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Recovery of Plasma Electron Temperature Profile from Electron Cyclotron Emission Diagnostics in Ohmic Heating Regime at the L-2M Stellarator

The technique of determining the electron temperature profile from the spectrum of electron cyclotron emission (ECE) at the second harmonic is widely used in experiments on plasma heating in toroidal magnetic traps. It is based on recovery of the plasma electron temperature profile from measurements of the spectral intensities of ECE of plasma electrons at different frequencies. The intensity of plasma ECE is usually characterized by the radiation temperature $T_{\mathrm{rad}}(\omega)$, which is related to the electron temperature $T_{\mathrm{e}}(r)$ as follows:

$$T_{\mathrm{rad}}(\omega) = Q\,T_{\mathrm{e}}(r_{\mathrm{res}})\ . \tag{1}$$

Here, $Q = 1 - \exp(-\tau)$ is the integral absorption coefficient, τ is the plasma optical thickness, and r_{res} is the radius where the electron cyclotron (EC) resonance conditions for the ω frequency are satisfied.

However, several limitations on the applicability of this method for measuring the electron temperature must be taken into account when interpreting the results of ECE measurements. First, as follows from formula (1), for insufficient optical thickness of the plasma, $\tau \leq 1$, the measured radiation temperature T_{rad} turns out to be lower than the plasma electron temperature T_{e}. In addition, at low magnetic field gradients, the region where the EC resonance conditions are satisfied may be rather broad, which can cause considerable errors in binding the measured temperature to a certain radius. Both of these disadvantages of ECE diagnostics considerably affect the results of measuring the electron temperature in the ohmic heating (OH) regime at the L-2M stellarator.

Experiments were performed at L-2M, a classical two-turn stellarator (number of helical windings $l = 2$, number of field periods along the torus $N = 7$) with major radius $R = 1$ m, plasma radius $a = 0.115$ m, and toroidal magnetic field $B_0 = 1.34$ T [1]. To obtain stable discharges with low radiation loss, the walls of the vacuum chamber were boronized [2]. Typical time evolution of the plasma parameters in the shot after boronization is shown in Fig. 1 (shot #64118).

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We recover the electron temperature profile from the radiation temperature profile measured by the electron cyclotron emission diagnostics in the Ohmic heating regime under conditions of the low integral plasma absorption coefficient, $Q < 1$. The Temperature profile is recovered using one frequency channel of the ECE diagnostics in one facility shot. 1

The Stellarator Path to an FPP—A Public & Private Endeavor

This mini-conference will be held at the 65th Annual Meeting of the APS Division of Plasma Physics in Denver, Colorado, October 30–November 3, 2023. 3

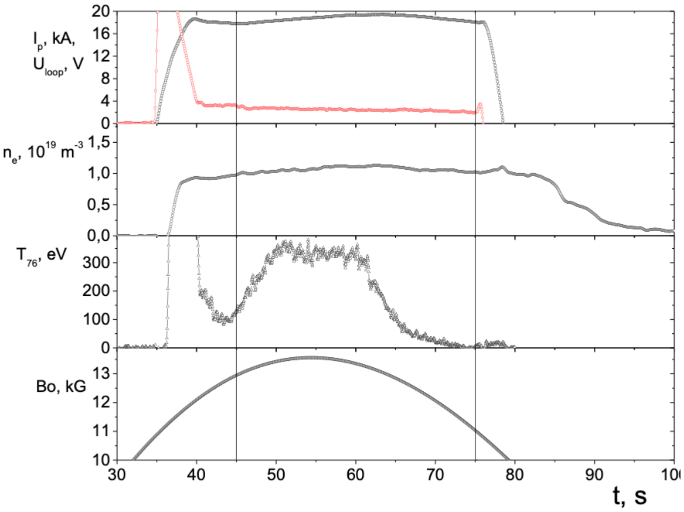

Fig. 1. Time evolution of basic plasma parameters in shot #64118. From top to bottom: plasma current I_p, loop voltage U_{loop}, electron density n_e, electron temperature T_e, and magnetic field B_0.

The figure shows that for 30–40 ms, such parameters as the electron density, plasma current, and loop voltage remain constant (within 10%) (i.e., the OH power is constant), as are the radiation losses, which, as a rule, do not exceed 25% of the heating power. Thus, it can be expected that the on-axis electron temperature and, probably, the electron temperature profile also remain constant during this time interval. The last statement will be experimentally confirmed below using the ECE diagnostics. At the same time, during the stationary discharge phase, the magnetic field amplitude changes considerably. In the shot shown in Fig. 1, in the time interval from 45 to 75 ms, the magnetic field first increases from 13 to 13.6 kG and then decreases to 11 kG. When the magnetic field changes, the region of EC resonance (for example, for the frequency of 76.5 GHz) first moves from the peripheral regions toward the plasma center and then back toward the plasma edge. In such stable shots with a long-lasting stationary phase, it becomes possible to measure the radiation temperature profile in one shot using the signal of one frequency channel.

