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# Advanced Laser Diagnostics for Electron Density Measurements

Kazuo KAWAHATA, Tsuyoshi AKIYAMA, Rostislav PAVLICHENKO, Kenji TANAKA, Yasuhiko ITO, Kazuya NAKAYAMA<sup>1)</sup>, Shigeki OKAJIMA<sup>1)</sup> and Shunji TSUJI-IIO<sup>2)</sup>

*National Institute for Fusion Science, Toki 509-5292, Japan*

<sup>1)</sup>*College of Engineering, Chubu University, Kasugai 487-8501, Japan*

<sup>2)</sup>*Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8550, Japan*

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This paper describes innovative laser diagnostics under development at the National Institute for Fusion Science, aiming for the establishment of reliable density measurement techniques in the next step magnetically confined fusion devices. There are two approaches, interferometry and polarimetry. A new type of two color laser (47.6/57.2- $\mu\text{m}$  CH<sub>3</sub>OD) interferometer has been developed and its original function, vibration subtraction, was confirmed in a test stand. The line integrated density measurement at Compact Helical System by using the polarimeter based on Cotton-Mouton effect was demonstrated by the use of a 337- $\mu\text{m}$  HCN laser source.

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## 1. Introduction

Measurements of the refractive index of the plasma by using electromagnetic waves are a well-established tool for measuring electron density profiles in high temperature plasmas. In the Large Helical Device (LHD) [1], a 13-channel far infrared laser interferometer [2] has been constructed and routinely operated for the precise measurements of the electron density profile almost every shot except in the case of a high-density plasma produced by an ice pellet injection. In the latest experimental campaign of the LHD, a super dense core plasma as high as  $5 \times 10^{20} \text{ m}^{-3}$  has been achieved [3] by an internal diffusion barrier created by the use of the local island divertor and multiple pellets injection. In these high density plasmas, steep density gradient is formed leading to the fringe jumps on the density traces measured by fringe counters. In order to overcome this difficulty there are several approaches, which are classified into two categories, the interferometry and the polarimetry.

In the first category, interferometry, we need to develop short wavelength laser diagnostics to avoid the beam bending effect caused by the density gradient. However, it is also necessary to equip a second wavelength interferometer to compensate for a fringe shift due to mechanical vibrations of the optical components since the fringe shift caused by the vibrations is inversely proportional to the wavelength. In the LHD, a CO<sub>2</sub> laser imaging interferometer [4] has been developed for detailed profiled measurements of density and density fluctuation. For the sake of vibration compensation a 1.06- $\mu\text{m}$  YAG laser interferometer is employed. In this way, the conventional two color laser interferometer systems use two independent laser interfer-

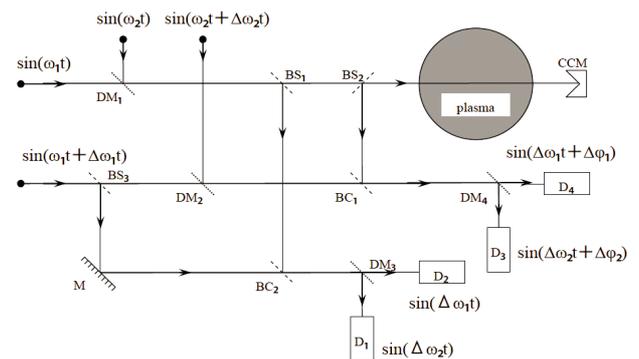


Fig. 1 Schematic drawing of the conventional two color laser interferometer of the Michelson type. Two laser oscillation lines are combined and separated with the dichromatic mirrors (DM). BS: Beam Splitter, BC: Beam Combiner, M: Beam Reflection Mirror, D<sub>2</sub>, D<sub>4</sub>: Detector for  $\omega_1$ , D<sub>1</sub>, D<sub>3</sub>: Detector for  $\omega_2$ .

ometers [5–7] as is schematically shown in Fig. 1. Probing laser beams ( $\omega_1$  and  $\omega_2$ ) are combined and made coaxial at the DM<sub>1</sub> dichromatic mirror, and divided into two beams at BS<sub>1</sub>, a probe beam and a beam which is used in the reference arm for a heterodyne signal detection. The probe beam is combined with the local beam which also contains two laser beams (with angular frequency  $\omega_1 + \Delta\omega_1$  and  $\omega_2 + \Delta\omega_2$ ) at BC<sub>1</sub> after passing through the plasma, and then separated into two laser components by using the DM<sub>4</sub> dichromatic mirror, and finally detected by the appropriate detectors (D<sub>3</sub> and D<sub>4</sub>). By using 4 output signals we can get information about the fringe shifts caused by the plasma and by the mechanical vibrations. In this type of the two color system, the fringe shift caused by the mechanical

author's e-mail: kawahata@lhd.nifs.ac.jp

vibrations cannot be canceled out completely since the optical path difference between two independent interferometers remains and effects due to optically dispersive components are significant when the wavelength of two laser sources is different largely.

