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First results with the triple-laser polarimeter system at RTP

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Abstract

A new method is presented for performing combined interferometric and polarimetric measurements on tokamak plasmas with high temporal resolution. The method can be regarded as a generalization of techniques suggested by others. A triple-laser far-infrared system serves to generate three frequency-offset laser beams, of which two are used to probe the plasma in orthogonal polarization states. The method has been implemented at the Rijnhuizen Tokamak Project. Some features of the method will be discussed and first plasma measurements will be presented. © 1997 Elsevier Science S.A.

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1. Introduction

The current density distribution in tokamak plasmas plays a crucial role in determining the plasma equilibrium and its stability. The current profile can be derived from a measurement of the Faraday rotation of the plane of polarization of far-infrared laser radiation transmitted through the plasma (polarimetry).

Many schemes have been proposed for the difficult measurement of the typically small Faraday rotation angles [1]. Nowadays, new methodological developments are directed towards techniques that actively modulate the polarization vector before sending the beam through the plasma. This offers the advantage that both the interferometer phase shift and the Faraday rotation can be measured using a single detection element for each probing beam, an almost essential requirement in multibeam systems.

At the Rijnhuizen Tokamak Project (RTP) a new polarimeter scheme has recently been developed and implemented [2] which can be regarded as a generalization of earlier schemes by Dodel and Kunz [3] and by Rice [4]. The problem of cross-talk from the polarimeter into the interferometer data, which existed in both of these schemes, is now eliminated and the temporal resolution is set by signal-to-noise limitations only.

2. Method description

Propagation of an electromagnetic wave in a plasma can, if the typical gradient lengths in the plasma are much larger than the wavelength used, be described by the well-known Appleton–Hartree formula. This formula, which is the plasma dispersion relation solved for the refrac-

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tive index, in a magnetized plasma generally has two distinct solutions associated with polarization eigenstates of propagation. An arbitrarily polarized incident wave will excite both orthogonal eigenstates, each of which will experience the corresponding refractive index upon propagation.

When the angle between the direction of propagation of a wave and the external magnetic field is not very close to 90°, the two eigenstates are (for interferometer wavelengths) approximately counter-rotating circularly polarized. The Faraday effect is caused by a difference in phase velocity of these eigenstates: an incident linearly polarized wave can be decomposed into two counter-rotating circular ones with equal amplitude. Upon emerging from the plasma, one of these waves will have undergone a slightly larger phase change than the other. The emerging compound wave, which is again linearly polarized, will have its polarization vector rotated over an angle equal to half this phase difference. When the two polarization eigenstates are not exactly circular, the plasma will exhibit the cotton–mouton effect and the polarization of the emerging wave will become slightly elliptical. However, at appropriate probing wavelengths this effect is small and can be corrected for in the analysis.

In the method recently developed and implemented at RTP, three far-infrared (FIR) lasers have been applied (see Fig. 1). Two of the laser beams are used for probing the plasma, whereas the third one acts as a local oscillator (LO). A slight frequency difference between all three lasers is introduced, such that after polarization-sensitive detection three frequency-separated beat signals are obtained. By setting the polarizations of the probing beams to counter-rotating circular (the polarization eigenstates of the plasma), it is possible to independently probe both refractive indices. Owing to the frequency offsets, the obtained information is spectrally resolved and can be retrieved by separating the carriers after detection and performing a separate phase measurement on each. Hence the detected spectrum will consist of three frequency bands that need to be well separated. Two of the bands are due to mixing of the LO beam with either of the probing beams. The phase change of these beams can be added to give twice the interferometer phase change or be subtracted to give twice the polarimeter phase change. The third spectral band, due to mixing between the two probing beams, carries direct information on the (line-integrated) difference between the two refractive indices and thus on the Faraday angle. If the LO beam is omitted, only this band remains detectable and the scheme reduces to the polarimetric part of the Dodel–Kunz scheme. Since the LO phase is constant, its presence enables one to directly measure the phase change of each of the probing beams independently.

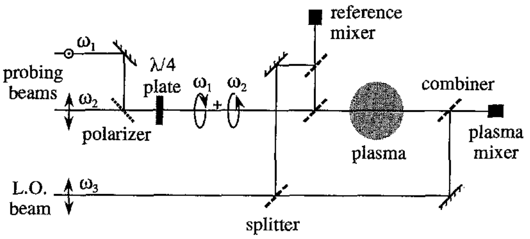

Fig. 1. Schematic one-channel depiction of three-laser set-up at RTP. The probing beam polarizations are made orthogonally linear. The probes are coaligned, without power loss, using a polarizing grid and are passed through a quarter-wave plate oriented at 45° to either polarization. Thus counter-rotating circularly polarized waves are obtained.

