Conceptual Design of Electron Density Measurement System for DEMO-Relevant Helical Plasmas*)

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Electron density measurement remains indispensable to control fueling on a DEMO reactor. For steady-state operation of the DEMO reactor, density measurement should be highly reliable and accurate. A dispersion interferometer and a Faraday polarimeter are free from measurement errors caused by mechanical vibrations. Hence combination of the two diagnostics yields a suitable system for density measurement on future steady-state fusion reactors. A wavelength around 1 μm is one of the desirable candidates in terms of the fringe shift and the Faraday rotation angle, the variety of optical components, and the efficiency of frequency doubling for the dispersion interferometer. This paper presents a conceptual design for the dispersion interferometer and Faraday polarimeter with a 1 μm light source.

Keywords: dispersion interferometer, polarimeter, Faraday effect, Cotton-Mouton effect, Nd:YAG laser

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1. Introduction

Electron density measurement is indispensable for fueling control and physical analysis. Considering steady-state operation of future fusion reactors, density measurement should be reliable and accurate. Interferometers are currently used for continuous density measurement on most fusion devices. Although they have high temporal and density resolutions, measurement errors because of mechanical vibrations must be suppressed. They sometimes suffer from fringe jump errors, which significantly degrade their reliability. Two-color measurement, which uses two different wavelengths, can compensate for phase shifts due to vibrations, and a short-wavelength laser can reduce the risk of fringe jump errors. However, these are not fundamental solutions; the introduction of different schemes in principle is necessary to establish a highly reliable density measurement system, especially for a helical DEMO reactor, whose plasmas will be high density and steady state.

2. Alternative Density Measurement Methods

Three alternatives to the conventional interferometer have been proposed: a Faraday polarimeter (FP), a Cotton-Mouton polarimeter (CMP), and a dispersion interferometer (DI). The FP and CMP measure the rotation angle α ($\propto \lambda^2 \int n_e B_\perp dl$) of the plane of polarization and the phase difference between O- and X-modes ϕ_{CM} ($\propto \lambda^3 \int n_e B_{//}^2 dl$), respectively [1]. The DI uses dispersion of in a plasma between the fundamental and the second harmonic of the laser light. Since all are insensitive to mechanical vibrations, they do not need vibration compensation systems. The phase shift due to a plasma smaller than one fringe is acceptable in terms of the signal-to-noise ratio because the phase error due to vibrations is negligible. This means that they can be free from fringe jump errors if an appropriate wavelength is selected. Because of these advantages, they are suitable for use in future fusion reactors.

Electron density measurement using an FP or a CMP has been successfully demonstrated on various devices [2–5]. Their sensitivity to magnetic fields provides the additional option of measuring the magnetic field. Vice versa, the line-averaged density measurement itself is weighted by the magnetic field profile, which is a disadvantage if the diagnostic is dedicated for control purposes. In addition, coupling between the Faraday and Cotton-Mouton effects causes measurement errors when they are large (they are generally limited to approximately less than 10° to reduce the coupling effect).

The phase shift measured with a DI depends only on the electron density, and there is no coupling component. Hence, interpretation of the measured data is straightforward. Because good temporal and density resolution have already been confirmed with CO_2 lasers (wavelength 10.6 μm) [6–9], the DI is the most promising candidate.