In order to overcome these difficulties, new types of two color interferometers [4–6] have been developed to establish more reliable two color laser interferometers. At NIFS, we have been developing new laser sources operating in the wavelength region of 40 to 70  $\mu\text{m}$ , which is suitable for high density operation of LHD and for future fusion devices. In the process of searching for new laser oscillation lines, we have successfully achieved many oscillation lines around 40 to 70  $\mu\text{m}$  by the use of a  $\text{CO}_2$  laser pumped far-infrared laser [8]. Among these oscillation lines a unique laser operation was found by using  $\text{CH}_3\text{OD}$  molecular gas excited by the 9R(8)  $\text{CO}_2$  laser line. This laser operation provides two laser oscillation lines (57.2 and 47.6  $\mu\text{m}$ ) simultaneously, which lead to the construction of a new type of two color laser interferometer [9]. In section 2, progress of the development of the two color laser interferometer system is described.

The second category is polarimetry, where the Faraday rotation and Cotton-Mouton effects influence on the polarization of the laser beam which propagates through a magnetically confined plasma. The magnitude of the both effects depends on the magnetic field strength and electron density. When the magnetic field strength is known as in low beta helical devices, electron density information is available from the measurements of rotation angle or the ellipticity of the laser beam. In comparison with the conventional interferometry, this technique can be considered to deliver more robust measurements of the line integrated electron density, since it does not depend on the past time history of the discharge when the rotation angle is set to be less than  $2\pi$  radians by optimizing a laser wavelength for the target plasma [10]. We have already demonstrated the usefulness of Faraday rotation polarimetry for density profile measurement on LHD [11]. Another type of polarimeter, Cotton-Mouton polarimeter, has been proposed for ITER for density profile measurements [12] aiming to achieve a reliable diagnostic for long pulse discharges. On the Compact Helical System (CHS) a Cotton-Mouton polarimeter with a 337- $\mu\text{m}$  HCN laser was developed [13] in order to see the accuracy and limitations of polarimetry since there are very few applications [14, 15] for electron density measurement on the magnetically confined plasmas. One typical result obtained in CHS is described in the section 3.

## 2. New Type of Two Color FIR Laser Interferometer

Figure 2 shows the conceptual drawing of a new type of two color laser interferometer system of the Michelson type, which is a rather simple system compared with Fig. 1.

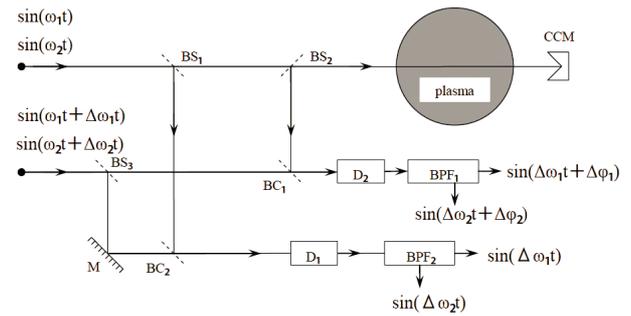


Fig. 2 Schematic drawing of a new type of the two color laser interferometer of the Michelson type. The optical components are the same as a conventional heterodyne interferometer with a single laser oscillation line. The detector output includes two heterodyne beat signals,  $\Delta\omega_1$  and  $\Delta\omega_2$ .

The optical arrangement is similar to a single heterodyne interferometer system. The laser source is a twin optically-pumped  $\text{CH}_3\text{OD}$  laser, which simultaneously oscillates at 57.2 and 47.6  $\mu\text{m}$  in wavelength, which are pumped by the 9R(8)  $\text{CO}_2$  laser line. Each laser line has different polarization, so that a Martin-Puplett diplexer is used to make a co-polarized beam [9]. By tuning the cavity lengths, the beat frequency of each heterodyne interferometer can be set at an optimum value, around 500 kHz for 57.2  $\mu\text{m}$  and 1.2 MHz for 47.6  $\mu\text{m}$ , which is determined considering detector IF frequency band width, laser tunability and frequency characteristics of band-pass filters to separate beat signals of each laser interferometer. The main components to construct the system are beam splitters and beam combiners made of a silicon etalon with high resistivity, which is a low absorption material (absorption coefficient  $\alpha = 0.56 \text{ cm}^{-1}$  at 47.6  $\mu\text{m}$ ) in the short wavelength FIR regime compared with quartz ( $\alpha_o, \alpha_e = 6.6 \text{ cm}^{-1}, 4.9 \text{ cm}^{-1}$ ). Visible light is not transmitted through silicon so that an YAG laser beam of 1.06  $\mu\text{m}$  in wavelength is used for alignment of the optical axis with infrared sensor cards. The interference signals are detected by Ge:Ga photoconductive detectors,  $D_1$  and  $D_2$ , operating at liquid helium temperature. The Ge:Ga detector has almost the same sensitivity at both laser frequencies, and the detected signals are separated electronically into two wavelength components. Each frequency component is fed into a phase comparator for phase measurement.

