Faraday rotation measurements on compact helical system by using a phase sensitive heterodyne polarimeter

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A phase sensitive heterodyne polarimeter was installed on compact helical system (CHS). An HCN laser (337 μm) and Schottky barrier diodes are used for the radiation source and for detection, respectively. By using a phase sensitive heterodyne scheme, the Faraday rotation angle can be measured from the phase variations caused by the phase difference between the right- and left-handed waves in the magnetized plasma. The purpose of the polarimeter on CHS is for a stable density monitor which is free from fringe jump and for the measurements of the internal magnetic field induced by the plasma current. The present resolution of the Faraday rotation angle is 0.1° with 10 ms time resolution and 1° with 1 ms. These are mainly determined by the laser instability. © *1999 American Institute of Physics.* [S0034-6748(99)50701-6]

I. INTRODUCTION

The polarimeter measures the Faraday rotation angle of incident electromagnetic wave, which is shown below:[1]

$$\psi(\mathrm{rad}) = 2.62\times 10^{-13}\lambda(m)^2 \int n_e(m^{-3}) B_{\parallel}(T)\, dz, \qquad (1)$$

where λ is the wavelength of the incident electromagnetic wave, n_e is the electron density and $B_{\parallel}$ is the magnetic field parallel to the incident beam axis. It consists of the line integration of n_e and $B_{\parallel}$.

When the electron density profile is measured by interferometer, from Eq. (1), $B_{\parallel}$ can be obtained and it is possible to measure current profile. On the other hand, when $B_{\parallel}$ is well known, it gives electron density.

In the former case, the plasma current profile measurements by using polarimeter were successfully demonstrated by Soltwisch on TEXTOR tokamak.[2]

In the latter case, it is proposed to use as a density monitor on tokamak midplane[3] and on current free Stellarator,[4] where the magnetic field is well known. In this case, compensations of the mechanical vibration are not necessary, however, it is technically more difficult than an interferometer because of measuring the small phase angle.

There are several schemes of the polarimeter described in Refs. 2, 5–10. Here, we took Howard's phase sensitive heterodyne scheme,[10] because of its relatively simple arrangements and good phase resolution.

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II. PRINCIPLE AND EXPERIMENTAL SETUP

A. Principle

The detailed theory of the phase sensitive heterodyne scheme is described in Ref. 10. In this article we briefly describe the principle of this scheme. Figure 1 shows the basic setup of the phase sensitive heterodyne polarimeter. Here, we assume that the linearly polarized wave is injected to the magnetically confined plasma and rotated by the Faraday rotation. This polarization is described with the Jones vector as follows:

$$e^{i(\omega_0 t+\phi)}\begin{pmatrix}\cos\psi\\ \sin\psi\end{pmatrix}, \qquad (2)$$

where ω_0, the frequency of the probe beam, ψ, the polarization angle induced by the Faraday rotation, and the ϕ phase shift due to the change of the refractive index is caused by the electron density. The linearly polarized wave becomes elliptical by the perpendicular magnetic field to incident beam axis,[1] but this effect is negligible on the present experiment on CHS.

The linearly polarized wave consists of the left- and right-handed circularly polarized wave, therefore Eq. (2) is expressed as follows:

$$\frac{1}{\sqrt{2}}\, e^{i(\omega_0 t+\phi)}\left[e^{-i\psi}\begin{pmatrix}1\\ -i\end{pmatrix} + e^{i\psi}\begin{pmatrix}1\\ i\end{pmatrix}\right]. \qquad (3)$$

The former and latter terms indicate left- and right-handed circularly polarized waves, respectively. Polarization transforming reflector (PTR)[11] consists of the wire grid and flat mirror. By tuning the distance between these, it works as a wave plate. In this scheme PTR works as a quarter wave plate. Since the direction of the wire is parallel to the y axis,

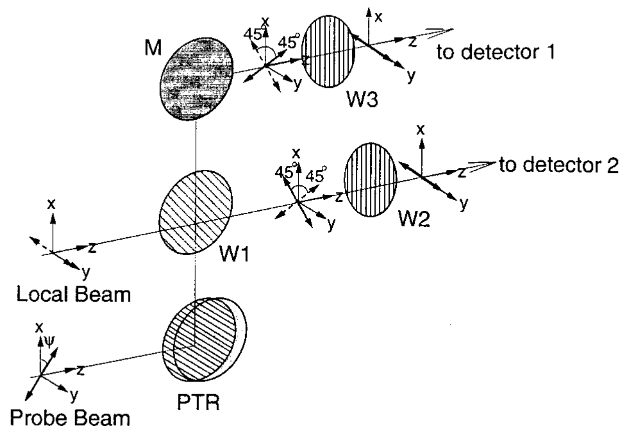

FIG. 1. Optical arrangements of a phase sensitive heterodyne polarimeter. Electric vectors of the probe beam are shown as plain line and local beam are shown as dotted line. ψ is a Faraday rotation angle; PTR is a polarization transforming reflector (Ref. 11) M is a mirror and $W1$, $W2$, $W3$ are wire grids.

