Polarization Measurement Techniques Suitable for ITER Poloidal Polarimeter

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ITER poloidal polarimeter (PoPola) will be installed into ITER in order to measure current profile. Laser wavelength of PoPola is 119 μm. PoPola measures both Faraday effect and Cotton-Mouton (CM) effects and reconstructs current profile from polarimetric data [1]. Design needs to maximize reliability, availability, maintainability and inspectability, satisfying the measurement requirement of current profile[2]. This study compares a rotating quarter-wave plate method and other methods working on existing experimental fusion devices from such a view point. The other methods to be compared are as follows; a dual PEM (photo-elastic modulator) method (JT-60U), the Dodel-Kunz (DK) method (MST, C-Mod, NSTX, LHD) and JET polari-interferometer method (JET, ToreSupra). Fig. 1 summarises all measurement techniques to be discussed in this study. As a result, the most promising technique is rotating waveplate method. The concerns and challenges of each technique are as follow.

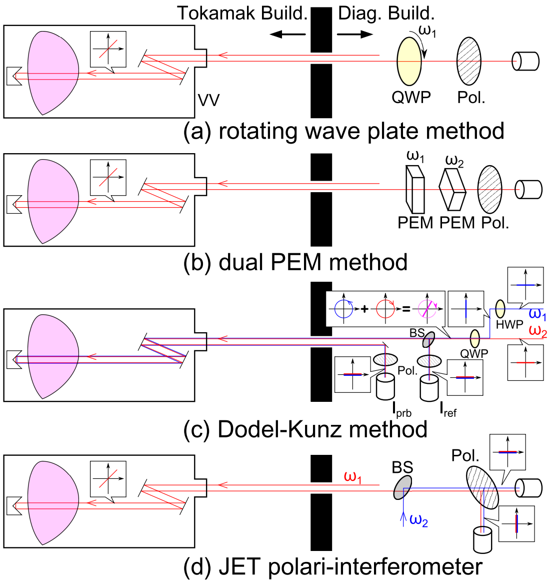

Figure 1: *Overview of techniques measuring polarization state. VV, HWP, Pol and BS denote vacuum vessel, half waveplate, polarizer and beam splitter, respectively.*

Rotating Waveplate Method

The rotating waveplate method is a well-known fundamental method for measuring polarization state, while this method has never been used in experimental fusion devices. A laser beam passes through a rotating quarter waveplate (QWP) followed by a horizontal linear polarizer before being passed to the detector. By using second and fourth harmonic components of detector signal, polarization state can be identified. Usually, this method has been applied to measure static polarization state. In order to apply this method to PoPola, the authors proposes that QWP is rotated by high speed motor (>10,000 rpm).

Experiments of rotating wave plate method under the following condition were carried out by using FIR laser in Chubu university [3] for the first time; the light source is Far-infrared (FIR) of 119 μm wavelength and QWP was rotated fast and continuously. Hollow shaft motor with 10,000 rpm ($= \omega_1$) was used. That is to say, time resolution of measuring polarization state is 6 ms and smaller than ITER measurement requirements of current profile, 10 ms[2]. The result of the experiment was that systematic and random error of polarization angle were a few degrees and approximately 0.5 degrees, respectively. The obtained systematic error was not problem because it can be calibrated. On the other hand, obtained random error was not preferable. The origin of the random error is axial run-out with same frequency of $2\omega_1$ and $4\omega_1$.

Now the authors plan a new configuration of the rotating waveplate method. Laser passes through rotating waveplate from surface and rear face twice. The new configuration can reduce the axial run-out effect because polarization state can be identified by sixth and eighth harmonic components.

Dual PEM Method

A laser beam passes through two PEMs and polarizer to reach the detector. Fundamental and second harmonic components of detector signal provide polarization state. Commercial PEM designed for 57 μm light exits (HINDS, II/SI-40 and II/SI-50), while that for 119 μm does not. Hereafter, let 57μm-PEM denotes PEM designed for 57μm light.

First, this study identified characteristics of 57μm-PEM by using the above-mentioned FIR laser. Transmittance of 57μm-PEM for 119 μm was 80 %. Retardation of 57μm-PEM for 119 μm was 70 % of that for 57 μm ($0.7 \times 0.5\pi$ at maximum). Next, polarization measurement using 119 μm laser and 57μm-PEM were carried out. The measured polarization states were far from true values because anti reflection (AR) coating was not optimized for 119 μm and modulated interference effects in PEM [4, 5] makes it difficult to measure elliptic polarization state.

AR coating needs to be optimized for 119 μm to measure linear polarization. However, even if AR coating is optimized, it is difficult to measure elliptic polarization because the modulated interference effect of fundamental and second-harmonic component cannot be simultaneously eliminated [6].

DK Method

The DK method measures phase shift between co-aligned left-handed and right-handed circularly polarized light (LHC and RHC). The phase shift is measured by the phase shift between

$\Delta\omega(=\omega_1-\omega_2)$ component of $I_{\rm prb}$ and $I_{\rm ref}$. Here, ω_1 and ω_2 denote frequency of LHC and RHC, respectively, and $I_{\rm prb}$ and $I_{\rm ref}$ denote detector signal of probing and reference beam, respectively. There is discussion that the DK method is suitable for ITER PoPola because signal of the DK method represents pure Faraday rotation (FR) even if CM effect is not negligible [7, 8]. This study confirms whether the DK method is suitable for PoPola or not.

