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Electron Density Measurement for Steady State Plasmas

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Abstract

Electron density of a large tokamak has been measured successfully by the tangential CO_2 laser polarimeter developed in JT-60U. The tangential Faraday rotation angles of two different wavelength of 9.27 and 10.6 μm provided the electron density independently. Two-color polarimeter concept for elimination of Faraday rotation at vacuum windows is verified for the first time. A system stability for long time operation up to ~10 hours is confirmed. A fluctuation of a signal baseline is observed with a period of ~3 hours and an amplitude of 0.4 ~ 0.7°. In order to improve the polarimeter, an application of diamond window for reduction of the Faraday rotation at vacuum windows and an another two-color polarimeter concept for elimination of mechanical rotation component are proposed.

Keywords:

Electron density, tangential Faraday rotation, CO_2 laser, polarimetry, diamond window

1. Introduction

For steady state plasmas, extremely high reliability and stability of diagnostic systems are required. Especially, to establish reliable electron density measurement is one of the principal and basic subjects. A laser polarimetry for electron density measurement based on tangential Faraday rotation is a promising technique for this purpose [1,2]. The laser polarimetry is more reliable than the conventional laser interferometry because; 1) a time history of the signal is not needed, 2) error like "fringe jump" does not occur, 3) no influence from change in beam path length by mechanical vibrations and displacement of optics, 4) very high quality laser characteristics are usually not needed (only stable linear polarization of laser light is enough).

We have studied the laser polarimetry in order to realize electron density measurement for fusion plasmas as follows: the consideration of Faraday rotation at vacuum windows (window component) and the development of the two-color polarimeter concept to eliminate the window component [3], an application proposal of photoelastic modulators (PEMs) for infrared CO_2 laser polarimetry [3], the first measurement of the Faraday rotation of a tangential CO_2 laser wave (λ = 9.27 μm) for the proof of principle [4], evaluation of electron density by laser polarimetry with λ = 9.27 μm [5], and commissioning of basic operation characteristics with two wavelength polarimeter (λ = 9.27 and 10.6 μm) [5,6]. However, calibration accuracy for a polarimetry with 10.6 μm was not high enough.

Recently, as calibration progressed, electron density is sufficiently evaluated independently in polarimetry with both wavelengths. Furthermore, electron density is obtained under the two-color polarimeter concept. Additionally, a long time stability of the polarimetry is examined aiming for steady state diagnostics.

This paper presents electron density measurement by the tangential CO_2 laser polarimetry and its aspects for steady state plasmas.

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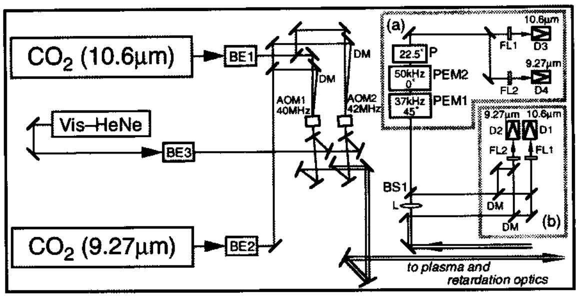

Fig. 1 Optical arrangement on the vibration isolation bench (3 × 1.5 m). (a) optics for polarimetry, (b) optics for interferometry.

2. Optical Arrangement

Major instruments of the polarimeter are installed at a basement of the JT-60U building [4]. Figure 1 shows the optical arrangement on the vibration isolation bench at the basement. Laser oscillators, beam-guiding optics, vacuum windows are used in common with the dual CO_2 laser interferometer [7,8]. (therefore, the system is called as the dual CO_2 laser interferometer/ polarimeter.) Naturally, probing laser beams of the polarimeter and the interferometer are identical, this enables cross check between each signals easily. Note a single polarization modulation unit, which consists of a couple of PEMs and a polarizer plate, is commonly utilized for two different wavelength of 9.27 and 10.6 μm.

Calibration of the polarimeter is performed by use of an another polarizer plate which is mounted on a manually or an automatically rotated stage. When the manually rotated stage is used, the polarizer plate is installed between a beam splitter (BS1) and a focusing lens (L). On the other hand, when the automatically rotated stage is used to set a step angle more precisely, the polarizer plate is installed at the downstream of BS1 since the present stage is too big to insert between BS1 and the lens. In this case, since the polarization characteristic of BS1 is not included, measured angles are normalized by the calculated angles from density profiles measured by Thomson scattering diagnostic. Anyway, both calibration data provides almost same results.