PTR gives 90° phase difference between the x and y components of the electric field. After this procedure, Eq. (3) becomes as follows;

$$\frac{1}{\sqrt{2}} e^{i(\omega_0 t+\phi)}\left[e^{-i\psi}\begin{pmatrix}1\\1\end{pmatrix}+e^{i\psi}\begin{pmatrix}1\\-1\end{pmatrix}\right]. \tag{4}$$

Equation (4) indicates that left- and right-handed circularly polarized waves are converted to 45 tilted linearly polarized waves. These linearly polarized waves are orthogonal and can be separated by the W1 in Fig. 1, which is the wire grid tilted by 45° to the x axis, then the local beam is mixed for the heterodyne detection, Detector 1 detects the following components:

$$\frac{1}{\sqrt{2}} e^{i[(\omega_0+\omega_{\mathrm{IF}})t+\phi]}e^{-i\psi}\begin{pmatrix}1\\1\end{pmatrix}, \tag{5}$$

and detector 2 detects the following components.

$$\frac{1}{\sqrt{2}} e^{i[(\omega_0+\omega_{\mathrm{IF}})t+\phi]}e^{i\psi}\begin{pmatrix}1\\-1\end{pmatrix}, \tag{6}$$

where ω_{IF} is the IF frequency for the heterodyne detection. The phase difference between Eqs. (5) and (6) gives 2ψ, which is twice the Faraday rotation angle.

B. Experimental setup

Figure 2 shows a multichannel Michelson-type interferometer polarimeter on CHS. This system has three chords, one is fixed at the center, the other two can be scanned shot by shot to measure spatial profile of the electron density and Faraday angle. The lower scanning channel is modified to the polarimeter. The radiation source is a 337 μm HCN laser, of which output power is about 30 mW. A Fabry-Perot interference copper mesh filter was used as an output coupler