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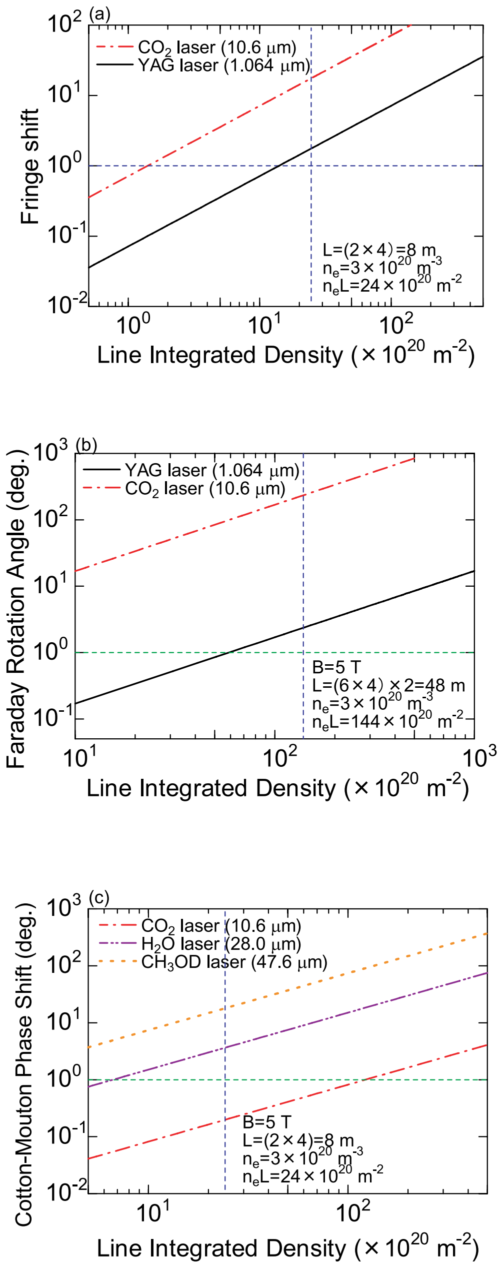

Fig. 1 Dependences of (a) the fringe shift (dispersion interferometer), (b) the Faraday rotation angle, and (c) the Cotton-Mouton phase shift on the line-integrated density and the wavelength. Vertical dashed lines indicate the line-integrated density n_eL expected for the corresponding sightline in the helical reactor. See text for details.

3. Wavelength Selection for DEMO-relevant Helical Plasmas

In this study, the helical DEMO reactor is assumed to be four times larger than the Large Helical Device (LHD): the major radius $R = 3.6 \times 4 = 14.4$ m, and the averaged minor radius $a = 0.6 \times 4 = 2.4$ m. The line-averaged density is 3×10^{20} m^{-3}, and the central magnetic field strength is 5 T.

Figure 1 shows the dependences of values measured using the above alternative methods on the line-integrated density and wavelength. The fringe shift measured with the DI smaller than 1 fringe is preferable to be free from fringe jump errors; the density is uniquely determined if the maximum phase shift is smaller than 1 fringe. In Fig. 1 (a), a horizontal line of sight with a path length of $2 \times 4 = 8$ m in the horizontally elongated cross section is assumed (the path length in an LHD plasma is about 2 m). Thus, the expected line-integrated density is $(3 \times 10^{20}) \times 8 = 24 \times 10^{20}$ m^{-2}. The fringe shift of Nd:YAG laser light (1.064 μm) for the expected electron density is slightly larger than 1 fringe. Although a shorter wavelength is preferable to reduce the fringe shift, a continuous-wave (cw) laser source powerful enough for second harmonic generation is not currently available. Hence, the fringe jump error remains in this device size, and compensation for the jump is necessary. Nevertheless, fringe jump correction is much easier than conventional interferometer because of the smaller number of the fringe shift. Therefore, high accuracy is not required for the compensation diagnostics.

An FP using a Nd:YAG laser with a tangential line of sight (round-trip path length is $(6 \times 4) \times 2 = 48$ m) is suitable for support diagnostics. As shown in Fig. 1 (b), the expected Faraday rotation angle, 2.4°, is appropriate; it is comparable to the typical rotation angle in LHD [3]. For the CO_2 laser polarimeter, an angle resolution of 0.01° with a time constant of 3 ms was achieved, and the Faraday rotation angle was measured with a signal-to-noise ratio greater than 100. The rotation angle of CO_2 laser light is so large that coupling between the Faraday and Cotton-Mouton effects becomes nonnegligible. On the other hand, the wavelengths of CO_2 and CH_3OD (47.6 μm) [10] lasers are too short and too long, respectively, for a CMP, as shown in Fig. 1 (c). In this calculation, the same line of sight is assumed as that for the DI. An H_2O laser with an output frequency of 28 μm is a candidate for the CMP's laser source. The H_2O laser has been used in an interferometer and a polarimeter [11]. However, because this wavelength range has not been widely used commercially, it is necessary to optimize the measurement method, optical materials, and detector.

These calculations indicate that a combination of the DI and FP will be a realistic density measurement system for DEMO-relevant helical plasmas.

