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ABSTRACT

The propagation of submillimeter-waves (smm) in tokamak plasmas has been investigated both theoretically and experimentally to ensure successful measurements of electron density and plasma current distributions in tokamak devices. Theoretical analyses have been carried out to study the polarization of the smm waves in TFTR and ISX-B tokamaks. A multichord smm wave interferometer/polarimeter system has been employed to simultaneously measure the line electron density and poloidal field-induced Faraday rotation in the ISX-B tokamak. The experimental study on TFTR is under way. Computer codes have been developed and have been used to study the wave propagation and to reconstruct the distributions of plasma current and density from the measured data. The results are compared with other measurements.

INTRODUCTION

The measurement of the radial distribution of the toroidal plasma current is of fundamental importance in fusion research of tokamaks. A method for measurement of this parameter was proposed by DeMarco and Segre[1] and further developed by Craig[2] and Segre.[3] Their analyses show that the distribution can be obtained indirectly by measurement of the poloidal magnetic field which can be determined by projecting linearly polarized smm laser beams through the plasma and measuring the Faraday rotation of the polarization. If the Voigt effect is negligible and the wave is initially linearly polarized parallel or

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perpendicular to the toroidal magnetic field, the wave will undergo simple Faraday rotation, θ_p, which is proportional to the line integral of the electron density times the poloidal magnetic field along the chord. In the case where the Voigt effect is large, a wave equation must be solved for the polarization evolution on the Poincare sphere. Recently, Vuolo and Galvao[4] derived the equation of propagation including collisional attenuation to first order. Gomez and Lax[5] have also examined the Voigt effect on the measurements of plasma current distributions in the Alcator tokamak. Since the rotation of the polarization is dependent on the electron density and magnetic field, the electron density profile must also be measured simultaneously in order to unfold the current distribution. In earlier papers, we described our experiments on ISX-B[6,7] and TFTR[8] tokamaks. This paper presents our recent results of both theoretical and experimental studies. Detailed mathematical analyses and experiments will be reported at the symposium. Only a brief description of the work is, therefore, presented in the following.

THEORETICAL ANALYSES

An algorithm for the solution of the polarization equation has been developed and has been used to determine the polarization evolution on the Poincaré sphere including collisional attenuation. Computer codes have been utilized to calculate the ellipticity, ε, and the rotation angle of the vibrational ellipse, ϕ, of the polarization. Analyses have been carried out to evaluate the measurements on both ISX-B and TFTR tokamaks. As expected, it is found that the effect of ellipticity of the polarization is negligible for the measurements on ISX-B. For TFTR however, because of the large size, high plasma current, and the double-path of the probing beam in the plasma, large rotation angle and ellipticity are expected. The pertinent parameters for TFTR are major radius, R = 265 cm; minor radius, a = 110 cm; central electron density, $n_o = 10^{14}/\text{cm}^3$; plasma current, I_p = 2.5 MA; toroidal field, B_T = 5.2 T; wavelength, λ = 119 μm. In this case, the maximum ϕ is approximately 15° with a maximum ellipticity of 0.045 for double path of the beam. The output signals of the interferometer detector, V_i, and polarimeter detector, V_p, can be expressed by the following relations.

$$V_i = V_{io}\text{Cos}(\phi)\left[1 + \varepsilon^2\tan^2(\phi)\right]^{1/2}\,\text{Cos}(\Delta\omega t + \psi + \psi_i) \quad (1)$$

$$V_p = V_{po}\text{Sin}(\phi)\left[1 + \varepsilon^2\text{Cot}^2(\phi)\right]^{1/2}\,\text{Cos}(\Delta\omega t + \psi - \psi_p) \quad (2)$$

where V_{io} and V_{po} are the calibration constants for the interferometer and polarimeter, respectively, ψ is the phase shift, and ψ_i and ψ_p are given by

$$\psi_i = \tan^{-1}\left[\varepsilon \tan(\phi)\right] \qquad \psi_p = \tan^{-1}\left[\varepsilon\,\text{Cot}(\phi)\right]$$

It can be seen in Eqs. (1) and (2) that both the amplitude and the phase of the signals depend strongly on the ellipticity of the polarization which cannot be measured easily due to limitations on the experimental techniques. An appropriate evaluation of the measured data is, therefore, necessary. For present TFTR operations (Dec. 15, 1984), R = 265 cm, a = 110 cm, $n_o = 5 \times 10^{13}/cm^3$, I_p = 1 MA, B_T = 3 T. The maximum ϕ is approximately 3°, and the maximum ε is 1.6×10^{-3}. The error of density measurement due to neglecting of the ellipticity is very small (0.02 percent), and the error of Faraday rotation measurement is less than 0.048 percent.

