Recent Progress in Two-Color Laser Diagnostics

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Abstract. This paper describes an innovative laser diagnostic instrument, a two color FIR laser interferometer/polarimeter, under development at the National Institute for Fusion Science, aiming for the establishment of reliable electron density/current density profile measurement techniques in the next step magnetically confined fusion devices such as ITER. In the process of searching for new laser oscillation lines, we have successfully achieved the powerful laser lines simultaneously oscillating at 57.2 and 47.7 μm, which lead to the construction of a new type of two color laser interferometer. So far we have been developing a two color laser interferometer, and confirmed its original function, vibration subtraction, in a test stand. In this conference, development of laser diagnostics which is a combined system of a two color laser interferometer and a polarimeter including hardware development necessary for future fusion devices will be presented.

1. Introduction
Measurements of the refractive index of plasmas by using electromagnetic waves are a well-established technique for measuring electron density profiles in high temperature plasmas. In the present large fusion devices such as JET, JT-60U and LHD, far-infrared (FIR) laser diagnostics have widely been used for density profile measurement. The wavelength of the FIR lasers used in these devices is around 100 to 200 μm, which is optimized from the viewpoints of the plasma refraction and mechanical vibration effects for target plasmas. Recent progress in particle fuelling technique combined with particle pumping system makes it possible to produce high density plasmas [1] of more than 10²¹ m⁻³ in the Large Helical Device (LHD). In these high density plasmas, a steep density gradient is formed leading to the fringe jumps on the density traces measured by FIR laser interferometers. To overcome this problem we have been developing short wavelength FIR laser diagnostics around 50 μm, and achieved a powerful 57.2 μm CH₃OD laser [2] pumped by a continuous wave 9R(8) CO₂ laser. After that, by optimizing lasing conditions we have successfully achieved high power two color laser oscillations [3] at 57.2 and 47.7 μm. The total output power is over 2.4 W, which is the highest cw laser output power in the far-infrared wavelength regime. This new two color laser oscillations enabled us to develop a new two color FIR laser interferometer [4], which has several benefits compared with conventional two color FIR laser interferometers as follows: (i) low refractive effects in high-density plasma; (ii) no additional laser interferometer for vibration compensation; (iii) no optical path difference between two color laser interferometers; (iv) one detector simultaneously
detects the beat signals of two color laser oscillation lines. We already demonstrated [5,6] usefulness of this two color laser diagnostic for mechanical vibration compensation in a test stand.

For application to an ITER laser diagnostic, a poloidal polarimeter for current density profile measurement, we have been developing a polarimeter with silicon photo-elastic modulators (PEMs) for the 57.2 and 47.7 μm laser. Since there were no PEMs for the FIR wavelength range so far, a new PEM for the wavelengths was developed [7] with HINDS instruments. Good linearity between actual and evaluated polarization angles is achieved with an angular resolution of 0.01 (0.025) degrees and a temporal resolution of 1 (0.1) ms [8], which satisfy requirements from ITER. In this symposium, recent progress in the development of two color laser diagnostics will be presented.

2. Optimization of laser wavelength

For future large fusion devices such as ITER, a poloidal polarimeter system [9] is being designed for measuring the current density profile. A 118.8-μm CH3OH laser has been proposed as a probing light source for the polarimeter, since the 118.8-μm CH3OH laser line was the shortest far infrared laser oscillation line with the highest power. But in this case the beam bending effect due to plasma density gradient is large. If we consider shorter wavelength lines, the next candidate is the 10.6-μm CO2 laser line. In this case, the Faraday rotation angle is less than one degree for a typical poloidal chord on ITER. When a linearly polarized electromagnetic wave, whose electric field vector is parallel to the toroidal magnetic field, transverses a poloidal plasma cross section perpendicular to the plasma current, the phase of the wave is changed by φ and its plane of polarization rotates by angle Ω due to the plasma as follows:

\[
\phi[\text{rad}] = 2.82 \times 10^{-15} \frac{\lambda}{[\text{m}]} \int n_e(z) \left[ \text{m}^{-3} \right] dz \\
\Omega[\text{rad}] = 2.62 \times 10^{-13} \frac{\lambda}{[\text{m}]} \int n_e(z) \left[ \text{m}^{-3} \right] B_i \left[ \text{T} \right] dz
\]

where \( \lambda \) is the wavelength of probing laser light, \( n_e \) is the electron density, \( B_i \) is the component of the poloidal magnetic field parallel to the laser light. In order to obtain the current density profile from the values of \( \Omega \), the electron density profile should be measured by the interferometry or by using the Cotton-Mouton effect. The ellipticity \( \epsilon \) due to the Cotton-Mouton effect is given by

\[
\epsilon[\text{rad}] = 2.45 \times 10^{-11} \frac{\lambda}{[\text{m}]} \int n_e(z) \left[ \text{m}^{-3} \right] B_i \left[ \text{T} \right]^2 dz
\]

