5aB02

Equilibrium Reconstruction of Burning Plasma Utilizing Laser Polarimetry
レーザー偏光法を用いた核燃焼プラズマの平衡再構築に関する研究

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1. Introduction

Information of a plasma current profile (or equivalently, a safety factor, q, profile) is essential for controlling and understanding magnetohydrodynamic (MHD) activity. In ITER, information of locations of $q = 1.5$ and 2 will be utilized for a real-time control of neo-classical tearing mode (NTM) suppression, and information of locations of minimum q will be utilized for a real-time control of a reverse shear profile. In order to obtain the information, a poloidal polarimeter and a motional Stark effect diagnostics will be installed in ITER. We have developed a design of ITER poloidal polarimeter [1-4], and this paper reviews the recent new knowledge obtained in the development.

A poloidal polarimeter is utilized in magnetic confinement fusion devices, e.g. JT-60, JET, TFTR, TEXTOR, ToreSupra, C-Mod, etc. When a linearly-polarized electromagnetic wave passes through magnetized plasma, the polarization state rotates owing to the Faraday effect. The rotation angle is proportional to $\int n_\mathrm{e} B_\parallel \mathrm{d}Z$, where n_e, $B_\parallel$ and Z denote an electron density, a component of a magnetic field parallel to a probing laser, and the direction of the laser, respectively. A plasma current profile can be obtained by reconstruction of $B_\parallel$ utilizing multi viewing chords of the poloidal polarimeter and data of other n_e measurements.

Differences between polarimetry for ITER-like burning plasmas and the existing tokamak plasmas are (1) the coupling between the Faraday and the Cotton-Mouton effect and (2) a relativistic effect. The Cotton-Mouton effect changes a linear polarization to an elliptic polarization. The coupling was neglected in the existing polarimeter. However, since the density will be high and the plasma size will be large, the coupling will not be negligible in the ITER-like burning plasmas. When the coupling is not negligible, the rotation angle becomes complicated not to be proportional to $\int n_\mathrm{e} B_\parallel \mathrm{d}Z$. The relativistic effect is caused by breakdown of the cold plasma dispersion relation owing to a high electron temperature of the burning plasma. Owing to the relativistic effect, a change of polarization state depends not only a magnetic field, B, and n_e but also an electron temperature, T_e. Whether an accurate reconstruction of the current profile under such complex conditions of the burning plasmas is possible or not has been an open question.

We have demonstrated for the first time that the accurate reconstruction is possible even when the coupling and the relativistic effect are not negligible [1]. Moreover, we have demonstrated for the first time that it is possible to reconstruct not only B-profile but also n_e-profile and T_e-profile from a polarimeter [5]. This paper presents the details of these results.

The reconstruction carried out in the above results has supposed plasma to be in stationary equilibrium. This paper presents a new method for solving the equilibrium.

2. Equilibrium Reconstruction Utilizing Faraday and Cotton-Mouton Effects

We have developed a reconstruction code CUPID (CUrrent Profile IDentification), which includes the coupling and the relativistic effect. CUPID code determines coefficients of a function representing a toroidal current density in a manner consistent with the measurement data of a poloidal polarimeter. The polarimeter provides an orientation angle (θ) and an ellipticity angle (ϵ) of the polarization state. The change of θ and ϵ are mainly related to the Faraday and the Cotton-Mouton effect, respectively. Under the process of the reconstruction, the two-dimensional profile of n_e and T_e are obtained by mapping measurement data of Thomson scattering diagnostics to surfaces of equal poloidal fluxes. Unlike other reconstruction codes utilizing kinetic information (e.g. EFIT, EQUINOX, etc.), only the coefficients of the toroidal current density are the fitting parameters. Thus, it is not necessary to adjust weights for the data of the polarimeter and the kinetic information.

CUPID code has shown that (1) neglecting the relativistic effect causes a significant error of the current profile reconstruction, (2) an accurate reconstruction including the coupling and the relativistic effect is possible, and (3) utilizing both θ and ϵ increases the accuracy of the reconstruction (while a conventional polarimeter measures only θ for the reconstruction).

3. Equilibrium and Kinetic Reconstruction from Laser Polarimetry

The relativistic effect degrades the Faraday effect, while enhances the Cotton-Mouton effect [6]. Usually, the laser polarimetry is utilized under the condition that the Cotton-Mouton effect is small and measures only the Faraday effect. However, we have proposed the polarimeter using long wavelength in order to obtain the large Cotton-Mouton effect, and have proposed the reconstruction of T_e from the measurement data of the Faraday and the Cotton-Mouton effect (i.e. θ and ϵ). It is reasonably expected that the reconstruction is possible by utilizing the different dependencies of the both effects on T_e.

The above expectation has been tested under the condition of ITER poloidal polarimeter. Utilizing the measurement data of the polarimeter and information of a location of a plasma boundary, simultaneous reconstruction of B, n_e and T_e has been successfully demonstrated [5]. It should be noted that not only the reconstruction of T_e but also the simultaneous reconstruction of B and n_e is a novel achievement. By contrast, a conventional method reconstructed only B-profile from a polarimeter by utilizing data of other n_e measurements.

The total plasma current, I_p, can be calculated from the reconstructed B-profile. When the plasma boundary is detected by a method except of magnetics (e.g., reflectometer), our method can measure I_p by utilizing history-independent measurement data. Thus, our method is applicable to I_p measurement for a steady state operation.

Existing fusion experimental devices utilize many diagnostics. However, a future reactor needs to be operated by fewer diagnostics. This study suggests that the multi-parameter measurement utilizing the polarimeter is promising in the future reactor.

4. New Approach for Solving Equilibrium

When the reconstruction of the magnetic field is carried out, the boundary of the plasma can be fixed. This is because the boundary can be identified regardless of whether the plasma current profile is unknown or not. In the above studies, the Grad-Shafranov (GS) equation has been solved under the condition of the fixed boundary by utilizing a finite element method (FEM). In order to avoid difficulties of FEM (e.g. mesh problem, difficulty of coding, expensive calculation cost, etc.), we have proposed a new method to apply meshless methods, especially RBF-MFS and Kansa's method to inhomogeneous and nonlinear partial differential equations (PDE) [7]. Although the RBF-MFS and Kansa’s method are applicable to the inhomogeneous PDE, the application of these methods to the GS equation is not straight-forward. Since the current profile is usually parameterized by a normalized poloidal flux, the inhomogeneous term of the GS equation contains the normalized poloidal flux, not just a poloidal flux. This is a difficulty for solving the GS equation.

Accuracy and calculation time of the meshless method and FEM has been compared in a condition of a same total number of nodes. The results have shown that an error of a magnetic field obtained by the meshless methods is one hundredth of that by FEM and that a calculation time of the meshless method is one tenth of that of FEM. Moreover, calculation processes of the meshless methods can be easily accelerated by parallel computing.

5. Summary

We have shown that the accurate equilibrium reconstruction utilizing the polarimeter is possible even under the condition of ITER-like burning plasmas. Our studies suggest that the polarimeter is promising in the future reactor because it provides the multi parameters, i.e. B, n_e, T_e and I_p, simultaneously. Finally, we have proposed the new method to solve the GS equation with the fixed boundary, which is applicable to the equilibrium reconstruction utilizing the polarimeter and can solve GS equation more accurately and faster than FEM.

Acknowledgement

A part of this work was supported by JSPS KAKEN Grant Number 24740376.

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