Characteristic features of SXR spectra measured in the stage of initial ECR plasma heating in the L-2M stellarator

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Abstract. SXR spectra measured in the stage of initial plasma heating in the L-2M stellarator were analyzed. It was ascertained that the two-slope SXR spectra usually measured in the quasistationary stage of the L-2M shots are not observed in the stage of initial plasma heating. In the initial stage of plasma heating, the suprathermal electrons are not generated. The electron temperature profiles were also measured in this stage. In contrast to the temperature profiles measured in the quasi-stationary stage of the discharges which have flat top in the radial range of $r/a_p \leq 0.4$, the temperature profiles measured in the stage of initial plasma heating have narrow shape. The differences in some plasma properties in two stages of plasma heating which result in different shapes of SXR spectra and temperature profiles are discussed.

1. Introduction

In the experiments on electron cyclotron resonance plasma heating (ECRH) at the L-2M stellarator, non-Maxwellian two-slope spectra of soft X-ray (SXR) radiation were observed in the quasi-stationary stage of the discharge [1]. A typical SXR spectrum is shown in Figure 1 as a semilogarithmic graph. Semilogarithmic representation of a Maxwellian spectrum is a straight line with a slope equal to the plasma temperature. It can be seen in Figure 1 that, in the ranges of high and low photon energies, the measured spectrum can be approximated by two straight lines with different slopes. It can be seen that the spectrum consists of a thermal part and a suprathermal “tail” with electron energies in the ranges of $E < 3.2 \text{ keV}$ and $E > 3.2 \text{ keV}$, respectively. In experiments on ECR plasma heating at the L-2M stellarator, the SXR spectra are always two-sloped in all experimental regimes when the plasma density and heating power change in wide ranges. The mechanism for formation of suprathermal part of the spectra is not understood completely. To obtain additional
information on the possible causes of the two-slope SXR spectra formation, spectral measurements were performed in the stage of initial ECR plasma heating preceding the quasi-stationary stage of plasma confinement.

2. SXR spectra measurement technique.
SXR spectra were measured with the help of the scanning SXR spectrometer that operates in the range of photon energies from 1 to 80 keV and has a counting rate of \( V = 1.5 \times 10^5 \) photons per second. Spectral resolution of the spectrometer was measured using the \(^{55}\)Fe source of radioactive radiation. In the energy range near 6 keV, it is \( \Delta E = 320 \) eV. Si(Li) detector is used in the spectrometer.

To carry out chord measurements of SXR spectra, the spectrometer was placed on a scanning platform. The spectra were measured through the horizontal window of the vacuum chamber. Scanning was performed in a vertical plane. The scanning system allows measuring the spectra along the chords that are in the angular range from \(-23.5^\circ\) to \(+26.5^\circ\). Negative and positive angles correspond to the chords below and above the equatorial plane, respectively. The zero angle corresponds to the chord along which the signal was detected from the \(^{55}\)Fe source of radioactive radiation installed in the equatorial plane of the facility on the inner wall of the vacuum chamber. The chords corresponding to the maximum scanning angles are tangent to the magnetic surfaces with the mean equivalent radii of \( r/a_p = -0.55 \) and 0.85 (\( a_p \) is the mean radius of the last closed magnetic surface).

To measure SXR spectra in the initial stage of ECR plasma heating, a special ECRH mode was established in the facility. In the ordinary working shots (\( P_{\text{ECRH}} = 400 \) kW, \( n_e = 2 \times 10^{19} \) m\(^{-3}\)), the duration of the stage of initial plasma heating is about 3–4 ms. During this time, it is impossible to measure statistically reliable SXR spectra. In experiments under consideration, a special operation mode was set (\( P_{\text{ECRH}} = 150 \) kW, \( n_e = 2.5 \times 10^{19} \) m\(^{-3}\)) in which the duration of the initial heating phase was increased to 6–7 ms. Time evolution of the fundamental plasma parameters in one of the shots of this series (shot #21418) is shown in Figure 2. The figure shows (from top to bottom) the plasma density averaged along the central chord \( n_e(t) \),
plasma energy content $W(t)$ and its derivative $dW(t)/dt$, power of radiation loss $P_{rad}(t)$, and ECRH power $P_{ECRH}(t)$. The vertical line corresponds to time when the stage of initial heating proceeds to the quasi-stationary stage.

