Development of a Safety-Factor Profile Identification Method for Assessing Measurement Accuracy of the ITER Poloidal Polarimeter

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1. Introduction

The ITER poloidal polarimeter measures a change in a polarization state of linearly polarized far-infrared laser light ($\lambda = 118\ \mu$m) which is caused by the Faraday and Cotton-Mouton (CM) effects and will be utilized in order to identify a safety factor (q) profile. Although a requirement for accuracy of q has been defined as 10 % in ITER[1, 2, 3], accuracy needed for the polarimeter has not been given. A previous study on the q-profile identification has not dealt with this problem.[4] A purpose of this study is to assess the necessary measurement accuracy of the polarimeter.

In this study, we have developed a new method for identifying the q-profile from the polarimetric measurement data and other data whose accuracy are determined in ITER. The created program code is called CUPID (CUrrent Profile IDentification).[5] Conventional methods for the q-profile identification usually require data from magnetic diagnostics (poloidal magnetic field and poloidal flux on a vacuum vessel).[6] However, the accuracy of the magnetic diagnostics have not been given in ITER[1, 2, 3]. CUPID uses not the magnetic data but a location and shape of the last closed flux surface (LCFS), whose required accuracy is defined from the gaps between the plasma and the first wall panels in ITER. Assuming that the location and shape of LCFS is already determined within the required accuracy, CUPID identifies the q-profile to satisfy the measurement data: the polarization state of the probing laser beam measured by the poloidal polarimeter, the location and shape of LCFS, A, the total plasma current, I_p, the radial profiles of electron density, $n_e(R)$, and temperature $T_e(R)$. The respective accuracy of these measurement data [1, 2, 3] except for the polarimeter are included in CUPID. We show a relation between the accuracy of the polarimeter and q-profile identification.[5]

2. q-Profile Identification Method

CUPID expresses toroidal current density, j_ϕ, as a function of the poloidal magnetic flux, ψ;

$$j_\phi(\psi) = a\left(R + \frac{b}{R}\right)\bar{\psi}\left\{\left(1 - \sum_{i=1}^{N_G} c_i\right) + \sum_{i=1}^{N_G} c_i \bar{\psi}^i\right\}, \tag{1}$$

where $\bar{\psi}$ is a normalized poloidal flux defined by $(\psi - \psi_{\mathrm{edge}})/(\psi_{\mathrm{ax}} - \psi_{\mathrm{edge}})$, and $\psi_{\mathrm{edge}}/\psi_{\mathrm{ax}}$ is the poloidal flux of the magnetic axis/separatorix. Using this expression of j_ϕ, CUPID solves

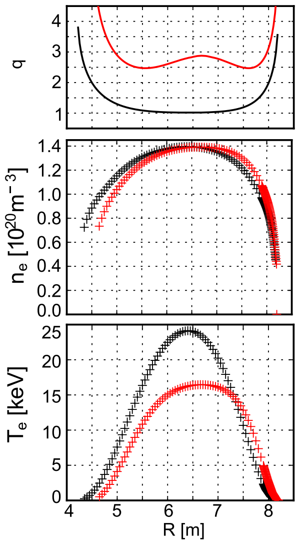

Figure 1: q-profiles (upper column), n_e-profiles (middle column) and T_e-profiles (lower column) of S2 (black) and S4 (red) calculated by TOSCA

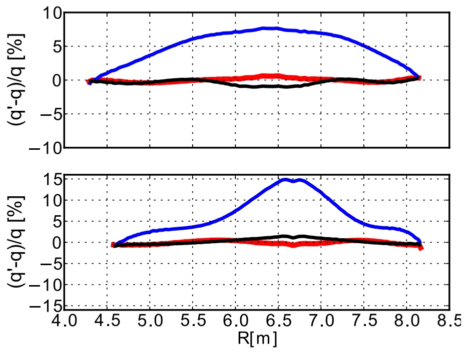

Figure 2: Profiles of q-identification error (q: true value, q': estimated value) in S2 (upper) and S4 (lower). All cases assume that the input data have no error. The red lines show the results of CUPID using $\vec{\Omega}^r$, θ and ε. The black lines show the results of CUPID using $\vec{\Omega}^r$ and θ. The blue lines show the results using $\vec{\Omega}^c$, θ and ε.

the Grad-Shafranov (GS) equation to obtain ψ.

