Formation of flat electron density profiles at the L-2M stellarator at high ECRH powers

A I Meshcheryakov\textsuperscript{1,2}, I Yu Vafin\textsuperscript{1} and I A Grishina\textsuperscript{1}

\textsuperscript{1} Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, 119991 Russia
\textsuperscript{2} E-mail: meshch@fpl.gpi.ru

Abstract. The shapes of the electron temperature profiles were analyzed at the L-2M stellarator based on the data obtained in experiments on the axial ECR plasma heating performed at different plasma densities and heating powers. It was ascertained that, at the reduced ECRH power exceeding some threshold value, the electron temperature profiles become broadened and flat in the axial region of the plasma column. The appearance of the flat temperature profiles correlates with the occurrence of the density profiles with a dip in the axial region forming at high reduced heating powers as a result of the density pump-out effect. It was concluded that, as a result of occurrence of the density profiles with a dip in the axial region, the mechanism for the microwave radiation absorption changes. Apparently, the cyclotron absorption of the electron Bernstein waves becomes the main mechanism for the microwave radiation absorption, which, in turn, results in the occurrence of the broad and flat (in the axial region) electron temperature profiles.

1. Introduction

At the L-2M stellarator, for creation and heating of hydrogen plasma, the electron cyclotron resonance heating (ECRH) is used. Plasma is heated by the extraordinary wave (X-wave) with the frequency equal to the second harmonic of the electron gyrofrequency (75 GHz). Currently, the MIG-3 gyrotron complex \cite{1} is used for plasma heating, which makes it possible to perform the experiments with high reduced ECRH powers of up to $P_{ECRH}/V = 4 \text{ MW/m}^3$, where $V$ is the plasma volume in the facility. At so high reduced heating powers, the changes in the shape of the electron temperature profiles were observed at the L-2M stellarator: the profiles measured become flat in the axial region of the plasma column. This phenomenon is studied in this work.

In \cite{2}, in the framework of the linear theory of absorption, the simulations were performed of the X-wave absorption in plasma of the L-2m stellarator. The simulations showed that, under conditions of the axial ECR heating, the power density profile of the absorbed microwave radiation is very narrow; it is similar in shape to the Gaussian curve with a full width at half maximum (FWHM) of approximately $\Delta x = 0.1 \times (r/a_p)$ (Figure 1, curve 1). For the L-2M stellarator, this FWHM value is $\sim 1.0$ cm. At so narrow profile of the absorbed power, it is natural to expect that the electron temperature profile will be peak-shaped and will abruptly decrease from the plasma axis to the periphery. However, in the ECRH experiments, the different shapes of the electron temperature profiles are observed. These profiles can be peak-shaped (Figure 1, curve 2), or flat in the axial region of the plasma column ($r/a_p < 0.4$) (Figure 1, curve 3).
In this work, to clear up the reasons for the difference in shapes of the experimental and calculated electron temperature profiles, we studied the electron temperature profiles measured at the L-2M stellarator in the regime of the axial ECR plasma heating.

2. Experimental conditions and measurement techniques

The experiments were performed at the L-2M stellarator in Prokhorov General Physics Institute of the Russian Academy of Sciences. It is a classical two-pole stellarator [3] (the number of helical windings is \( l = 2 \), and the number of toroidal magnetic field periods is \( N = 7 \)) with a major radius of \( R = 1 \) m, and a mean radius of the last closed magnetic surface of \( a_0 = 0.115 \) m. In the experiments described, the ECRH power and plasma density varied in the ranges of \( 100 - 750 \) kW and \( (1 - 3) \times 10^{19} \) m\(^{-3} \), respectively.

The electron temperature distribution was measured using the foil method. The multichord soft X-ray (SXR) diagnostics [4] was used, which makes it possible to obtain in one shot the electron temperature distribution over the cross section of the plasma column and to watch its time evolution during the plasma pulse.

The plasma electron temperature was also determined from the SXR spectra recorded by the spectrometer with a counting rate of \( K = 1.5 \times 10^5 \) photons per second, operating in the energy range from 1 keV to 80 keV [5]. The spectral data were accumulated during several facility shots in the quasi-stationary stage of the discharges. To perform the chord measurements of the SXR spectra, the spectrometer was installed on the scanning platform.