The variations of the phase of the two color interferometer,  $\phi_1$  and  $\phi_2$ , (for the wavelengths  $\lambda_1$  and  $\lambda_2$ , respectively) caused by variation in the plasma density  $n_e$  and by optical path length variation  $\Delta L$  are given by following equations,

$$\phi_{1,2} = 2.82 \times 10^{-13} \lambda_{1,2} \int n_e dl + 2\pi \Delta L / \lambda_{1,2} \quad (1)$$

By using two color interferometer ( $\lambda_1 > \lambda_2$ ), we can compensate for the mechanical vibrations by using the follow-

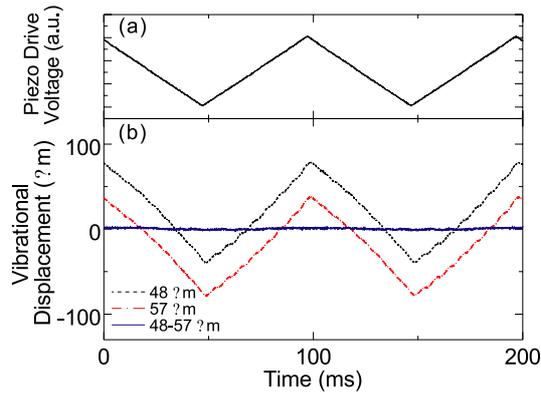


Fig. 3 (a) Waveform of the applied voltage on the piezo-electric transducer. (b) The measured displacements of the vibration mirror by a 57  $\mu\text{m}$  and 48  $\mu\text{m}$  CH<sub>3</sub>OD laser interferometers, and their difference. The mechanical vibration is simulated by using a piezo-electric transducer.

ing equation [16],

$$\phi_p = \frac{\phi_1 - \gamma\phi_2}{1 - \gamma^2} \quad (2)$$

where  $\phi_p$  is the phase shift due to the plasma in the interferometer of  $\lambda_1$ , and  $\gamma$  is the ratio of the wavelengths,  $\lambda_2/\lambda_1$ .

In order to develop new type of two color interferometer, a single channel two color interferometer system is constructed and operated in the laboratory, where main key issues to establish this innovative diagnostics are as follows; 1) development of laser control system to achieve stable simultaneous oscillation at 57 and 48  $\mu\text{m}$ , 2) development of optical components to construct short wavelength FIR laser diagnostics such as beam combiner/splitter, polarizer, beam optics to compromise with two different frequencies and detectors. An example of vibration subtraction test is shown in Fig. 3. In this case the reflecting mirror is placed on a piezo-electric transducer to confirm the idea of the two color laser interferometer and to find out what kind of problems need to be solved. The position of the mirror is modulated in a triangular waveform (Fig. 3(a)) at 10 Hz with the amplitude of  $\sim 118 \mu\text{m}$  to change the optical path length. The displacements of the mirror measured by 57 and 48  $\mu\text{m}$  laser interferometers are shown in Fig. 3(b). The difference of these displacements measured is also plotted in Fig. 3(b), which shows the effectiveness of the vibration compensation using two color laser oscillations. At the present the phase noise level of the interferometer is about 1/25 fringes, which is mainly caused by cross talk of each beat frequency component and will be reduced by the use of more proper electric filter and by setting the beat frequencies at proper different frequencies to attenuate the unwanted frequency component.

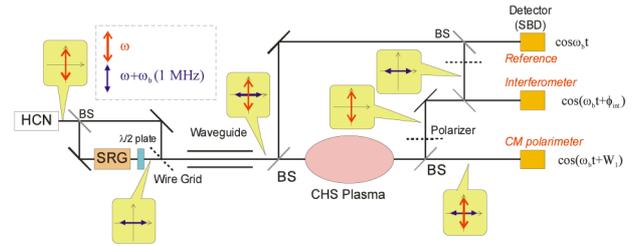


Fig. 4 Optical system of the Cotton-Mouton Polarimeter installed on CHS. Since the polarization component parallel to a receiving antenna in the SBD is detected, SBDs are tilted by  $\pi/4$ , and they remove the need for polarizers.

