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Real-time control of electron cyclotron wave polarization in the LHD

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ABSTRACT

Peripheral plasma with finite electron density gradients and finite magnetic shear is known to affect polarization of electron cyclotron (EC) waves. Calculation of the ratio between the ordinary (O) mode and the extraordinary (X) mode, integrated in the ray-tracing code developed for EC heated plasmas in the Large Helical Device (LHD), enables the search for the optimum EC wave polarization in order to excite the pure O/X mode at the EC resonance layer. The real-time control system of the incident polarization was developed for maximum single-pass absorption of EC waves, based on the dependence of optimum EC wave polarization on peripheral density profiles. The polarization control system is equipped with a fast field programmable gate array, which processes in real time the calculation of the peripheral electron density profile and the optimum EC wave polarization for motion control of the polarization rotator and the elliptical polarizer on the transmission line. The real-time control in LHD experiments functioned properly in maintaining the absorbed power of the EC wave higher than that without the control, demonstrating that the purer heating mode was successfully excited.

1. Introduction

In electron cyclotron resonance heating (ECRH) experiments on the Large Helical Device (LHD), attempts have been made to adjust the deposition location or the incident wave polarization of ECRH, which have contributed to obtaining high electron temperature plasmas and fulfilling demands from a physical point of view [1,2]. The post-processing ray-tracing calculation with the “LHDGauss” code after every discharge using ECRH provides not only the deposition location but also the ratio between the ordinary (O) mode and the extraordinary (X) mode of each electron cyclotron (EC) wave [3]. The distinctive feature of this code is that the O/X-mode ratio is calculated by solving the one-dimensional (1D) full-wave equation with a given polarization along propagation through the plasma peripheral region from each launching antenna to the EC resonance layer in the LHD. The feature clarified that the O/X-mode ratio is affected by the existence of finite electron density gradients and strong magnetic shear at the plasma peripheral region outside the last closed flux surface (LCFS) [4,5]. Thus, exciting the pure O mode or the pure X mode at the EC resonance layer requires optimization of the incident wave polarization depending on the peripheral plasma. The impact of a plasma peripheral region on pure excitation of the O/X mode as well as on refraction of rays is a common characteristic in magnetically confined plasmas with comparable scale lengths for the electron density gradients and change of the magnetic shear, such as in the stochastic region of LHD plasmas or in tokamak plasmas at the pedestal region or the SOL (scrape-off-layer). This effect is important in order for effective absorption of EC wave power and to prevent damage to inner vessel components from the undesired stray wave radiation.

As physical quantities such as the electron density evolve in time during a single discharge, the optimum incident polarization or the optimum launching direction for effective absorption of EC waves can change in time accordingly, although in most experiments those settings are fixed during a discharge. Trials of feedforward polarization control and real-time control of the deposition location of EC waves have been recently made during ECRH discharges at ASDEX Upgrade for their specific objectives [6,7]. The characteristic of the deposition location control is that fast beam-tracing calculations are performed in real time. In the LHD, experiments were carried out for feedforward polarization control [5], feedback steering mirror control [8], and feedback polarization control [9]. The electron temperature measured with the electron cyclotron emission (ECE) diagnostic was used as a reference signal for their feedback control. It is obvious, however, that only the changes of the deposition location or the polarization of EC waves do not always change the ECE temperature. For example, fueling or magnetohydrodynamic instabilities can change the ECE temperature.

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Even if launching parameters of the EC waves are reaching their optima, the ECE temperature can decrease due to other causes. The situation can give rise to an increased stray radiation level due to the launching parameters set away from their optima. Although power-modulation ECRH and resultant modulated ECE signals help to evaluate the accurate deposition location, fast estimation of the deposition location is necessary for real-time control purposes and losing ECRH power during modulation is an inefficient use of a gyrotron for steady-state operations.

An idea arises for achieving effective absorption of EC waves: an incident EC wave polarization can be optimized by real-time control using a reference data set regarding peripheral plasmas with different electron density profiles with the help of the recently upgraded ray-tracing code LHDGauss. This method is based on the power absorption model of EC waves, thereby contributing to future upgrades of the numerical model by comparison with experimental results and to more secure use of the ECRH system. This paper describes real-time control of the incident EC wave polarization using this method. Section 2 describes the real-time control system of the incident EC wave polarization. In Section 3, results on proof-of-principle experiments of the real-time control are presented and discussed. Section 4 summarizes this paper.

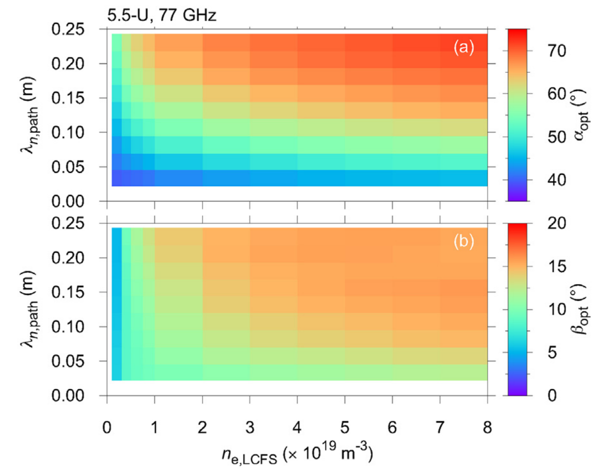

Fig. 1. Dependence of optimum incident EC wave polarization on peripheral density profile: (a) the optimum polarization rotation angle α_{opt} and (b) the optimum polarization ellipticity β_{opt} for different electron density $n_{e,LCFS}$ at the LCFS and the scale length for the density gradients $\lambda_{n,\text{path}}$ along the EC beam path.