3. Evaluation of Electron Density

Figure 2 shows the typical waveforms of the dual CO_2 laser interferometer/polarimeter operated for JT-60U discharge. Usually, data acquisition of the polarimeter is available from −10 s to 20 s. In Fig. 2, calibration coefficients obtained by the automatically rotated stage are applied for polarization rotation signals. Traces of rotation angles are vertically shifted so that rotation angles to be zero at 0 s.

Figure 3 shows traces of line-averaged electron

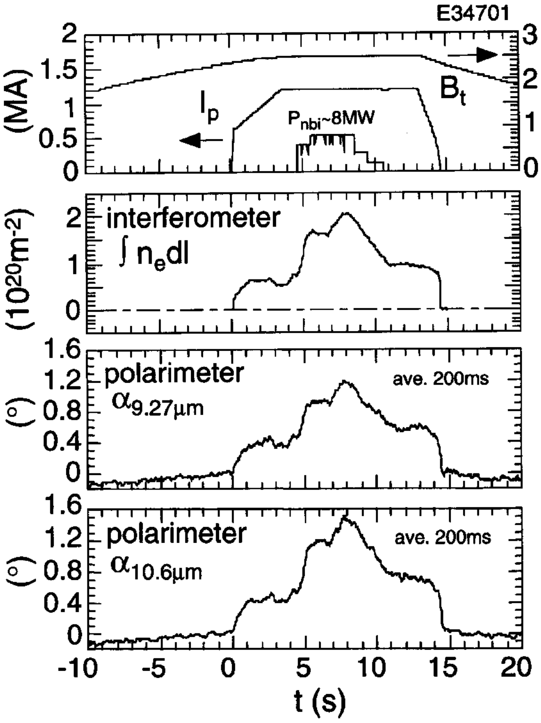

Fig. 2 Typical waveforms of the dual CO_2 laser interferometer / polarimeteter.

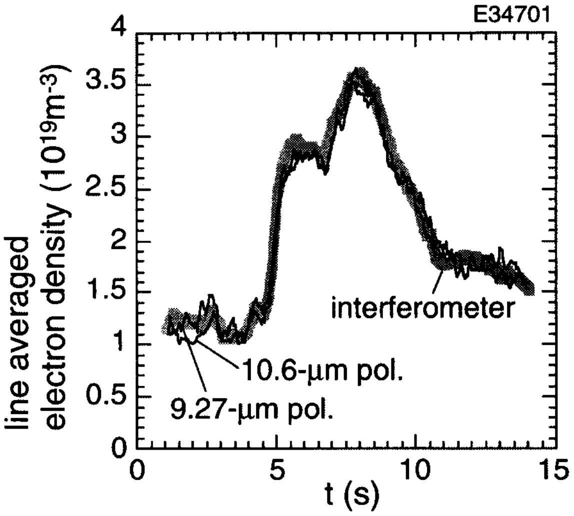

Fig. 3 Line-averaged electron density measured by the 9.27 μm polarimeter, the 10.6 μm polarimeter, and the dual CO_2 laser interferometer, respectively.

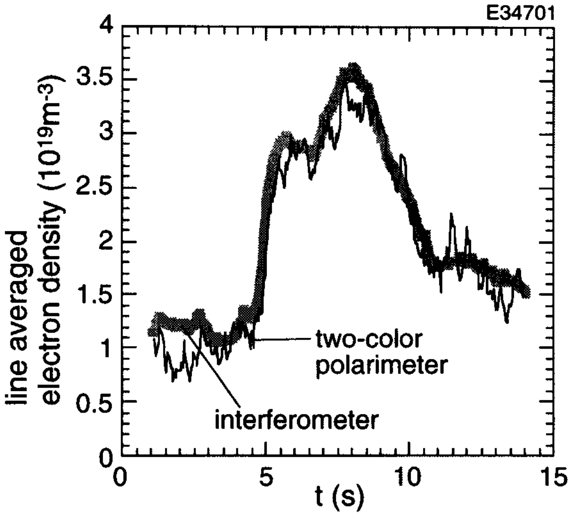

Fig. 4 Line-averaged electron density obtained under the two-color polarimeter concept.

