Longitudinal electric fields in the OH and ECRH heating modes of the L-2M stellarator

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Abstract. The soft X-ray spectra were measured at the L-2M stellarator in the OH and ECRH modes, which occurred to be considerably non-Maxwellian. In the OH mode, the SXR spectra considerably deviate not only from the Maxwellian spectrum, but also from the model bremsstrahlung spectrum of plasma in the longitudinal electric field. This can be due to the fact that, under ohmic heating conditions, plasma waves can be excited and absorbed by plasma electrons. In the OH mode, the radial distribution of the longitudinal electric field was determined, which turned to be almost uniform over the radius. It was hypothesized that, in the ECRH experiments, the deviations of the measured SXR spectra from the Maxwellian spectrum are also caused by the presence of the longitudinal electric fields in plasma. These fields are the longitudinal vortex electric fields generated in plasma during the current drive.

1. Introduction
In the ohmic heating mode (OH) in the toroidal magnetic traps, electrons are accelerated by the vortex electric field that results in the distortion of the electron energy distribution function (EEDF) and the appearance of runaway electrons. These distortions can be seen in the soft X-ray (SXR) spectra of plasma emission. Typical SXR spectrum measured at the L-2M stellarator in the OH regime is presented in Fig. 1 on a semi-log scale. Curves 1 and 2 correspond to the experimental spectrum and the Maxwellian spectrum with a temperature determined from the experimental spectrum, respectively.

Figure 1 demonstrates that there are three different energy ranges, in which the SXR spectrum looks different. In the first energy range corresponding to low electron energies $W < W_b = 2.7$ keV the spectrum is close to the Maxwellian one, and the temperature of thermal electrons $T_e$ can be determined from it. In the second energy range $2.7 < W < 7$ keV, the spectrum is considerably different from the Maxwellian one. Electrons are accelerated by the electric field and acquire considerably high energy between the collisions, but do not yet become runaway electrons. The third energy range corresponds to runaway electrons with energies $W > W_{cr} = T_e/2\gamma$, where $\gamma = E/E_{cr}$, $E$ is the electric field and $E_{cr}$ is the Dreiser field. At present, the formation of runaway electrons and the related

![Figure 1. Typical SXR spectrum measured at the L-2M stellarator in the OH regime.](image-url)
physical processes are studied in detail, see, e.g., [1, 2]. The subject of this research is the SXR spectra in the intermediate energy range \(2.7 < W < W_{cr}\).

In the ECRH mode (unlike the OH mode), the induction current is not generated in plasma by the vortex electric field. However, the SXR spectra measured in the ECRH mode are also non-Maxwellian. In [3], the shape of SXR spectra was studied, but the mechanism for the spectra formation was not ultimately explained.

In this study, in the OH mode, the energy of \(\gamma\)-photons will be determined from the measured SXR spectra, above which the deviations of the measured SXR spectra from the Maxwellian spectrum can be considered noticeable. In [4, 5], the relation between this energy and the longitudinal electric field, in which electrons are accelerated in the OH mode, was obtained. Basing on this relation, the estimates will be obtained for the distribution of the longitudinal electric field over the minor plasma radius. We will also discuss the shape of SXR spectra in the indicated energy range and its correspondence to the bremsstrahlung model spectrum calculated for the magnetized plasma in the longitudinal electric field. The possibility of occurrence of the longitudinal electric fields in the ECRH mode and their effect on the shape of SXR spectra will be also discussed.

2. Experimental conditions

The experiments were performed at the L-2M stellarator. It is a classic two-pole stellarator (the number of helical windings is \(l = 2\) and the number of field periods along the torus is \(N = 7\)) with a major radius of \(R = 1\) m, a plasma radius of \(a = 0.115\) m, and the toroidal magnetic field of \(B_0 = 1.34\) T [6]. The experiments on the ohmic plasma heating were performed at a current of \(I_p = 18–20\) kA and a plasma density averaged over the central chord of \(n_e = (1.5–2.5) \times 10^{19} \text{ m}^{-3}\). The loop voltage was in the range of \(2.5–3.5\) V. Using the SXR scanning spectrometer, the SXR spectra of plasma emission were measured in a wide energy range.

3. Profiles of the longitudinal electric field in the OH mode

A typical SXR spectrum measured in the OH mode is shown in Fig. 1. The figure demonstrates that the measured SXR spectrum differs considerably from the Maxwellian spectrum at energies of \(\gamma\)-photons above \(W = 2.7\) keV.

In [4], the bremsstrahlung spectrum of the magnetized plasma in the longitudinal electric field was calculated in the energy range of \(2 < W/T_e < \gamma^{1/2}\). From these calculations, it follows that, if \(\gamma^{1/2}W/T_e \sim 1\), then the deviation of the spectrum intensity from the intensity of the Maxwellian spectrum will be of the order of the Maxwellian spectrum intensity. This condition is the criterion for the noticeability of the deviations of the measured spectrum from the Maxwellian spectrum. We denote the electron energy, at which the spectrum deviation from the Maxwellian spectrum becomes considerable, by \(W_b\). Then, according to [5], the estimate of the longitudinal electric field, in which the particles were accelerated, can be found from the relation

\[
E_{||} = \frac{4\pi e^2 n_e \ln \Lambda}{(W_b)^2} T_e / (W_b^2).
\]

For the spectrum in Fig. 1, we can obtain \(E_{||} \approx 0.35\) V/cm.