4. Conceptual Design of Optical System

4.1 Dispersion interferometer with Nd:YAG laser

Figure 2 shows a schematic view of the phase-modulated DI [6–9]. A mixed beam consisting of the fundamental and second harmonic components, which is generated with a nonlinear component, is used as a probe beam. The phase of the second harmonic component is modulated with a PhotoElastic Modulator (PEM). A phase

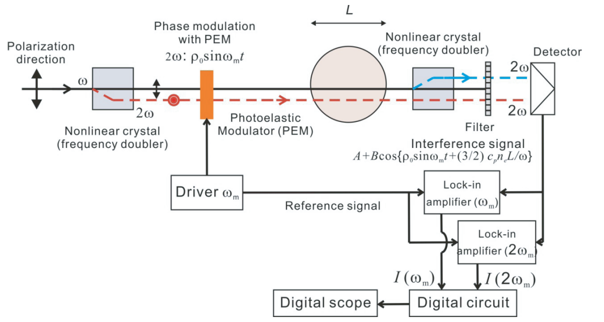

Fig. 2 Schematic view of the dispersion interferometer using the ratio of the modulation amplitude.

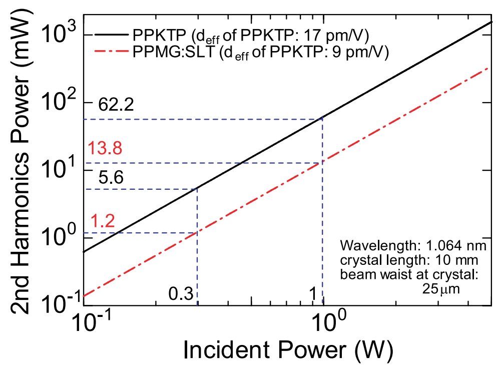

Fig. 3 Generated power of the second harmonic with PPMG:SLT and PPKTP.

modulation and phase extraction method using the ratio of modulation amplitudes [7–9] are applied to overcome a disadvantage of the DI: measurement errors caused by variations in the detected intensity. After passing through a plasma, another second harmonic component is generated from the fundamental. The fundamental is cut with a filter, and the interference signal between two second harmonic components is detected. Although the phase shift due to mechanical vibrations is the same in both second harmonic components, the shift due to the plasma differs because of dispersion. Hence, the phase shifts due to vibrations are canceled optically, and only that due to the plasma remains. This is why the DI is less sensitive to mechanical vibrations.

A key issue for the DI is the efficiency of second harmonic generation. The power density of a cw laser is generally too small to generate the second harmonic. Candidates of nonlinear components are periodically poled crystals such as PPMG:SLT and PPKTP, which have a large second harmonic conversion efficiency. Figure 3 shows the calculated power of the second harmonic for these crystals (the crystal length is 10 mm, and the beam radius at the crystal is 25 μm). At an injection power of 1 W, a second harmonic power of several tens of mW will be obtained.

Mirrors are expected to be installed in a vacuum vessel, and their reflectivity might be degraded by two orders of magnitude in the near-IR and visible range because of impurity deposition or sputtering on the mirror surface [12]. Although the transmission losses in several optical components (window, beam splitter, etc.) also attenuate the laser light, they are much smaller than that of in-vessel mirrors. A Si photodetector with a variable conversion gain of 10^3–10^{11} V/W (OE-200-SI, FEMTO Messtechnik GmbH) will be used to detect the second harmonics. Assuming that the reflectivity of the retroreflector deteriorates to 1% [12], the power of the fundamental and the second harmonic (P_1) for a laser source with a power of 1 W and a PPGM:SLT crystal are 1×10^{-2} W and 1.4×10^{-4} W, respectively, at the position of the second nonlinear crystal. Here, the transmission loss other than that at the retroreflector is neglected. The power of the second harmonic generated from the fundamental (P_2) is 1.4×10^{-6} W. If the interference coefficient is 100%, the power of the modulation component P_m is

$$\begin{aligned} P_m &= 2\sqrt{P_1 P_2} \\ &= 2\sqrt{(1.4\times10^{-4})\times(1.4\times10^{-6})} \\ &= 2.8\times10^{-5}\ \text{W}. \end{aligned}$$