3. Main results
The SXR spectrum measured along the central chord of the plasma cross section at the end of the phase of initial plasma heating is shown in Figure 3. It is evident that the measured spectrum is Maxwellian, that is, it has no suprathermal part. Thus, in the stage of initial plasma heating, the mechanism responsible for the formation of suprathermal part of SXR spectra does not work.

To clear up why the two-slope SXR spectra do not form during the stage of initial ECR plasma heating, it is necessary to study the properties of this phase in more detail.

In the stage of initial ECR plasma heating, the electron temperature profiles were measured using the scanning SXR spectrometer and multi-chord diagnostics of SXR radiation. Dynamics of the electron temperature profiles is shown in Figure 4. It can be seen that, in the course of plasma heating, the axial temperature increases and the dimensions of the heated plasma region also increase. Heating starts in the axial region (the region of resonant absorption of ECR radiation). Then heat spreads from the axis to the periphery, while the temperature profiles still have a narrow shape. During the whole initial stage, the plasma periphery remains cold which is confirmed by the absence of the floating potential signal of the Langmuir probe which is inserted by 5 mm into the plasma. As a result, power transported by the heat flux to the wall is much less than the heating power, and the particle flux to the wall is very weak.

In the stage of initial ECR plasma heating, the main channel of energy loss is plasma radiation. Figure 5 shows typical electron temperature profiles measured at the L-2M stellarator in the stage of initial plasma heating and in the quasi-stationary stage of the discharge (curves 1 and 2, respectively). The shapes of these profiles are considerably different. In contrast to the temperature profile measured in the stage of initial plasma heating, the quasi-stationary temperature profile has a flat top in the radial range of $r/a_p \leq 0.4$. In this case, the Langmuir probe signal shows that the temperature at the plasma periphery increases to 10–20 eV.
Apparently, the flattening of the temperature profile in the quasi-stationary stage of the discharge occurs due to the transformation of the absorbed microwave power profile, and, despite the fact that the axial ECR plasma heating is performed, a part of microwave power is absorbed not in the axial plasma region. Transformation of the absorbed microwave power profile can occur due to a change in the mechanism of microwave radiation absorption. In the stage of initial plasma heating, electron cyclotron absorption of the extraordinary gyrotron wave occurs. Radiation is absorbed in a small plasma region near the axis [2]. This results in the formation of narrow electron temperature profiles. In the quasi-stationary stage of the discharge, transformation of the plasma density profiles occurs. They become hollow-shaped, and the conditions can arise for the realization of the two-plasmon decay of microwaves [3]. Waves that appear as a result of two-plasmon decay can be absorbed far from the plasma axial region, and this will result in the flattening of electron temperature profiles. The same waves can create a mechanism for the formation of suprathermal electrons which manifests itself in the occurrence of the two-slope SXR spectra.

4. Conclusions
The SXR spectra were measured in the stage of initial ECR plasma heating. It turned out that, in this stage, the suprathermal part of SXR spectrum, which was reliably measured in the quasi-stationary stage of the discharge, does not form. In the stage of initial plasma heating which precedes the quasi-stationary stage, some plasma properties were studied. Studies of the dynamics of the electron temperature profiles show that, in this stage, the electron temperature on the plasma axis gradually increases. Throughout the entire stage of initial ECR heating, the shape of the temperature profiles is narrow, which indicates that microwave radiation is absorbed in the axial plasma region in accordance with the electron cyclotron resonance absorption mechanism. In the quasi-stationary stage of the discharge, the temperature profiles become flat, which indicates the transformation of the absorbed microwave power profile. Apparently, this is due to the change in the microwave absorption mechanism. Then, to explain the mechanism of formation of the suprathermal “tail” of SXR spectrum in the quasi-stationary stage of the discharge, it is necessary to consider other mechanisms of microwave radiation absorption, for example, the absorption of microwaves that occurs due to the process of two-plasmon decay of microwaves.

Acknowledgments
The authors are grateful to the L-2M team for their help in conducting the experiments. This study was supported by the Russian Foundation for Basic Research (project no. 18-02-00609). The experiments at the L-2M stellarator were carried out at the expense of the federal budget under the state contract no. AAAA-A18-11801300279-8.

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