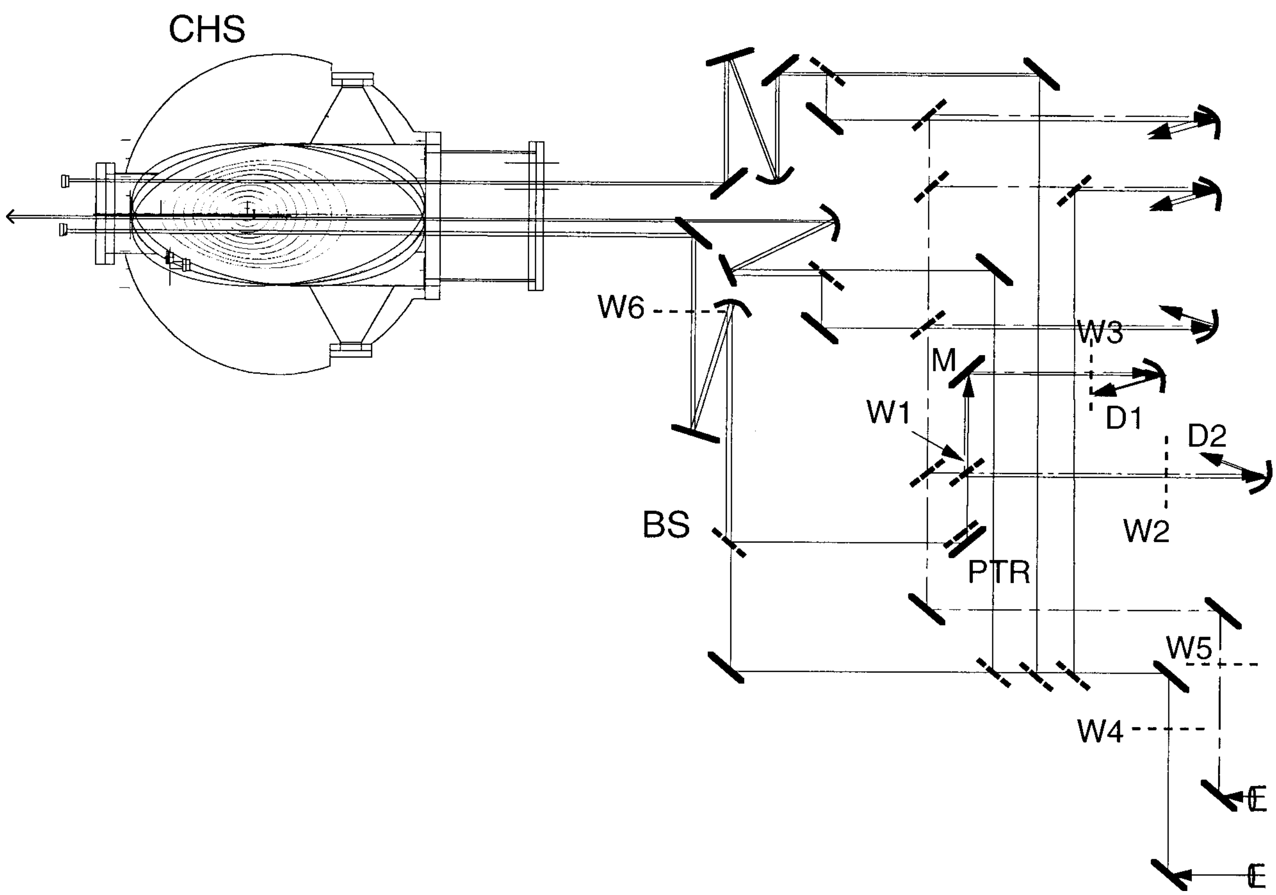

FIG. 2. Experimental setup on CHS. Probe path is indicated as plain line, local path as dotted line. PTR, M, $W1-W3$ correspond to the ones in Fig. 1. $D1$ and $D2$ indicate detector 1 and 2 in Fig. 1. $W4$ and $W5$ are wire grids to filter linearly polarized wave. BS is Mylar beamsplitter. $W6$ is the rotating wire grid for the calibration experiments. $W6$ is placed only during calibration experiments.

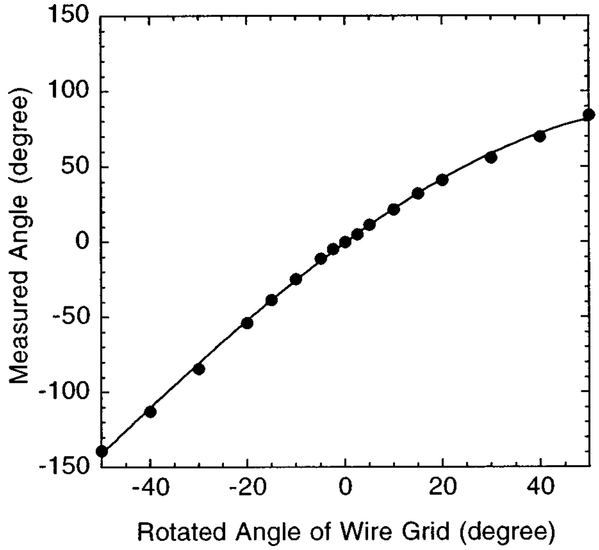

FIG. 3. The result of calibration experiments. Black circle symbols are measured data, and thin plain line is fitting curve, which is the third order polynomial function.

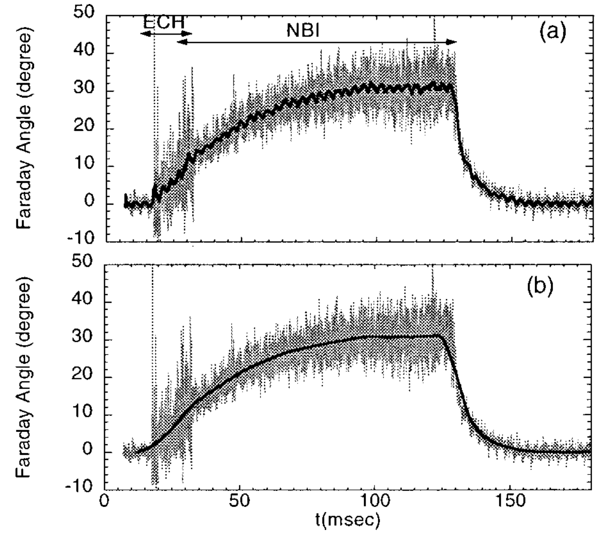

FIG. 4. Time trace of Faraday rotation obtained from NBI heated plasma. A black thick line indicates polarimeter phase; (a) numerical boxcar averaged 100 data sample, and (b) numerical boxcar averaged 1000 data sample. A gray thin line indicates phase without smoothing. Faraday rotation angles are calibrated by using Fig. 3. These were measured at $r/a = 0.49$.

