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Development of CO_2 Laser Polarimetry for Long-Pulse Operations of LHD

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Abstract

A CO_2 laser densitometer measuring the Faraday rotation was developed for long-pulse operations of the Large Helical Device (LHD). The frequency-shift heterodyne techniques with the use of acousto-optic modulators (AOM) were adopted to measure the Faraday rotation angle with a high resolution. A two-channel polarimetry system was installed on LHD. The first results reveal that a rotation angle resolution of about 0.02 degrees was achieved with a time resolution of 16 ms.

Keywords:

polarimeter, frequency-shift heterodyne, Faraday rotation, CO_2 laser, LHD

1. Introduction

Tangential polarimetry in the midplane has been proposed to monitor the electron density in large tokamaks [1]. This technique has several advantages over interferometry. The polarimetric measurement does not depend on the past history of the discharge since the Faraday rotation angle can be designed to be less than 2π with a proper choice of the probe beam wavelength. Hence the polarimetry is free from the miscount of fringes from which interferometers often suffer so that it is suited for long-pulse operations of fusion devices. It has another advantage of being insensitive to vibration of optical components, by which the system becomes simpler. The feasibility of the tangential polarimetry has been demonstrated by a CO_2 laser polarimeter using a couple of photoelastic modulators on the JT-60U tokamak [2].

An accurate measure of the rotation angle would enable us to monitor the electron density of stellarator/heliotron plasmas, where the confining magnetic field can be computed at least for low plasma pressure. An infrared polarimeter using acousto-optic modulators has been developed [3] to back up the interferometer system on the Large Helical Device (LHD). The Faraday rotation angle is less than a degree except high density discharges even along the tangential chords of LHD plasmas when we use CO_2 laser beam to avoid refraction effects. Thus sophisticated techniques are required to measure the angle with a resolution of less than 0.1 degrees. The frequency-shift heterodyne techniques [4,5] were adopted to measure the angle with high resolution. The method is insensitive to beam ellipticity and laser power fluctuations and robust against common-mode refractive effects.

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The polarimeter was installed on LHD and its first results are presented.

2. Optical Arrangement

Figure 1 shows the optical setup of the frequency-shift heterodyne polarimeter. The laser beam passes through an acousto-optic modulator (AOM), operating at about 40 MHz. The Doppler shifted beam is then recombined with another diffracted beam such that the two slightly frequency offset components are polarized perpendicularly to each other. These are then passed through a quarter wave plate to generate counter-rotating circularly polarized beam components and launched into the plasma along a few chords using polarization insensitive beamsplitters.

Retro-reflectors with a clear aperture of 70 mm are used to displace the returning beams by 40 mm vertically so that the detector optics are separated from the probe beam optics. The retro-reflector was manufactured from aluminum alloy (A6063) and its mirror surface was coated with gold. It weighs only 540 g. Although mirror blocks were screwed on a base plate to avoid the use of resin or adhesives, an accuracy of less than 0.5 mrad of parallelism was achieved.

The beam emerging from the plasma is passed through a polarizer and detected to give an oscillating signal at the beat frequency that suffers a phase retardation proportional to the Faraday angle. Note that the phase difference between the reference and probe signals is four times the Faraday rotation angle owing to the double beam path in the plasma.

The total beam path length from the CO_2 laser (MPB GN-802-MES) to detectors was designed to be about 30 m. The beam path in the vacuum vessel to and from the retro-reflector is about 20 m. To focus the beam diameter at the retro-reflector to about 10 mm, a beam expander with a beam expansion ratio of three was placed at a path length of 2.5 m from the laser. The beam diameter at the ZnSe window with an aperture of 88 mm is calculated to be less than 18 mm.

3. Probe Chords in LHD

The Faraday rotation of the CO_2 laser beam through LHD plasmas was numerically evaluated as a function of the tangent radius to optimize the probe chords. We used the MHD equilibrium database of LHD computed with the VMEC code. Figure 2 plots the distribution of the Faraday rotation angle divided by the line electron density with a tangent radius of 3.8 m in the two cases of volume averaged plasma betas of 0.32% and 1.76%. We assumed the electron density profile as $n_e = n_{max}\ (1-S)^j$, where S stands for the toroidal magnetic flux normalized to that at the outermost flux surface. Flat and parabolic profiles are expressed by j = 0 and 1, respectively.