The electron density profiles were measured using the Michelson interferometer based on the HCN laser (337 \( \mu \)m).

3. Analysis of electron temperature profiles

All available electron temperature profiles measured under different conditions were divided into two groups in accordance with the distinctive features of their shapes. The peak-shaped profiles were in the first group (the profiles monotonously decreasing from the axis to the plasma edge, Figure 1, curve 2),
and the profiles flat in the axial region of the plasma column (Figure 1, curve 3) were in the second group. The electron temperature profiles were measured in the quasi-stationary stage of the discharge in the ECR plasma heating regime. The available database is shown in Figure 2. The main shot parameters (the microwave power $P_{ECRH}$ and the plasma density averaged along the central chord $<n_e>$) are shown on the graph axes and the shapes of the electron temperature profiles in the shots with the corresponding parameters are indicated using different icons: triangles and circles correspond to the peak-shaped and flat profiles, respectively. It can be seen that the most of the peak-shaped profiles correspond to the range of parameters, which is above and to the left of the line representing a certain critical level of the reduced heating power ($P_{ECRH}/n_e$)$_{cr} = 120$ kW/10$^{19}$ m$^{-3}$. In the regimes with the reduced powers less than the critical power ($P_{ECRH}/n_e$)$_{cr}$, the peak-shaped profiles are generally observed.

Figure 2. Database of the temperature profiles. On the axes, there are microwave heating power and plasma density averaged along the central chord. Triangles and circles correspond to the peak-shaped and flat temperature profiles, respectively.

![Figure 2](image)

Figure 3. Peaking factors of the peak-shaped electron temperature profiles as a function of reduced heating power. Horizontal line corresponds to the peaking factor averaged over all profiles presented. Vertical line corresponds to the critical reduced power. As a rule, when the reduced power exceeds the critical value, the peak-shaped temperature profiles are not observed.

The peak-shaped electron temperature profiles can be characterized by the peaking factor, which is usually defined as $k = T_e(0)/T_e(0.5 \times r/a_p)$. However, we will use the expression $k = T_e(0)/T_e(0.4 \times r/a_p)$, since the available multichord SXR diagnostics allows measuring the electron temperature profiles only

![Figure 3](image)
in the range of dimensionless radii of \(-0.41 < r/a_p < 0.44\). The peaking factor quantifies how peaked the profile is.

Figure 3 shows the peaking factor of the electron temperature profiles as a function of the reduced heating power for the available peak-shaped profiles. Here, the horizontal line is the peaking factor averaged over all peak-shaped profiles under consideration, \(<k> = 1.6\), and the vertical line is the critical reduced power \((P_{ECRH}/n_{e})_{cr} = 120 \text{ kW}/10^{19} \text{ m}^{-3}\). As a rule, when the reduced power exceeds the critical value, the peak-shaped electron temperature profiles are not observed. It is amazing that the peaking factor of the peak-shaped temperature profiles does not depend on the reduced heating power, while the appearance of the peak-shaped or flat profiles depends just on the reduced power, and this dependence has the threshold nature: the flat profiles appear when the reduced heating power exceeds a certain threshold value \((P_{ECRH}/n_{e})_{cr}\). And when the reduced heating power is less than a threshold value, the peaking factors of all profiles are approximately the same for all heating powers.

The data presented in Figure 3 suggests that there are two ranges of the reduced heating powers, within which the mechanisms for the microwave radiation absorption are different. At the reduced heating powers lower than the threshold power \((P_{ECRH}/n_{e})_{cr}\), the measured electron temperature profiles are always peak-shaped (Figure 1, curve 2). This is consistent with the results of theoretical calculations [2], in which, for all plasma densities less than the cutoff density, the absorbed power profiles are always peak-shaped (Figure 1, curve 1). In the framework of the linear theory of the extraordinary wave resonance absorption used in [2], the absorbed power profiles (and, hence, the temperature profiles) of other shape cannot be obtained. But the experiments show that, at the reduced heating powers exceeding the threshold value, the different mechanism for the microwave radiation absorption appears, as a result of which the absorbed power profiles are no longer picked, which, in turn, results in the formation of the electron temperature profiles flat in the axial region of the plasma column.