to tune the reflectivity, and Lab 6 (hexaboride lantanum) was used as a cathode material. The laser became more stable and powerful (about a factor of two increase of the output power) after the cathode was replaced from tantalum to Lab 6.

Off-axis parabolic mirrors are used for the polarimeter channel and they focus the beam about 1 mm diameter on the detector. The detector is a corner cube reflector-type Schottky barrier diode which was developed at Tohoku University and RIKEN.[12] Super rotating grating (SRG),[13] which was developed at Kyoto University, was used for the frequency shifting.

The grating of SRG is fabricated on the top of the rotor of a turbomolecular pump, therefore it provides very high frequency shifts (up to 1.45 MHz) and is very quiet, because it rotates under a magnetically levitated state. Although phase noise caused by the mechanical vibration was about 5° using conventional electrical motor grating, it became negligible by using SRG. Under the present experiments, SRG operates at 620 kHz frequency shifting. A 620 kHz IF signal was digitized at 100 kHz and the effective IF signal frequency was 20 kHz. The Faraday angle was numerically calculated by using the demodulation technique[10] from the phase difference of the two polarimeter channels.

C. Calibration experiments

Calibration experiments were done by rotating the wire grid to simulate the Faraday rotation. The rotating wire grid was placed at the position shown in Fig. 2. Figure 3 shows the results of the calibration experiments. The zero degree in Fig. 3 indicates the initial phase of the polarimeter without plasma.

As shown in Fig. 3, the measured angle is not linear to the rotating angle of the wire grid. If everything is ideal, the measured angle should be twice that of the rotating angle of the wire grid, as described in Sec. II A. However, the measured angle is about 1.6 times of positive rotating, and about 2.8 times negative rotating. It is not clear what causes this nonlinear effect; one probable reason is the change of reflectivity of the Mylar beam splitter, which is shown in Fig. 2, depending on the polarization angle. At present, we must use this nonlinear calibration curve, which is well fitted with the third order polynomial function.

III. EXPERIMENTAL RESULTS FROM PLASMA DISCHARGE

In order to demonstrate the capability of the phase sensitive heterodyne polarimeter, the Faraday angle of CHS was measured. CHS at the National Institute for Fusion Science (NIFS) is a medium sized heliotron/torsatron device having the major radius of the vacuum vessel $R = 1$ m and the averaged plasma minor radius $a = 0.2$ m.[14] The multipolarity and the toroidal period number are $l = 2$ and $m = 8$, respectively.

On CHS, plasma is initiated by electron cyclotron heating (ECH) or ion Bernstein wave (IBW) and auxiliarily heated by neutral beam injection (NBI).

A. Noise level of the polarimeter signal

Figure 4 shows one example of measured Faraday rotation on ECH and NBI heated plasma. As shown in Fig. 4(a) with 100 data points (1 ms duration) smoothing, incoherent noise is smoothed out, although sinusoidal coherent noise, which corresponds to 1° remains. This coherent noise is from the fluctuation of the laser output power, and is caused by the ripple of the power supply. On the other hand, as shown in Fig. 4(b), sinusoidal noise is smoothed out with 1000 data points (10 ms duration) and the noise level goes down to 0.1°.

During the ECH phase, the polarimeter signal suffers from spike noise. Incoherent noise increases as the Faraday rotation angle increases (the same as the density increase),