The coefficients of j_ϕ (a, b and c_i) are determined by the least-squares method, especially the Marquardt method, in order to satisfy the measurement data. The quantity χ^2 of the Marquardt method is defined as: $\chi^2 = \sum_i \left(\theta^G - \theta^E\right)^2/\sigma_{\theta i}^2 + \sum_i \left(\varepsilon^G - \varepsilon^E\right)^2/\sigma_{\chi i}^2$, where θ and ε denote the orientation angle and the ellipticity angle of the polarization state, respectively, suffix G and E denote a given value and a estimated value, respectively, and σ denotes an error associated with the measurement. The input data except for θ^G and ε^G include errors assumed in ITER; the errors of A, I_p, $n_e(R)$ and $T_e(R)$ are ± 5 mm, ± 5 kA, ± 5 % and ± 2.5 %, respectively. The electron density and temperature are expressed as a polynominal function of ψ, and $n_e(\psi)$ and $T_e(\psi)$ are fitted to $n_e(R)$ and $T_e(R)$, respectively. The cost function of the least-squares method, χ^2, does not include these quantities (A, I_p, $n_e(R)$ and $T_e(R)$). Since χ^2 is written by the data of the polarimeter, our scheme is suitable for discussing the relation between the error of q-profile and the measurement accuracy of the poloidal polarimeter.

3. Input Data

CUPID was applied to an inductive operation scenario II (S2), and a non-inductive operation scenario IV (S4)[7]. Figure 1 shows the q-, n_e- and T_e-profiles at a start of a burn phase of S2 and S4 calculated by TOSCA. In this figure, the spacial resolution of '+' marks in the n_e- and T_e-profiles consists with the spacial resolution of Thomson scattering diagnostics in ITER.

4. Evaluation of Relativistic and Cotton-Mouton Effect

Relativistic Effect: The change in the polarization state of the probing laser beam is expressed by the Stokes equation, $d\vec{s}/dz = \vec{\Omega}(z) \times \vec{s}(z)$, where z is a direction of light travel, $\vec{s}$ is a reduced Stokes vector and $\vec{\Omega}$ is a vector representing the optical properties of plasma.[8] When T_e is high, $\vec{\Omega}$ is expressed as $\vec{\Omega}^r \approx \vec{\Omega}^c + T_e/m_e c^2 \left(9/2\Omega_1^c,\ 9/2\Omega_2^c,\ -2\Omega_3^c\right)$ where $\vec{\Omega}^c$ denotes $\vec{\Omega}$ for cold plasma [8] and the second term of the right hand side denotes the relativistic effect.[9]

We evaluate influence of the relativistic effect on the q-profile identification. Assuming that the input data have no error and the input data of θ and ε are calculated by $\vec{\Omega}^r$, we calculated two cases; CUPID using $\vec{\Omega}^r$ and CUPID using $\vec{\Omega}^c$. Viewing chords are illustrated in fig. 3(a), and the wavelength of the probing laser beam was 118 μm. Figure 2 shows the results of two cases. The red lines and the blue lines show the results using $\vec{\Omega}^r$ and $\vec{\Omega}^c$, respectively. The errors with $\vec{\Omega}^c$ exceeded 7.7 % and 15 % in S2 and S4, respectively. Therefore, $T_e(R)$ is used as input data to take into account the relativistic effect.

Cotton-Mouton Effect: In high electron density plasma like ITER, the Faraday and CM effects couple to affect the polarization state. We compared the q-profile identification results using data of both θ (mainly the Faraday effect) and ε (mainly the and CM effect) and using data of θ only, and show the results in fig. 2. The red lines show the results using θ and ε, and the black lines show the results using θ. In the both cases of S2 and S4, the results using θ and ε are better than those using θ. Using ε reduces the error by approximately 0.5 %. Therefore, we use both θ and ε as the input data of CUPID in order to identify the q-profile more accurately.