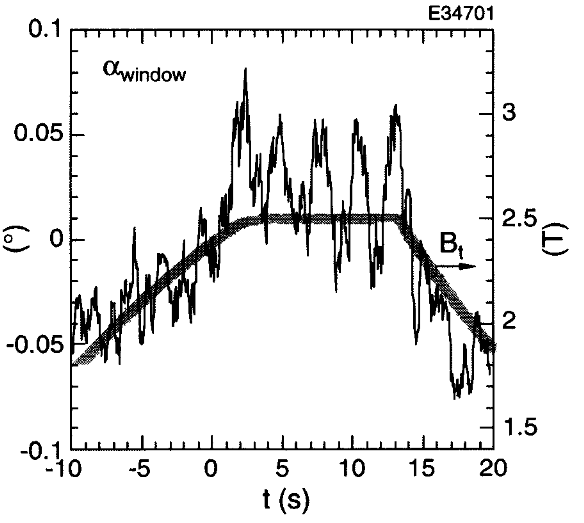

Fig. 5 Window component extracted by the two-color polarimeter concept.

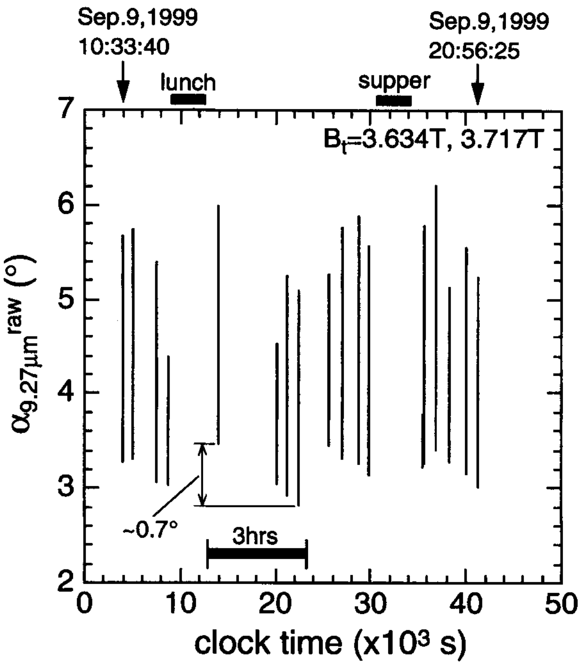

Fig. 6 A long time (~10 hours) stability of the 9.27 μm polarimeter

density of the JT-60U plasma measured by the 9.27 μm polarimeter, the 10.6 μm polarimeter, and the dual CO_2 laser interferometer, respectively. A constant density profile is assumed in Fig. 3. Window components during the discharge are subtracted by the use of the toroidal magnetic field (B_t) signal, where coefficients of window components against B_t is obtained before and after the discharge. In Fig. 3, both electron density traces measured by polarimeters show good agreement with that measured by the interferometer. Hence, a single color polarimeter is feasible for actual use in a plasma experiment.

The two-color polarimeter concept is applied for general operation of the polarimetry, where no another information is needed to eliminate window components. Figure 4 shows line-averaged electron density obtained under the two-color polarimeter concept for the first time. The rotation angles shown in Fig. 3 are used. Though the S/N is reduced as expected [3], the electron density by the two-color polarimeter agrees with that by the interferometer. Figure 5 shows the extracted window component. A temporal behavior similar to that of B_t is identified. Though it is almost resolution limit, an oscillating feature of the window component signal with a period of ~3 s is seen during the discharge. The reason of the signal oscillation is now under investigated. According to Figs. 4 and 5, the two-color polarimeter concept is well verified.

4. Long Time Stability

Figure 6 shows a day history (~10 hours) of the rotation angle measured by the 9.27 μm polarimeter (raw data: without vertical shift). Each line corresponds to data for an individual discharge from −10 s to 20 s. The minimum value of a line means rotation angle at −10 s without a plasma but with B_t (on the other hand, maximum value of a line corresponds to the maximum