### 3. Cotton-Mouton Polarimeter

Figure 4 shows the optical system of the Cotton-Mouton polarimeter with a HCN laser (a wavelength of 337  $\mu\text{m}$ ) installed on CHS [13]. As probe and reference beams, combined beams of O- and X-mode beams with a slight frequency offset are used. The frequency of one beam is shifted by 1 MHz with a super rotating grating (SRG) [17]. The Cotton-Mouton effect can be measured as a phase difference between probe and reference beat signal, whose beat frequency is 1 MHz. Because of the phase measurement, this system is immune to oscillation instability of a laser and beam bending effect caused by the electron density gradient in a plasma. By selecting the orthogonal polarization component from probe and reference beams before mixing them, usual interferometry can be done simultaneously with the same chord as that of the polarimeter. The phase difference due to the Cotton-Mouton effect along a plasma center chord is  $8.2^\circ$  when a magnetic field strength at the magnetic axis is 1.96 T and the electron density is  $1.2 \times 10^{20} (1 - \rho^8) \text{m}^{-3}$  in CHS. Hence the Cotton-Mouton polarimeter is free from fringe jump errors owing to the smaller phase shift than  $2\pi$ . This also means that at low signal to noise ratio, digital complex demodulation combined with band-pass filtering [18] is adopted to increase phase resolution.

Figure 5 shows an example of measurement results of the Cotton-Mouton polarimeter. The response time determined from the band width of the band-pass filter is 1 ms. Except for the beginning of the discharge, the line averaged electron density evaluated from the polarimeter is well consistent with that from the interferometer. While the interferometer suffered from fringe jump errors twice ( $t = 135$  and  $144$  ms) at the end of the discharge, when the amplitude of the beat signal decreased significantly, the Cotton-Mouton polarimeter showed just spike noise and the correct value after the amplitude of the beat signal recovered.

The beat signal contains side-band frequency components (frequency of  $1 \text{ MHz} \pm$  (rotation frequency of SRG 500 Hz)  $\times$  integer, amplitude less than  $-6$  dB), which are intrinsic to the SRG [17], which cause phase noise in the polarimeter. While the phase noise is negligible compared

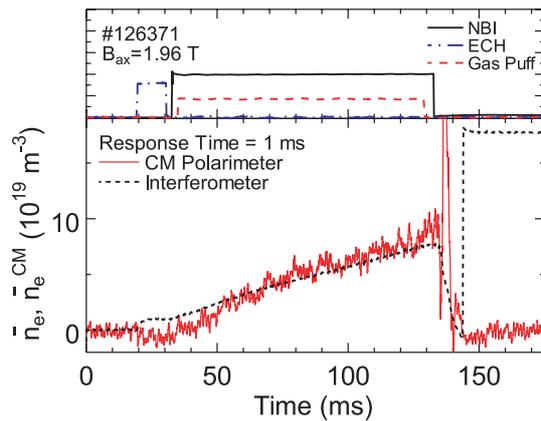


Fig. 5 Comparison of the line averaged electron density evaluated from the Cotton-Mouton Polarimeter with that from the interferometer.

with the phase shift of the interferometer (more than several fringes), they are significant in the Cotton-Mouton polarimeter because of the small phase shift. Hence, high phase resolution in the polarimeter requires higher quality of the beat frequency than that in the interferometer.

Cross talking between signals of the Cotton-Mouton polarimeter and the interferometer and back talking (multi-reflection between a detector and optical components) of the polarimeter are also causes of modulations of the phase difference similar to polarimeters based on the Faraday effect [19]. The inverse time evolution from  $t = 0$  to 20 ms might be related to that. Electrical signal separation in a data acquisition system and suppression of multiple reflections are essential.

#### 4. Summary

We have been developing a new type of the two color laser interferometer with an optically pumped  $\text{CH}_3\text{OD}$  laser which provides two laser lines simultaneously oscillating at 57.2 and 47.6  $\mu\text{m}$ . Excellent features of the new type of two color interferometer system in comparison to the conventional two color interferometer system are as follows: (i) the wavelength of around 50  $\mu\text{m}$  is considered to be appropriate value to avoid refractive effects and to provide enough signal to noise ratio for the expected phase

shift in high density operation of LHD and in future fusion devices, (ii) the optical system to construct the interferometer is much simpler, (iii) no additional laser instrument is needed to compensate the fringe shift due to mechanical vibrations, (iv) both laser beams pass through the same optical path in the interferometer without any optical path difference and are simultaneously detected by one detector. Fundamental function of the system for vibration compensation was confirmed in the test stand. Another type of a diagnostic for electron density, a Cotton-Mouton polarimeter with a 337  $\mu\text{m}$  HCN laser was developed and applied on CHS. The measured density is found to be almost consistent with that measured by an interferometer, and its robust diagnosis was confirmed.

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