We will try to find some plasma parameter, which depends on the reduced heating power and changes stepwise when the reduced heating power exceeds a certain threshold value. Such a parameter, which can cause changes in the mechanism for the microwave radiation absorption in plasma, is the shape of the electron density profile.

**4. Effect of the density profile shape on the extraordinary wave absorption under conditions of the axial ECR heating**

At the L-2M stellarator, with increasing ECRH power, the shape of the density profiles changes [6]. At average densities of \(n_e = (1.5–2.5) \times 10^{19} \text{ m}^{-3}\), which are standard for the L-2M stellarator, and low heating powers of \(P_{ECRH} = (100–250) \text{ kW}\), the parabolic density profiles are observed that monotonously decrease from the center to the periphery of the plasma column. If the heating powers are higher than 250 kW, the density profiles with a dip in the axial region are observed, that is, the plasma density in the axial region of the plasma column becomes less than that at the periphery (Figure 4, curve 1). Moreover, the depth of the dip on the density profile increases with further increasing ECRH power. During the ECR plasma heating, the appearance of the density profiles with the dip is the manifestation of the density pump-out effect observed in experiments at many toroidal magnetic traps (see, e.g., [7, 8]). At the L-2M stellarator, in experiments on the axial ECR heating, the effect of appearance of the dip-shaped density profiles is especially pronounced. This is due to the possibility of creating the reduced ECRH powers record high for the toroidal magnetic traps: up to \(P_{ECRH}/V = 4 \text{ MW/m}^3\), where \(V\) is the plasma volume inside the facility [9]. It is noteworthy that, in experiments on the axial ECR plasma heating, the formation of flat electron temperature profiles correlates with the appearance of dip-shaped density profiles. That is, in those regimes, in which the density profiles are formed that monotonously decline towards the plasma periphery, the peak-shaped \(T_e(r)\) profiles are observed, and, in the regimes with the dip-shaped density profiles, the flat or even slightly dip-shaped \(T_e(r)\) profiles are measured, as it can be seen in Figure 4, (curves 1 and 2). Thus, at the reduced heating powers less than 120 kW/10^{19} \text{ m}^{-3}\, the density profiles are formed in the plasma that monotonously decline from the axis to the periphery, and the plasma heating occurs as a result of the cyclotron resonance absorption of the extraordinary wave at the second harmonic of the electron cyclotron frequency. This mechanism
forms the central profile of the absorbed power and the peak-shaped profile of the electron temperature. And when the reduced heating power is higher than 120 kW/10^{19} m^{-3}, the density profiles are formed with a dip in the axial region of the plasma column, and the opportunity is created for the implementation of another mechanism for the microwave radiation absorption, different from the mechanism for absorption of the extraordinary wave at the second harmonic of electron cyclotron resonance frequency, considered in [2].

In [10, 11], the nonlinear processes of the extraordinary wave decay in plasma are considered. It was shown that, if the radial density distribution in plasma is nonmonotonic, and there are regions in plasma with the reversed gradient (the density increases from the axis to the periphery), then, in these regions, the X-wave can decay into two Bernstein waves: the localized electron (EB) and ion (IB) Bernstein waves. And, for these decay processes to occur, relatively low microwave powers are required, usually available in experiments on the ECR plasma heating. The authors of [10, 11] performed preliminary calculations, which showed that such decay processes can occur in plasma of the L-2M stellarator in experiments on the axial ECR heating, if the ECRH power is high enough to ensure formation of the dip-shaped density profiles. The first decay of the X-wave is followed by a cascade of decay processes, the number of which is finite: the primary EB wave decays into the secondary localized EB wave and the IB wave. The secondary localized EB wave decays into the tertiary localized EB wave and the IB wave, and so on. Such a consideration of the decay processes shows that finally the X-wave can turn into the electron Bernstein wave, which can be absorbed not at the cyclotron resonance surface in the center of the plasma column, but in the region of the reversed density gradient, where this wave is localized. Apparently, just this absorption mechanism works in experiments on the axial ECR heating at the L-2M stellarator under conditions of high heating powers and the corresponding dip-shaped the density profiles. It is consistent with the experimentally measured profiles of both the electron density and temperature shown in Figure 4 (curves 1 and 2, respectively). Additionally, the pressure profile of the plasma electron component measured in the quasi-stationary stage of the plasma shot (in arbitrary units) is also shown in Figure 4 (curve 3). It can be seen that the pressure profile is also flat in the axial region, similarly to the electron temperature profile.