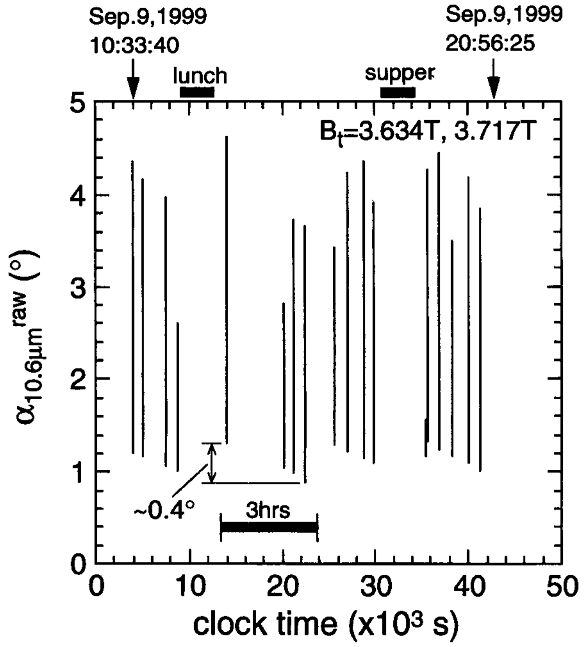

Fig. 6 A long time (~10 hours) stability of the 10.6 μm polarimeter

electron density of a discharge). Here, those data are collected from discharges that have similar B_t pattern with flat top of 3.634 T and 3.717 T. The influence from the difference between 3.634 T and 3.717 T is less than 0.01° (negligible). Therefore, temporal change in minimum values of lines shows the change in the baseline ("zero" position) of the polarimeter. Since the baseline dose not drift seriously, a long time (~10 hours) stability is confirmed.

In detail in Fig. 6, a fluctuation of the baseline with a period of ~10^4 s (~3 hours) and an amplitude of ~0.7° is observed. A fluctuation with similar period and phase is also observed in common for the rotation angle measured by the 10.6 μm polarimeter as shown in Fig. 7. However, the amplitude of the fluctuation for the 10.6 μm polarimeter is somewhat smaller as ~0.4°. The reason of the fluctuation might be attributed to the fluctuation of circumstance temperature, which can change the relative position between the polarimeter and JT-60U device (mechanical rotation) and/or the Verde constant of vacuum window material.

5. Diamond Window

Though the two-color polarimeter works, efforts to reduce the Faraday rotation at vacuum windows are important. One way is to use window materials whose Verdet constant is small. The diamond is transparent at infrared range including the CO_2 laser wavelength and its Verdet constant is more than ten times smaller than that of zinc-selenide (ZnSe) which is generally used for windows of CO_2 laser diagnostic systems [6]. Additionally, the diamond is hardest material among minerals. Actually, the diamond is about hundred times harder than ZnSe. Such high hardness enables to use the diamond as a vacuum window with smaller thickness. As a result from a smaller Verde constant and smaller thickness, the Faraday rotation angle at a diamond window is expected to be about two order smaller than that of a ZnSe window. Recently, the artificially fabricated diamond plate with large diameter is getting available for high-power microwave applications [9]. To use the diamond window for diagnostic applications in large devices has been proposed [6].

6. Two-Color Polarimeter Concept for Elimination of Mechanical Rotation

For steady state operation of the polarimeter, when baseline fluctuations seen in Figs. 6 and 7 are not acceptable, either the detection of a zero position or the elimination of the fluctuation is needed. In general, since the mechanical component is independent of laser wavelength, the three-color concept with additional wavelength polarimeter must work to eliminate both window and mechanical components. However, the *S/N* would be degraded significantly. When the window component is negligible by the use of diamond windows and/or the installation of windows at far from the vacuum vessel, contribution of window component to the fluctuation is also negligible. The rest of the fluctuation may attribute to a mechanical rotation.

For this situation, another two-color polarimeter concept to eliminate mechanical rotation angle is proposed. The measured angles α by two different wavelength polarimeters are approximately written by

$$\alpha_1 = C\lambda_1^2\int n_e B_{//}\mathrm{d}l + \phi_m, \tag{1}$$

$$\alpha_2 = C\lambda_2^2\int n_e B_{//}\mathrm{d}l + \phi_m, \tag{2}$$

where subscripts 1 and 2 denote the wavelength difference, C is a constant coefficient, and ϕ_m is the mechanical rotation component. The integral is easily obtained by the combination of eqs. (1) and (2) as

$$\int n_e B_{//}\mathrm{d}l = (\alpha_1 - \alpha_2) / C(\lambda_1^2 - \lambda_2^2)\,, \tag{3}$$

where ϕ_m is eliminated. By using this new concept, more reliable and stable electron density measurement is expected for steady state plasmas.

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