For a gain of 10^4 V/W, the amplitude of the modulation component is 0.28 V. This is sufficient for a lock-in amplifier. If the reflectivity of other flat mirrors and the transmissivity of the windows are also degraded and the transmission coefficient of components other than the retroreflector is 1% (total transmission coefficient is 1% × 1% = 0.01%), then the power of the modulation component is 0.28×10^{-7} W. In this case, the same modulation amplitude can be obtained by increasing the gain to 10^7 V/W. A Nd:YAG laser with an output power of about 1 W and a narrow spectral linewidth of less than 1 kHz is commercially available (Mephisto, Innolight). The PEM is also available for this wavelength range (I/FS50, Hinds Instruments). An electro-optic modulator (EOM), whose modulation frequency is higher (∼ 1 MHz) than that of the PEM (∼ 50 kHz), is also available. Hence, it is possible to construct a phase-modulated Nd:YAG laser DI with existing optical components.

4.2 Faraday polarimeter with Nd:YAG laser

Because the Faraday rotation angle measured with the FP is independent of the beam path length, mechanical vibrations do not affect the FP. Two methods of measuring the Faraday rotation angle are typically adopted: the counter-rotating polarization method [3] and the method using two PEMs [2]. Although neither has been used with a Nd:YAG laser, all the necessary optical components are commercially available.

4.3 Possibility of combined method of dispersion interferometer and Faraday polarimeter

According to the fringe jump correction with the FP, using the same line of sight for both diagnostics increases

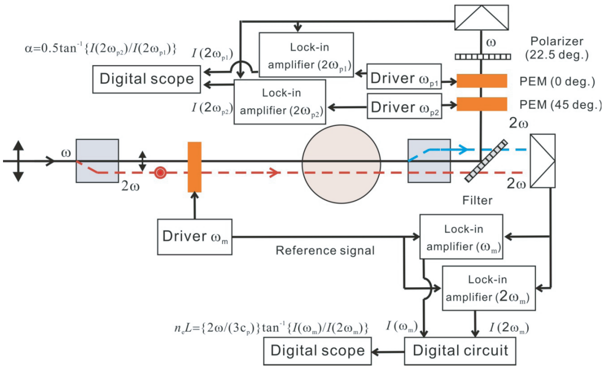

Fig. 4 Combination system of dispersion interferometer and Faraday polarimeter.

the accuracy of the correction. Figure 4 shows the combination system of the DI and FP. The fundamental component is separated (not just filtered out) after passing through a plasma and is transmitted to the polarimeter branch, which uses two PEMs having different modulation frequencies. No Faraday rotation occurs along the horizontal chord on the equatorial plane because $B_{//} = 0$; therefore, the line of sight must be tangential if this optical system is to have a finite Faraday rotation angle. Then, the fringe shift of the DI increases owing to the longer path length in a plasma. Hence, the availability depends on the device size and plasma parameters.

5. Challenging Task for Nd:YAG Laser Measurement

As mentioned in Sec. 4.1, the critical issues are the plasma facing first mirrors and the retroreflector required in the vacuum vessel, because their reflectivities will be reduced by plasma sputtering and impurity deposition. The latter is particularly critical for a hollow retroreflector, where impurity deposition tends to occur mostly in the central region. For example, in LHD, the reflectivity at the 1 μm range decreased by a factor of 10-100 because of impurity deposition during one experimental campaign (about four months) [12]. Passive shielding measures or active in-situ cleaning of the reflecting surfaces are options for maintaining a sufficiently high reflectivity. Passive shielding is achieved by covering windows or placing a bending cylinder with fins in front of the retroreflector [13]. In-situ cleaning can be achieved by using glow or electron cyclotron resonance discharges to remove carbon deposition by chemical sputtering and laser cleaning.

6. Summary

For a DEMO-relevant helical plasma four times larger than those of LHD, a combination of a DI and an FP is a candidate for reliable density measurement. An appropriate wavelength is around 1 μm for both diagnostics. An optical system consisting of the DI and the FP with a Nd:YAG laser source (1.064 μm) can be constructed of commercially available components. The challenging task is to maintain the reflectivity of in-vessel mirrors at short wavelengths.

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