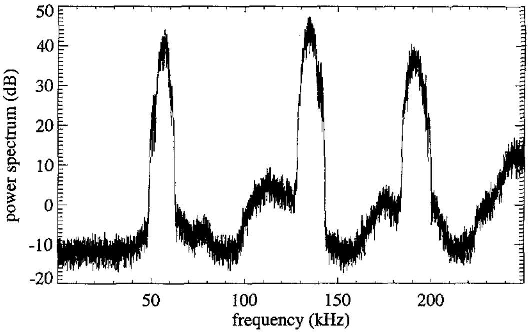

Fig. 2. Typical reference spectrum obtained after digitization of the raw IF signals. The middle peak is due to probe–probe mixing. Disturbance peaks, caused by non-linearity of the Schottky diode mixers, are also present but are too small to disturb the measurement. The peak width is mainly set by the frequency stability of the laser system.

The classical polarimetric method, utilizing a linearly polarized incident wave, has been demonstrated [5] to also perform satisfactorily when the eigenstates are not at all circular, although the argument becomes more complicated. In a similar manner the validity of the method suggested in Ref. [2] can be proved, provided that the polarization component parallel to the toroidal magnetic field is detected.

3. Experimental set-up and first results

The RTP tokamak ($R_o = 72$ cm, $a = 16.4$ cm, $I_p \leq 150$ kA, $B_{tor} \leq 2.4$ T) is equipped with a heterodyne FIR interferometer operating at 432.5 μm. The FIR laser system, originally consisting of two cavities, has recently been extended with a third one to enable implementation of the new polarimetric scheme. All three cavities are pumped by a single CO_2 laser. The two probing beams are coaligned directly behind the laser system and later expanded using parabolic optics to fill the RTP ports. Up to 20 Schottky diode corner cube mixers are used for polarization-sensitive detection of the slab beam. The width of the laser transition allows intermediate frequency (IF) offsets up to several megahertz between the various laser beams to be obtained by slightly detuning the relative cavity lengths.

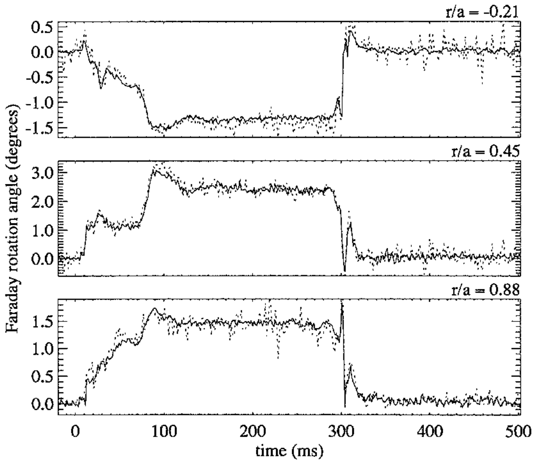

Fig. 3. Comparison of polarimeter signals obtained via direct phase determination of the probe–probe mixing peak (full line) and via subtraction of phases of the two probe–LO mixing peaks (dotted) for the same ohmic discharge as in Fig. 2 ($I_p = 80$ kA, $n_{e,o} = (5–6) \times 10^{19}$ m^{-3}). The discharge ends disruptively in the current ramp-down phase.

The measured signals are directly acquired at a digitization rate of 500 kHz without any electronic signal processing other than amplification and bandpass filtering (200–5000 kHz). For the data presented here, the laser IFs are set such that both the probe–probe mixing frequency and one of the probe–LO mixing frequencies are in the 500–750 kHz region. Necessarily, the third mixing frequency is then equal to either the sum or the difference of the other two. As a result of the relatively slow sampling rate, aliasing occurs upon digitization of the signal. Care is taken that this does not lead to an overlap between the peaks, so that all information is preserved. A typical power spectrum thus obtained is plotted in Fig. 2. The peaks are computationally isolated with bandpass filters and separately demodulated. The phases are extracted from the corresponding analytic signals [6].

The Faraday rotation can be derived either directly from the probe–probe mixing frequency or indirectly via the two probe–LO mixing peaks. The comparison of Fig. 3 demonstrates the equivalence of the two methods, where the difference in signal-to-noise level is caused by a variation in signal levels (see Fig. 2).