When we choose a probe chord with a tangent radius of around 3.8 m, the dependence of the normalized Faraday rotation on the electron density

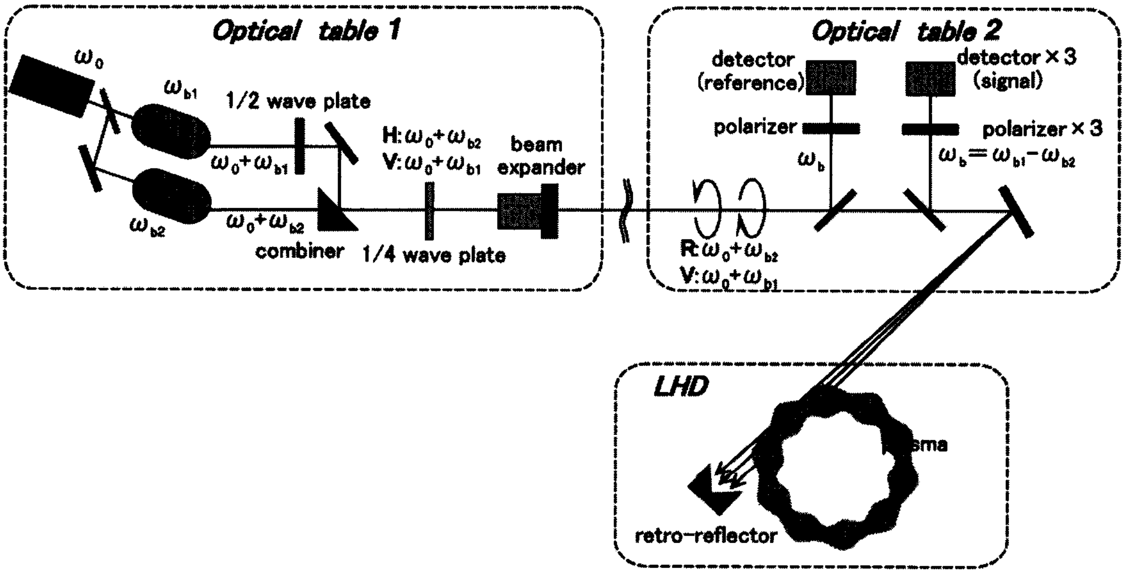

Fig. 1 Schematic of the frequency-shift heterodyne polarimeter system on LHD.

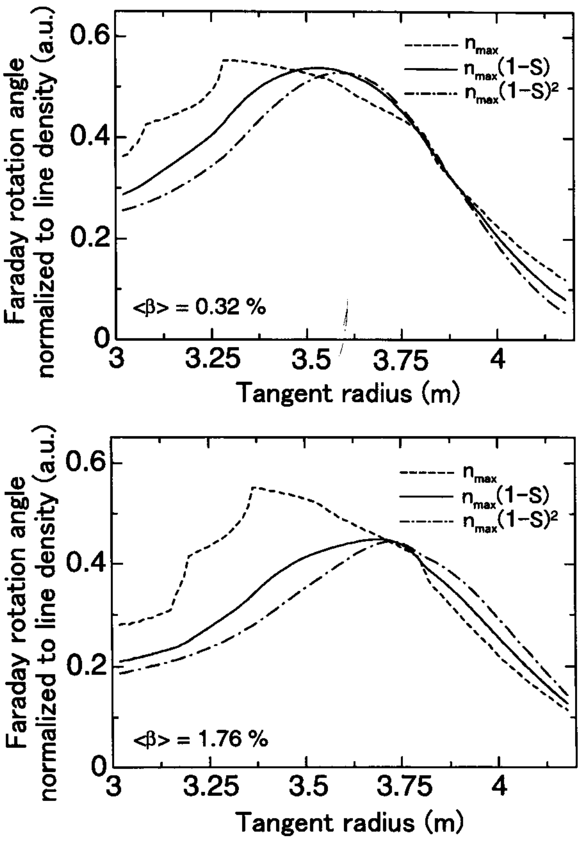

Fig. 2 Variation of the normalized Faraday rotation angle as a function of the tangent radius with three electron density profiles at two volume averaged betas.