EXPERIMENTS AND DISCUSSIONS

A schematic diagram of the interferometer/polarimeter system on ISX-B is shown in Fig. 1. Briefly, the system consists of a pair of cw 671 GHz iodomethane lasers, optically pumped by separate CO_2 lasers. The smm cavities are tuned such that the two oscillate at frequencies differing by Δf of the order of 1 MHz. The linearly polarized beam of the source laser is passed through a ferrite polarization modulator, a mechanical polarization rotator into the dielectric waveguide, and is then divided into five beams which are projected through the plasma. Emerging from the plasma chamber, each beam enters again into a waveguide and is directed onto a signal detector. Part of the beam from the reference laser is mixed first in a reference detector with a portion of the source laser, which is split off before passage through the modulator, and the remainder is guided to the signal detector to mix with the probing beam. Schottky diodes are utilized for all detectors. The output of the reference detector is a sinusoid at frequency Δf and is used as reference signal for phase detection. The output of each signal detector is filtered, amplified, and fed into a digital phase detection circuit to extract the phase shift due to plasma density. An envelope detection circuit is utilized to demodulate the phase-modulated signal, and provides a sinusoidal signal at the modulation frequency of 100 KHz whose amplitude is proportional to $J_1(\theta_m) \cdot \mathrm{Sin}(\theta)$, where θ_m is the amplitude of the modulation angle, θ is the sum of the rotation angles due to mechanical polarization rotator, θ_c, and Faraday rotation in plasma, θ_p. $J_1(\theta_m)$ is the Bessel function of the first kind with order one. This signal is synchronously detected by a lock-in amplifier, yielding an output voltage,

$$V_{out} = V_o \cdot \mathrm{Sin}\ (\theta_p)\ .$$

The calibration constant, V_o, can be obtained by setting the mechanical polarization rotator at a few degrees (<4°) and measuring the value of V_{out} without plasma in the chamber.

The system has been employed to study the plasmas in ISX-B tokamak. Figure 2 shows the time-resolved traces of (a) Faraday rotation and

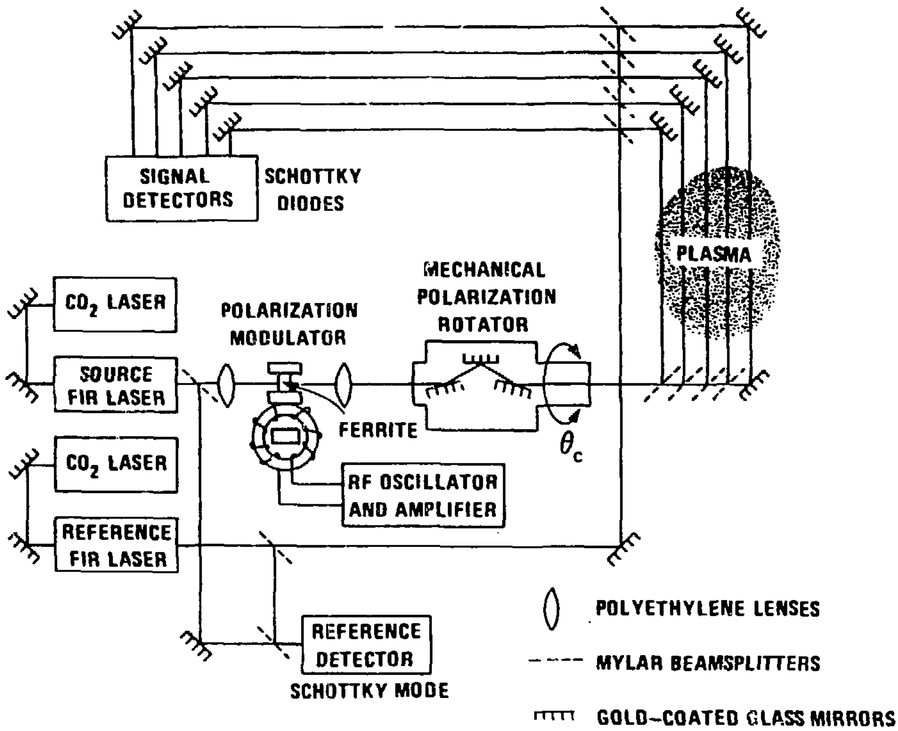

Fig. 1. Schematic of the multichord FIR interferometer/polarimeter system for simultaneous measurements of line-averaged electron density and Faraday rotation in ISX-B tokamak plasmas.

(b) line-averaged electron density, $\langle n_e \rangle$, of a typical plasma discharge. The position of each channel, relative to the center of the chamber is also indicated in the inset. The negative Faraday rotation on the central channel (channel 2) is due to the outward shift of the plasma center.