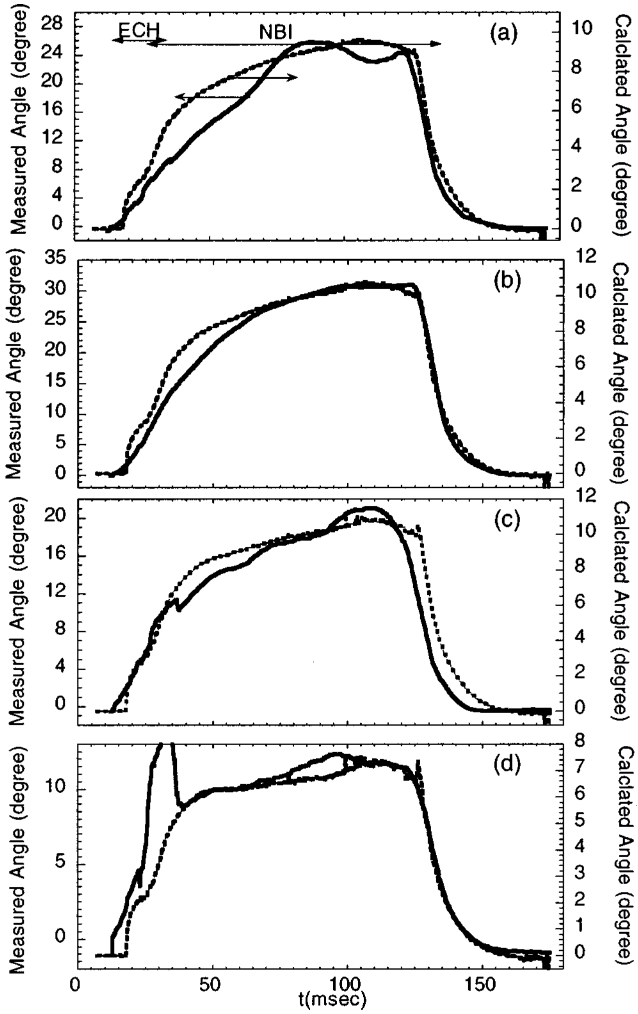

FIG. 5. Comparison of the time trace of measured (plain line) and calculated Faraday angle (dotted line) and line density at $B_t = 1.8$ T under ECH and NBI heating. Measured data are 1000 points smoothed data. (a) At $r/a = 0.39$, (b) 0.49, (c) 0.59, (d) 0.77. Disturbed signal in (d) is caused by ECH noise.

and at present it is not clear whether these are due to the increase of noise or increase of fluctuation of the density and magnetic field.

B. Comparison between measured and calculated Faraday rotation angle

In the conventional discharge of CHS, plasma currents, which are mainly beam driven currents, are less than 20 kA, which correspond to about 0.5° Faraday rotation. On the other hand, most of the magnetic field is produced by the external coil and the Faraday rotation angle is about 10° at toroidal magnetic field (B_t) 1.8 T and at the line averaged density $3 \times 10^{19}\ \mathrm{m}^{-3}$. Since the Faraday angle induced by plasma currents is less than one order smaller than the ones by the vacuum field, neglecting the former one, the expected Faraday angle can be calculated by using the vacuum field and electron density profile. This becomes a good check of the polarimeter.

Figure 5 shows a measured and calculated Faraday rotation angle at different positions at $B_t = 1.7$ T. Faraday angles are calibrated by using the calibration curve of Fig. 3. Faraday rotation angles are calculated from the vacuum magnetic field and radial density profile, which is from the simultaneous measurement by using the interferometer. The plasma current was 8 kA at maximum, since it corresponds to 0.2° of the Faraday rotation, this effect is negligible. Plasma beta was less than 0.2%, therefore the finite beta effect is also negligible.

Measured Faraday angles follow the calculated one except during the ECH phase (18–23 ms), however there are large discrepancies of the absolute value. The measured one is 1.5–3 times higher than the calculated value. This discrepancy is supposed to be partly caused by the refraction. The distance from W1 to D1 and D2 in Fig. 1 is set to be equal in order to make refraction effects the same for two detectors, however, the difference of the mixing of probe and local light and the difference of beam focusing on the detectors might cause a phase shift between D1 and D2 in addition to Faraday rotation. The alignment should be optimized to remove this effect.

IV. SUMMARY AND FUTURE DIRECTIONS

A phase sensitive heterodyne polarimeter was installed on CHS, present resolution of the Faraday rotation angle is 1° at 1 ms and 0.1° at 10 ms. Up to now, there is a big discrepancy between the measured phase angle and calculated angle, and these are probably caused by the refraction.

The polarimeter on the currentless heliotron torsatron and stellarator devices can be used as a density monitor. It is not easy to measure the current profile of these devices, because the Faraday angle induced by plasma current is so small. However, by using the vertical view, it is possible to measure the magnetic axis position from the change of the sign of the Faraday angle. This will provide useful information under high beta discharge.

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