Under assumption used by conventional the DK method, polarization coefficient α is supposed to be -1. Here, $\alpha = V-\sqrt{1+V^2}$, $V=\omega\omega_c\sin^2\theta/\{2(\omega^2-\omega_p^2)\cos\theta\}$, ω_c is electron gyro frequency, ω_p is electron plasma frequency, $\theta=\tan^{-1}(B_\perp/B_\parallel)$, and $B_{\perp(\parallel)}$ is magnetic field perpendicular (parallel) to laser propagation direction. Detector signals are given by $I_{\rm ref}=E_{R0}^2+E_{L0}^2+2E_{R0}E_{L0}\cos\Delta\omega t$ and $I_{\rm prb}=E_{R0}^2+E_{L0}^2+2E_{R0}E_{L0}\cos(\Delta\omega t-\varphi)$ where $E_{R0/L0}$ denotes amplitude of electric field of RHC/LHC. The phase shift between $I_{\rm prb}$ and $I_{\rm ref}$ is given by $\varphi=(e^3\lambda^2n_eB_\parallel\Delta z)/(4\pi^2\varepsilon_0 n_e c^3)$, which is FR.

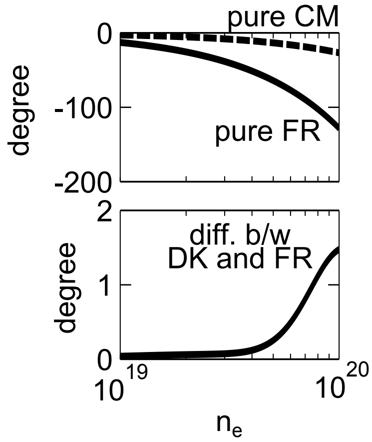

Figure 2: *pure FR, pure CM effect and difference between DK-method signal and pure FR as a function of n_e. Value of α was approximately* -0.9.

Assuming that Faraday effect is dominant and finite CM effect exits, the authors introduced φ and $I_{\rm prb}$ for the first time. The assumption of $\alpha\sim 1$ leads to

$$\varphi=\frac{e^3\lambda^2n_e}{4\pi^2\varepsilon_0n_ec^3}\left(\frac{e\lambda B_\perp^2}{4\pi m_ec}-\alpha B_\parallel\right)\Delta z, \qquad (1)$$

$$(\Delta\omega \text{ component of } I_{\rm prb})=2E_{R0}E_{L0}\left\{\cos(\Delta\omega t-\varphi)(1+\alpha)^2\sin^2\frac{\varphi}{2}\cos\Delta\omega t\right\}. \qquad (2)$$

Since the second order term of $(1+\alpha)$ is negligible, phase difference between $I_{\rm ref}$ and $I_{\rm prb}$ is given by φ again. However, φ does not represents pure FR.

Numerical experiments in $\alpha \not\approx -1$ were carried out. Differences between measurement data given by the DK method and pure FR components were compared. The DK-method signal was calculated by Jones matrix [9]. Calculation conditions were as follows; B_x was 0 T, B_y was 5.3 T (relevant to ITER), B_z was 1.5 T ($\approx \mu_0I_p/2\pi a$, $I_p=15$ MA, $a=2$ m and relevant to ITER). Magnetic field profile B_z along the laser propagation direction, z, were uniform. Fig. 2 shows pure FR, pure Cotton-Mouton effect and difference between the DK-method signal and pure FR as a function of electron density, n_e. Differences are order of one degree in ITER-relevant condition.

Both theoretical and numerical studies show that the coupling of the Faraday and CM effect cannot be cancelled in the DK method. Since the DK method is affected by the coupling, it cannot be concluded that the DK method is particularly more suitable than other methods.

JET Polari-Interferometer Method

The JET polari-interferometer method measures intensity and phase of E_x and E_y by using interferometer. Utilizing interferometer signal requires (1) high frequency stabilization of laser, (2) no sidebands of laser, (3) high accurate alignment of two beam, (4) compensation of mechanical vibration, and (5) less-distorted wavefront. The requirements (1) and (2) give rise to concerns on maintainability. This is because high quality laser is necessary. Uncertainty of future maintenance service and availability of special components are unknown, and maintenance frequency is high. The concerns on maintainability is common to all interferometric method (i.e. the DK method and the JET polari-interferometer method). The requirements (4) and (5) give rise to concerns on practice of real ITER. Since we need to complete fabrication of the system before plasma experiments, we will make many assumptions about mirror deformation and machine vibration in order to apply the JET polari-interferometer method to PoPola. Thus, application of the JET polari-interferometer method seems difficult at the present.

Maintainability of Mechanical Components

Finally, the authors briefly discuss maintainability of mechanical components. Although the rotating waveplate method and the dual PEM method has less concern about laser maintainability than interferometric methods, there is a concern about mechanical components. Features of the rotating waveplate method are as follows; motor lifetime is larger than 1500 h (=10,800 shot $\times$ 500 s) and several companies deal with high speed motor. Features of the dual PEM method are as follows; PEM lifetime (i.e. piezo lifetime) is unknown and only one company deals with PEM for FIR. Maintainability of the rotating waveplate method is higher than that of the dual PEM method.

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