For determining the radiation temperature profile in the OH shot, we select the ECE diagnostics channel with the frequency of 76.5 GHz, since when the magnetic field changes during the shot, the EC resonance region for this frequency moves crossing almost all magnetic surfaces of the L-2M stellarator. It is possible to correlate the ECE diagnostics signal with the magnetic field signal at each time point, using the data shown in Fig. 1. For each time point, the position of the resonance region for the frequency of the selected channel can be determined from the magnetic field amplitude, using the map of magnetic surfaces and lines of constant magnetic field for the L-2M stellarator. As a result, the ECE diagnostics signal turns out to be bound to the magnetic surface radius, from which the radiation comes to the detector, and it becomes possible to construct the radial profile of radiation temperature using the signal of one frequency channel (Fig. 2).

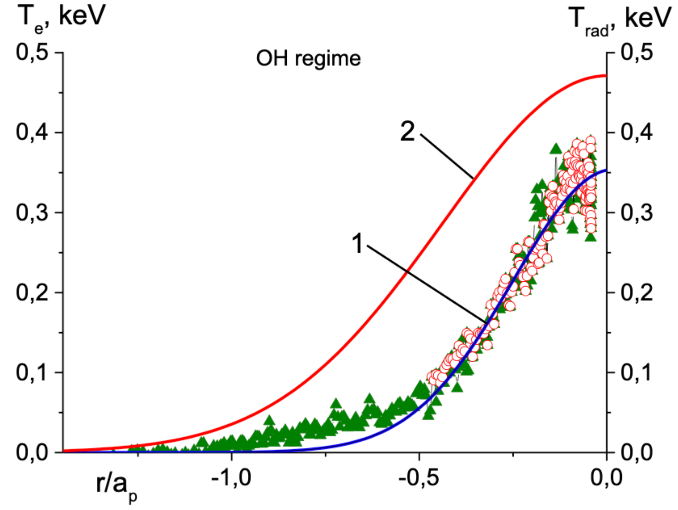

Fig. 2. Profiles of (1) radiation temperature corresponding to experimental data (circles and triangles) and (2) electron temperature recovered in shot #64118.

In Fig. 2, hollow red circles correspond to the first half of the shot (45–55 ms) (with increasing magnetic field), and green triangles correspond to the second half of the shot (55–75 ms) when the magnetic field decreases. The red and green icons lie along the same radiation temperature profile (curve 1), although they were measured during different time intervals. This occurs because the resonance magnetic field for a given frequency passes twice through the same plasma regions: first when the magnetic field increases, and again when the magnetic field decreases. This means that the electron temperature profile remains unchanged during this entire time interval.

To recover the electron temperature profile from the radiation temperature profile, it is necessary to perform simulations of the plasma ECE. In the simulations, we assume the electron energy distribution function to be Maxwellian. We use the plasma density profile close to that measured in the OH regime: $n_e(r) = n_0 [1 – (r/a_p)^4]$, and the on-axis electron temperature T_0 independently measured using the soft X-ray spectrometer. For the simulations, the electron temperature profile (curve 2 in Fig. 2) was chosen so that the calculated radiation temperature profile (curve 1 in Fig. 2) coincided with the experimental one (circles and triangles in Fig. 2). The differences in the radiation and electron temperature profiles and in the on-axis temperatures of these profiles are quite noticeable (approximately 30%). In the OH regime at the L-2M stellarator, the radiation temperature turns out to be considerably lower than the true electron temperature. In addition, the width of the radiation temperature profile turns out to be less than that of the true temperature profile. Therefore, it is impossible to obtain an accurate electron temperature profile by simply normalizing the radiation temperature profile to the on-axis electron temperature measured by the soft X-ray spectrometer.

Thus, in the OH regime at the L-2M stellarator, when the integral absorption coefficient is low ($Q < 1$) in the bulk of the plasma volume, it is necessary to use the proposed procedure for recovering the electron temperature profile from the data obtained from ECE diagnostics.

REFERENCES

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The Stellarator Path to an FPP—A Public & Private Endeavor

We are pleased to announce the mini-conference *The Stellarator Path to an FPP—A Public & Private Endeavor*, which will be held at the 65th Annual Meeting of the APS Division of Plasma Physics in Denver, Colorado, October 30–November 3, 2023.

Important plasma physics advances and key technological advancements are opening the way toward a stellarator fusion pilot plant (FPP). Public funding is continuing to support science, and a new influx of private funding is enabling stellarator design efforts. This mini-conference will host speakers and panelists from the public and private sectors. It will provide a forum to discuss scientific gaps and solutions, technological challenges and activities, and an evolving workspace. Theory, design optimization, and experiment issues that are independent of stellarator configuration will be considered. This conference aims to nurture collaboration between the public and private sectors and advance the goal of rapidly establishing the foundation for stellarator FPPs.

To speak at the mini-conference, submit an abstract to sorting category 11.02 before the July 14 deadline via https://engage.aps.org/dpp/meetings/annual-meeting

Mini-conference talks are contributed presentations (so do not submit through the invited speaker abstract portal). Mini-conference presenters are allowed one additional first author abstract submission in the regular annual meeting program.

Mini-Conference Organizers
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