At RTP a 110 GHz gyrotron is available for second-harmonic electron cyclotron heating (ECH). In the discharge of Fig. 4, 400 kW of additional heating was deposited at half the minor radius (ohmic input 200 kW or less). In this way the temperature and consequently the current profile were strongly reshaped, since much current was expelled from the plasma centre. A strong decrease in the central slope of the Faraday rotation profile was indeed observed that cannot be explained by the observed 10–15% decrease in electron density. This is in qualitative agreement with the change in central q-value from about 1 to close to 4 derived from the change in resistivity profile.

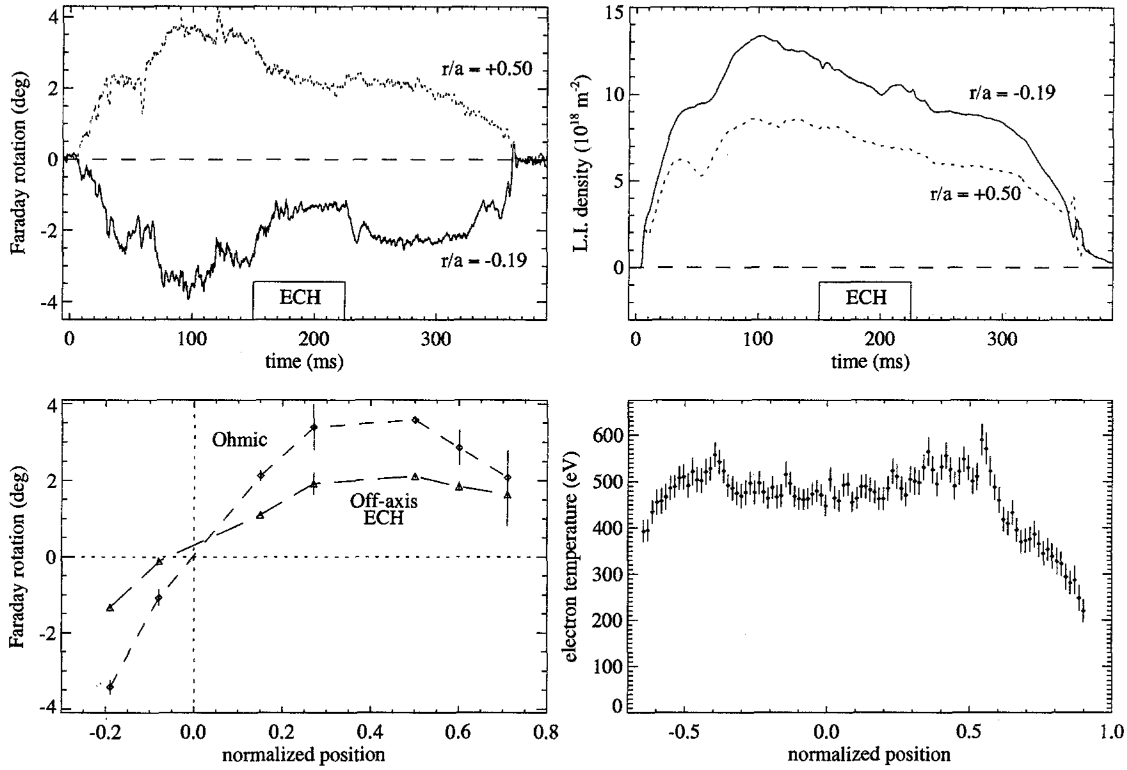

Fig. 4. Discharge where 400 kW of second-harmonic ECH power was deposited at half minor radius between 150 and 225 ms ($I_p = 80$ kA, $n_{e,o} = (6-9) \times 10^{19}$ m^{-3}, $B_{tor} = 2.28$ T, $q_a = 5.3$). Shown are time traces of Faraday rotation and line-integrated density for two channels as well as temperature and Faraday rotation profiles. The temperature profile was measured with multipoint Thomson scattering at 192 ms, i.e. well within the ECH pulse. The Faraday profiles were determined both before and during ECH by averaging over 20 ms at 100 and 200 ms. A clear profile change is observed.

4. Conclusions

A new method for doing polarimetry has been developed and implemented at RTP. First plasma measurements confirm the potential of the method, although the set-up presently still suffers from teething trouble. The method is capable of high temporal resolution polarimetric and interferometric measurements, limited only by the natural linewidth of the laser line and by bandwidth limitations imposed by signal-to-noise requirements. For the RTP system the resolution is expected to be of the order of 10 kHz for a measurement accuracy of 0.1°. Through evaluation of the algebraic equations underlying the method, one may prove that it does not suffer from cross-talk problems between interferometer and polarimeter, in contrast with earlier schemes [2]. Also, only one detector per channel is required.

Acknowledgements

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