2. Real-time control system of incident EC wave polarization

It is reported in incident polarization scan experiments using the 77 GHz EC wave launched from the 5.5-U (upper) port of the LHD that the polarization under the highest absorbed power obtained experimentally is in good agreement with that optimized in the mode content analysis with LHDGauss [3–5]. The fundamental O mode at 77 GHz is used for plasma heating under the standard magnetic field configuration of the magnetic axis of $R_{ax} = 3.6$ m and the magnetic field strength of $B_t = 2.75$ T. In order to excite the pure O mode at the EC resonance layer, the optimum incident EC wave polarization is calculated by solving the 1D full-wave equation along the inverse propagating direction, i.e., the direction from the right-handed wave (R) cutoff point to the launching antenna center, under the initial condition of the O-mode polarization. Taking into account the peripheral region outside the LCFS for the calculation results in good agreement with the experimental results.

Based on these results, the dependence of the optimum incident polarization on the electron density profile in the peripheral region outside the LCFS, as shown in Fig. 1, is adopted as a real-time control model of the incident polarization. In Fig. 1, the electron density profile outside the LCFS is modeled as an exponentially decaying function with $n_{e,LCFS}$ as the electron density at the LCFS and $\lambda_{n,\text{path}}$ as the scale length for the density gradients along the EC beam path. The polarization state is expressed with the polarization rotation angle α and the ellipticity β. Here, α is defined as the rotation angle to the axis, whose base vector is directed to $-\boldsymbol{k} \times (\boldsymbol{k} \times \boldsymbol{\varphi})$, which is almost the toroidal direction for launch from the 5.5-U port at the LHD. $\boldsymbol{k}$ and $\boldsymbol{\varphi}$ denote the wavenumber and the toroidal direction, respectively. (α_{opt}, β_{opt}) is the polarization state at the launching antenna center optimized to excite the pure O mode. The incident EC wave polarization can be adjusted during a discharge according to the dependence on those two parameters regarding the peripheral electron density profile in order for maximum single-pass absorption of the EC wave. This kind of dependence is generally applicable to other magnetic configurations, launcher locations, or gyrotron frequencies in magnetically confined fusion devices.

The multi-channel far-infrared (FIR) laser interferometer [10] is applicable to real-time diagnostics during long-pulse operations on the LHD, so that it is adopted to obtain the peripheral density profile in real time. Fig. 2 illustrates the developed real-time control system of the incident EC wave polarization. The real-time polarization control under real-time acquisition of the density profile is performed with real-time FPGA (field programmable gate array) processing, which is realized using a fast reliable hardware CompactRIO (cRIO) cRIO-9035 and its input/output modules made by National Instruments and its software through LabVIEW FPGA programming. The data set on the dependence of the optimum polarization on the peripheral density profile, as shown in Fig. 1, as well as the data set on the relationship between the optimum polarization and the rotation angles of the polarization rotator and the elliptical polarizer on the transmission line are saved into the FPGA memories in advance and referred to in real time. It is noted that there is not less than one combination of the rotation angles of the two polarizers in order to realize a polarization state [11]. Thus, the combination is selected so that the polarizers can rotate seamlessly during the real-time control. The maximum rotation speed of each polarizer is 200°/s. Each polarizer mirror is mounted on a rotating stage (Nikka Densok PF100-CHF-G1), whose worm gear ratio is 180:1. The stage is connected to a low-inertia servo motor and its amplifier (Panasonic MSME012G1N and MADHT1505), whose maximum rotation speed is 6000 rpm. Then the motor is connected to motion control modules NI 9512 and NI 9930P installed on cRIO and rotation of the two polarizers is smoothly and automatically controlled in real time without a control error through the LabVIEW SoftMotion Module.

Voltage signals equivalent to line-integrated electron density measured with the FIR laser interferometer are inputted into cRIO through a newly-made direct-current offset cancellation circuit. Since six channels are receivable by the circuit at present, the six channels of the FIR laser interferometer measured at major radii of R = 3.759, 3.849, 3.939, 4.029, 4.119, and 4.209 m are used to cover sufficiently the peripheral region of LHD plasmas. The core region of LHD plasmas are not fully covered but the selected area of the measurement is sufficient for experiments to realize optimum incident EC wave polarization because the ratio between the O mode and the X mode is determined during propagation on the peripheral region under the density range shown in Fig. 1. Abel inversion to the measured line-integrated electron density is implemented in FPGA as a simple matrix operation that is determined using the geometrical relationship between the observed radii and a plasma equilibrium [12], where the magnetic flux surfaces are approximated elliptic for simplicity because there is no method at present to calculate equilibria of LHD plasmas in real time. More accurate matrix operation is expected if the 3D equilibrium mapping [13] is possible in real time. The discrete electron density profile after the Abel inversion is fitted to a polynomial function with eighth even degree as is done for the electron density profile measured with the Thomson scattering diagnostics. The fitting is implemented in FPGA as the