pickup must be removed from a signal which can be modulated, we will describe the method in detail in another publication; briefly, the method consists of applying the output of the rf lock-in amplifier to the input of a second, low frequency lock-in which is synchronized to chopper C1.

III. RESULTS FOR THE ION BERNSTEIN WAVE

We demonstrated the FIR laser scattering diagnostic by scattering from an ion Bernstein wave. This wave is a hot magnetized plasma mode which is excited by an external or internal antenna driven at a frequency just beneath an ion gyrofrequency harmonic.[8] It has been observed in tokamaks, and is important in ion cyclotron frequency heating of plasmas.[9] A scattering diagnostic combined with an antenna to launch this wave has been used as an ion temperature diagnostic, since $k_\perp$ depends on the ion temperature.[10]

In the present experiment, a 12.5 MHz wave was launched with an internal antenna in a hydrogen plasma with a toroidal magnetic field of 4.3 kG, and was detected on the high field side of the first harmonic layer ($\omega = 2\Omega_{ci}$). The scattering angle was 4°, which corresponds to $k_\perp = 9.8\ \text{cm}^{-1}$. We observed the $k_\perp$ resolution of the diagnostic by changing the scattering angle by more than 1° and seeing the signal disappear.

The data are shown in Fig. 4. The lock-in amplifier output signal makes an interferometry trace as it is plotted against the radial position of the laser beam in the plasma. Interferometry traces are shown in Fig. 4 using both the double lock-in method and the single lock-in method.

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