Data analysis codes have been developed and have been used to reconstruct the asymmetric spatial profiles of electron density and plasma current from the line-averaged chordal measurements. The results are shown in Fig. 3 and are compared with the profiles measured by Thomson scattering. It can be seen in Fig. 3 that two density profiles appear to be in surprisingly good agreement, considering the limited number of channels used in the investigation. The possible reasons for the discrepancy between the current density profiles will be discussed at the symposium, and are currently under investigation.

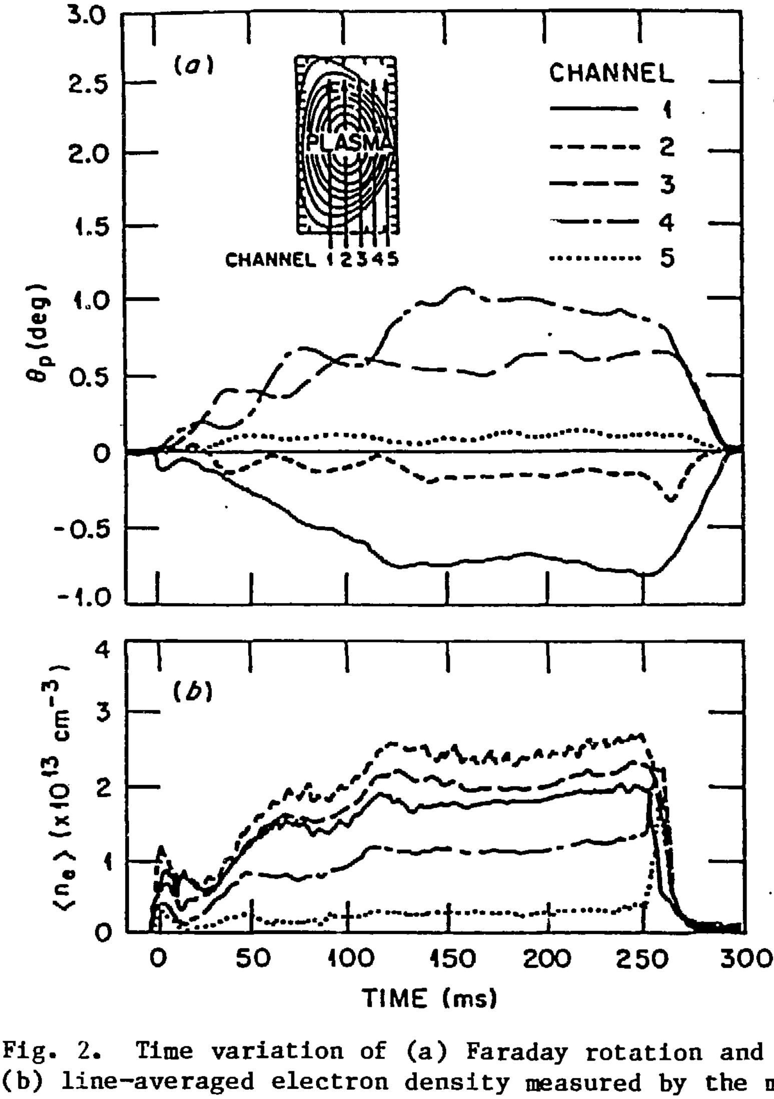

Fig. 2. Time variation of (a) Faraday rotation and (b) line-averaged electron density measured by the multichord FIR interferometer/polarimeter system on ISX-B tokamak.

The interferometer/polarimeter system on the TFTR tokamak has been reported[9] and the experimental study is under way.

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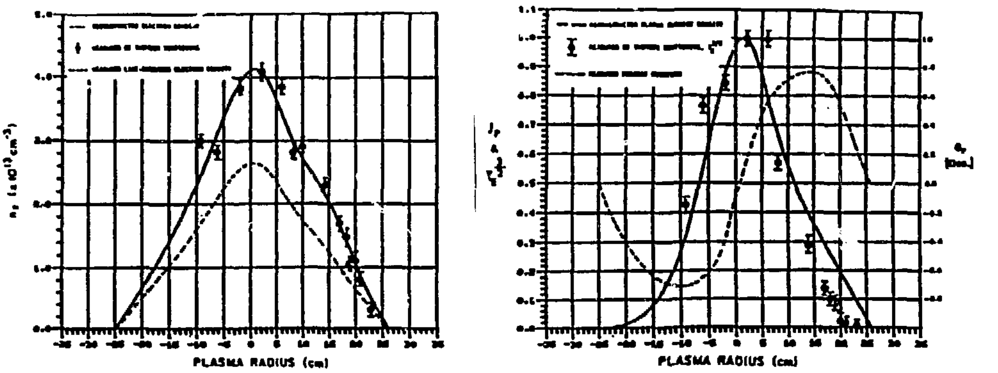

Fig. 3. Comparison of the reconstructed electron density and current density profiles with the profiles measured by Thomson scattering.

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