5. Conclusions
In this work, we analyzed the shape of the electron temperature profiles measured at the L-2M stellarator in experiments on the ECR heating at different plasma densities and heating powers. It was ascertained that, at low reduced heating powers (less than 120 kW/10^{19} m^{-3}), the temperature profiles are peak-shaped, and their widths are consistent with the calculation results assuming the electron cyclotron mechanism for the extraordinary wave absorption at the second harmonic of the EC wave.
resonance. If the reduced heating powers become higher than 120 kW/10^{19} m^{-3}, the shape of the electron temperature profiles changes. The profiles become flat in the axial region of the plasma column, and their widths at half maximum increase. The correlation is revealed between the appearances of the flat temperature profiles and the dip-shaped electron density profiles, which occur as a result of the “density pump-out” effect. It was concluded that the appearance of the dip-shaped density profiles in the plasma leads to the changes in the mechanism for the microwave radiation absorption. The regions with the reversed density gradient appear in the plasma, in which the cascade processes of the X-wave decay begin to develop, accompanied by the appearance of the electron Bernstein waves. The cyclotron absorption of the electron Bernstein waves becomes the main absorption mechanism, which occurs not in the axial plasma region, but approximately at half the radius of the plasma column (in the region of the reversed density gradient, where the electron Bernstein waves are localized). This, in turn, results in the formation of wide and flat (in the axial region) electron temperature profiles.

Acknowledgments
The authors are grateful to A.A. Letunov, E.V. Voronova and V.P. Logvinenko for the data on the electron density profiles measured in different operating regimes of the L-2M stellarator.

Funding
The work was supported by the Russian Foundation for Basic Research (project no. 18-0200609).

References
[1] Batanov G M, Belousov V I, Bondar Yu F et al 2012 Prikl. Fiz. 6 79
[2] Sakharov A S and Tereshchenko M A2002 Plasma Phys. Rep. 28 539
https://doi.org/10.1134/1.1494051
[3] Akulina D K, Andryukhina E D, Berezhetskij M S et al. 1978 Sov. J. Plasma Phys. 4 569
[4] Meshcheryakov A I and Vafin I Yu 2018 Prikl. Fiz. 5 42
[5] Meshcheryakov A I, Vafin I Yu and Grishina I A 2018 Instrum. Exp. Tech. 61 842
https://doi.org/10.1134/S0020441218050196
[6] Letunov A A, Voronova E V, Grebenshchikov S E and Logvinenko V P 2019 in XVIII National Russian Conference “Diagnostics of High Temperature Plasma”, Krasnaya Pakhra, 2019. Book of Abstracts p 203 http://dvp.iterrf.ru/images/downloads/sbornik_tez_i_doc.pdf
[7] Erckmann V and Gasparino U 1994 Plasma Phys. Control. Fusion 36 1869
[8] Makino R, Kubo S, Ido T et al. 2013 Plasma Fusion Res. 8 2402115
https://doi.org/10.1585/pfr.8.2402115
[9] Meshcheryakov A I, Vafin I Yu and Grishina I A 2020 Bull. Lebedev Phys. Inst. 47 10
https://doi.org/10.3103/S1068335620010042.
[10] Gusakov E Z and Popov A Yu 2016 Phys. Plasmas 23 082503
[11] Gusakov E Z and Popov A Yu 2019 Nucl. Fusion 59 104003