![Figure 1. Optimum wavelength of (a) interferometer, (b) polarimeter for ITER scale device](image-url)
The upper and lower limits of the optimum wavelength for an interferometer are determined by beam refraction and conditions of signal to noise ratio (S/N) of phase measurement, respectively. Figure 1 (a) shows the optimum wavelength space in the case of ITER scale device: optical path length in a plasma \( L = 4 \text{ m} \), \( n_e = n_0(1-\rho^2) = 1 \times 10^{20} (1-\rho^2) \text{ m}^{-3} \), changes in the optical path length by mechanical vibrations \( \Delta l = 1 \mu\text{m} \). It is supposed that the S/N is larger than 100 and beam displacement \( \Delta d \) due to the refraction in the plasma is less than the beam radius. On the other hand, optimum wavelength for a polarimeter is determined by the condition to suppress the Cotton-Mouton effect and S/N of measurement of the Faraday rotation angle. Figure 1(b) shows the optimum wavelength space, supposing that the uniform electron density of \( 1 \times 10^{20} \text{ m}^{-3} \) and the uniform perpendicular and parallel magnetic field \( B_\perp, B_\parallel \) are 5 and 0.5 T. Here, the Cotton-Mouton effect is less than 0.1 rad. and the S/N of the Faraday rotation angle is larger than 100; the angle resolution is 0.01 deg. From these two figures, the applicable density range of \( 50 \mu\text{m} \) is widest among wavelengths of 10.6, 50, and 119 \( \mu\text{m} \).

3. Combined system of interferometry/polarimetry

So far, we have been developing interferometry and polarimetry independently, and confirmed that the both diagnostics satisfy ITER diagnostics requirements [9]. The achieved angular resolution of the polarimeter is 0.01 degrees with a time constant of 1 ms [8]. Then, the system is being upgraded to the simultaneous measurements of a phase shift and a rotation angle. One of the key issues for simultaneous measurements is the development of a high quality filter to select one wavelength for polarimetry. Then, we have developed a Fabry-Perot filter operating in THz wavelength regime. Figure 2 shows a constructed tunable Fabry-Perot filter (a) and its power transmittance (b) as a function of cavity length. A metal mesh was applied as a reflector. The number of mesh wires is 1000/inch, and a wire width is 7.37 \( \mu\text{m} \) with the thickness of 5 \( \mu\text{m} \). The calculated value of reflectance is 82 \% and the measured one is 86 \%.

![Figure 2. (a) Fabry-Perot filter (b) Power transmittance as a function of a cavity length. Horizontal scale is measured from the initial position of the reflector.](image)

In the polarimeter part, one wavelength has to be selected for the detection of a rotation angle as is shown in Fig. 3(a). As a filter to select one wavelength, a Fabry-Perot interferometer filter is used. Figure 3 (b) shows an effect of the usage of the Fabry-Perot interferometer filter on the angle resolution. Compared with that in the case that 57.2 \( \mu\text{m} \) is selected with a polarizer, the angle resolution slightly deteriorates although the required resolution from \( q \)-profile measurement in ITER is still satisfied. The deterioration is due to contamination of other wavelength, 47.7 \( \mu\text{m} \), whose added...
optical retardation by the PEM is different. This would be improved by optimization of the Fabry-Perot interferometer filter, since larger cavity length would provide good elimination of unwanted component. In the real application to ITER diagnostics, we need to take into account the Faraday effect on the laser beam propagating through the vacuum windows. The rotation angle of $\theta$ is proportional to the beam path $l_w$ through the window and to the magnetic field strength parallel to the beam propagation at the window $H$, that is $\theta = V l_w H$, where the constant $V$ is well known as the Verdet constant. By the use of the two color polarimeter, the Faraday rotation component at the vacuum window is expected to be eliminated [10].

![Figure 3](image-url)  
**Figure 3.** (a) a polarimeter part of the optical system, (b) angular resolution with and without the Fabry-Perot interferometer.

### 4. Summary

We have been developing a two color laser interferometer/polarimeter using developed two color laser oscillation lines at 57.2 $\mu$m and at 47.7 $\mu$m. Laser oscillation lines around 50 $\mu$m are found to be optimum for the large fusion devices such as the ITER considering beam bending effect and expected signal to noise ratio for phase shift and Faraday rotation measurements. We found that both laser diagnostics, interferometry and polarimetry, satisfy the ITER diagnostics requirements. The achieved angular resolution is 0.01 degrees with the time constant of 1 ms.

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