5. Assessment of Measurement Accuracy of ITER Poloidal Polarimeter

We conservatively supposed $(0.5^\circ,\ 3^\circ)$ and $(1^\circ,\ 6^\circ)$ as the accuracy of the orientation angle and the ellipticity angle, $(\Delta\theta,\ \Delta\varepsilon)$. These accuracies are lower than those for far-infrared laser polarimeters in several tokamaks. We used CUPID to calculate the q-profiles 10 times varying the random error of θ, ε, A, I_p, n_e and T_e within each measurement accuracy and evaluated whether or not q-profile identification error satisfied the measurement requirement (± 5 %) in 10 times tests. Figure 3 shows the viewing chords and the radial profiles of the q-identification error which are the first demonstration of the relation between the q-identification error and the accuracy of the polarimeter. The necessary accuracy of the ITER poloidal polarimeter in the criteria of this study was $(\Delta\theta,\ \Delta\varepsilon) \leq (0.5^\circ,\ 3^\circ)$.

6. Discussion

The q-profile identification using a motional Stark effect and during the plasma startup and rampdown phases are next scopes.

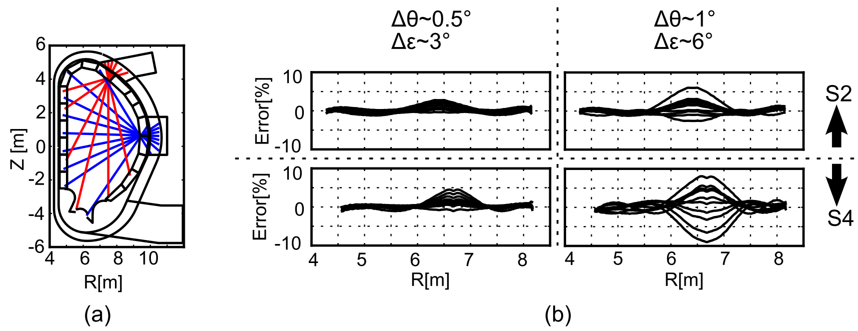

Figure 3: (a) Viewing chords and (b) the radial profile of q-identification error with $\lambda = 118\ \mu$m. The upper and lower column of (b) shows the results with S2 and S4, respectively. The left and right row of (b) show the results with $(\Delta\theta,\ \Delta\varepsilon) = (0.5^\circ,\ 3^\circ)$ and $(1^\circ,\ 6^\circ)$, respectively.

7. Conclusions

We have developed CUPID in order to assess the necessary measurement accuracy of the poloidal polarimeter under the condition that A, I_p, $n_e(R)$ and $T_e(R)$ satisfy the measurement requirements in ITER. Assuming that all measurement data have no error, we have evaluated the need for $T_e(R)$ and ε in order to identify q-profile more accurately. First, we have shown that $T_e(R)$ is important for the q-profile identification because the relativistic effect on the change in the polarization state has not been negligible in ITER. When the relativistic effect has not been included in the q-profile identification, the errors of the q-profile identification have exceeded 7.7 % and 15 % in S2 and S4, respectively. Next, it has been demonstrated for the first time that the accuracy of the q-profile identification using both θ (mainly the Faraday rotation) and ε (mainly the CM effect) has been better than that using only θ. Using ε has reduced the q-identification error by approximately 0.5 %. Finally, we have demonstrated the relation between q-identification error and $(\Delta\theta, \Delta\varepsilon)$, including errors of A, I_p, $n_e(R)$ and $T_e(R)$. The necessary accuracy of the ITER poloidal polarimeter in the criteria of this study was $(\Delta\theta,\ \Delta\varepsilon) \leq (0.5^\circ,\ 3^\circ)$.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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