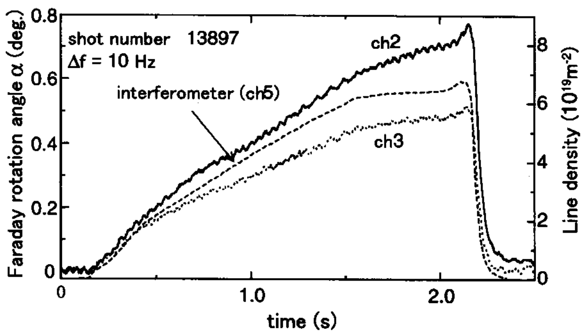

Fig. 3 Comparison of the Faraday rotation angle from digital processing with the interferometer data.

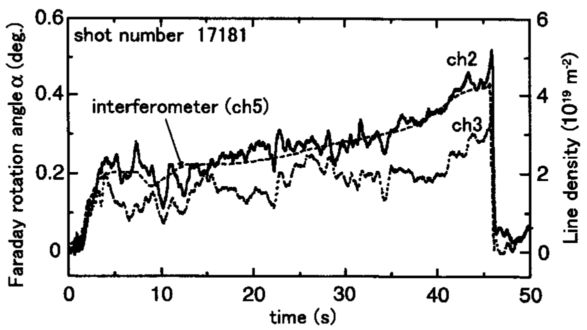

Fig. 4 Comparison of the Faraday rotation angle from lock-in amplifiers with the interferometer data.

profile shape is so weak that the Faraday rotation angle is a good measure of the line electron density. On the other hand, the normalized Faraday rotation along inner chords with a tangent radius of around 3.4 m is sensitive to the electron density profile shape. Accordingly we can draw information on the electron density profile from the polarimetric measurements along two tangential beam paths.

Two retro-reflectors which correspond to tangent radii of 3.72 m (ch 2) and 3.90 m (ch 3) were installed in the vessel in 1999. The installation of another retro-reflector for inner chord measurement (ch 1) was postponed until the next vacuum vent.

4. Experimental Results

An example of the 2-channel polarimeter measurement of an NB heated discharge at 2.75 T is shown in Fig. 3. The beat signals at 100 kHz were digitized in 12 bits at a sampling rate of 1 MS/s. Digital complex demodulation [6] was employed to improve the accuracy of phase evaluation. The trace of interferometer measurement along a vertical chord with a major radius of 3.67 m, which was close to the magnetic axis is shown by broken line for comparison. The observation that the rotation angle of ch 3 (tangent radius: 3.90 m) is almost the same as that of ch 2 (tangent radius: 3.72 m) in the early phase of the discharge is only explained by a hollow density profile.

The results indicate that the resolution of the Faraday rotation is about 0.02 degrees, which is equivalent to a resolution of the line averaged electron density of about 1×10^{18} m^{-3}, with the use of digital band-pass filtering from 99.99 kHz to 100.01 kHz.

Figure 4 shows the polarimeter traces of a long-pulse NB heated discharge at 2.75 T. In this case, two lock-in amplifiers (EG & G Princeton Applied Research Model 5302 for ch 2 and Stanford Research Systems SR 830 for ch 3) were used for the phase measurements. The rotation angle sometimes fluctuates with an amplitude up to 0.05 degrees in several seconds.

Although no cause for the seemingly common mode noise is identified, an improvement in the long-term stability of the phase measurement is required to monitor the line electron density of long-pulse operations.

5. Conclusions

A frequency-shift heterodyne polarimeter was developed to monitor the electron density of long-pulse discharges in LHD. The first results of the two-channel polarimeter reveal that the resolution of the Faraday rotation angle is about 0.02 degrees when digital band-pass filtering from 99.99 kHz to 100.01 kHz is employed. The suppression of the low-frequency noise up to 0.05 degrees is required for long-pulse operations of LHD.

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References

[1] F.C. Jobes and D.K. Mansfield, Rev. Sci. Instrum. **63**, 5154 (1992).
[2] Y. Kawano *et al.*, Rev. Sci. Instrum. **70**, 1430 (1999).
[3] H. Murayama *et al.*, Proc. of 1998 ICPP & 25th EPS Conf. on Control. Fusion and Plasma Phys., **Vol. 22C**, 1482 (1998).
[4] G. Dodel and W. Kunz, Infrared Phys. **18**, 773 (1978).
[5] J.H. Rommers and J. Howard, Plasma Phys. Control. Fusion **38**, 1805 (1978).
[6] D.W. Choi *et al.*, Rev. Sci. Instrum. **57**, 1989 (1986).