This method for estimating the longitudinal electric field was used to obtain the radial distribution of the longitudinal electric field in the OH mode. With the help of the scanning spectrometer [7], the SXR spectra of plasma emission were measured along different chords in the cross section of the plasma column. The “Maxwellian” parts of these spectra were used to obtain the radial distribution of the electron temperature. The \(W_b\) energies were also determined and, basing on these data, the radial distribution of the longitudinal electric field was
obtained (Fig. 2). It can be seen that, in the OH mode, the longitudinal electric field is almost uniformly distributed over the radius, and its strength is consistent with the strength of the electric field determined from the loop voltage (curve 3 in Fig. 2).

In [7], the EEDF of the magnetized plasma in the longitudinal electric field was calculated. Using the results of this work, we obtained the model bremsstrahlung spectrum of the magnetized plasma in the longitudinal electric field shown in Fig. 3 (curve 2). In the same figure, there are the SXR plasma emission spectrum recovered from the spectrum shown in Fig. 1 with allowance for the efficiency of radiation absorption by the detector (curve 1) and the Maxwellian spectrum (curve 3). It can be seen that accounting for the longitudinal electric field results in a strong deviation of the model spectrum from the Maxwellian spectrum. However, it is also clear that accounting for only the longitudinal electric field does not result in a good agreement between the model spectrum and the experimental one.

In the energy range of up to $10\ T_e$ (i.e., up to 3 keV), the experimental spectrum (curve 1) is in good agreement with the theoretical one obtained at $\gamma = 0,02$ (curve 2). At higher energies, the experimental spectrum deviates not only from the Maxwellian spectrum (curve 3), but also from the model bremsstrahlung spectrum of the plasma in the electric field (curve 2). Obviously, besides the acceleration in the electric field, there are additional mechanisms for the electron acceleration, which result in the formation of the spectrum observed in the experiment.

Let us consider the possible effect of electrons trapped in the stellarator magnetic field on the EEDF of plasma in the electric field. The presence in plasma of electrons trapped in the stellarator magnetic field decreases the plasma conductivity [9]. This is due to the fact that the particles trapped in the stellarator magnetic field participate in collisions, but do not participate in the current transport. Therefore, they are not accelerated and do not acquire additional energy in the electric field. Consequently, the presence of particles trapped in the stellarator magnetic field cannot result in the distortion of SXR spectra.

The EEDF can be distorted due to the fact that electrons can acquire additional energy in interactions with waves excited in plasma. Interaction with plasma waves can be one of such mechanisms of electron energy increase. The dispersion equation for the plasma waves is as follows:

$$\omega^2 = \omega_{pe}^2 + k^2\nu_{Te}^2,$$

where $\omega_{pe}$ is the plasma Langmuir frequency, $k$ is the wave vector, and $\nu_{Te}$ is the electron thermal velocity. The absorption of the wave energy
by electrons can occur due to the Landau damping mechanism under the condition of $v_{ph} = v_e$, where $v_{ph}$ is the longitudinal phase velocity of the wave, and $v_e$ is the electron velocity directed along the magnetic field. This condition makes it possible to estimate the phase velocity of the plasma wave under the assumption that the spectrum distortion occurs due to the absorption of the plasma wave by electrons. From Fig. 3, we can estimate the $v_e$ velocity from the $W_e$ energy, above which the experimental spectrum deviates from the model spectrum. In this case, $W_e = 3$ keV. Then $k = 2\pi \times 10^3$ m, and $\lambda \sim 1$ mm.

At the L-2M stellarator, there are no diagnostics suitable for experimental detection of the plasma wave excitation in the OH mode. However, it is known that plasma waves are efficiently excited by electron beams [10]. In the OH mode, such beams can be runaway electron beams. Thus, the absorption of plasma waves by plasma electrons can result in the deviation of the experimental SXR spectra from the model bremsstrahlung spectrum of plasma in the longitudinal electric field.

4. SXR spectra of plasma measured in the ECRH mode

The SXR spectrum measured at the L-2M stellarator in the ECRH mode at a heating power of $P = 100$ kW and a plasma density of $n_e = 2.0 \times 10^{19}$ m$^{-3}$ is shown in Fig. 4 (curve 1). This spectrum is also non-Maxwellian. The temperature of the thermal part of the spectrum is $T_e = 0.6$ keV. In Fig. 4, curve 2 shows the Maxwellian spectrum with a temperature of $T_e = 0.6$ keV. The suprathermal part of the spectrum is similar to the suprathermal part of the spectra measured in the OH mode.

In contrast to the OH mode, in the ECRH mode, the induction current is not generated by the vortex electric fields in plasma of the L-2M stellarator. In this mode, plasma is created and heated with the help of only microwave radiation. However, it is known that the non-inductive drag currents are generated in plasma as a result of the ECR heating. In tokamaks, the ECR heating is also used in the current drive experiments, see, e.g., [11]. In [12], calculations were performed which have shown that, in plasma of the L-2M stellarator, the drag currents should be also generated during ECR heating. They should be somewhat smaller than the plasma current in the OH mode. They increase to their maximum value in time of the order of 0.2 ms [12]. The presence of these currents was confirmed experimentally. The total plasma current in the ECRH experiments was measured by the Rogowski belt. This current increased during the entire microwave pulse (10 ms) without reaching the stationary value. The high inductance of the plasma column (due to the transformer used in the OH mode) impeded the rapid increase of the current. Calculations show that, in the L-2M stellarator, the response time of the circuit including the plasma column is approximately 100 ms. Therefore, during the ECR heating pulse, the drag currents do not have time to reach their maximum values, and it was impossible to measure the maximum drag currents. In this case, the electromotive force of self-induction (the longitudinal vortex electric fields) occurs in the plasma, which results in the occurrence of countercurrents. These electric fields should affect the plasma bremsstrahlung spectrum in the same way as the corresponding fields in the OH mode (Fig. 3, curve 1). Thus, we can assume that, under the ECRH conditions, the deviations of the measured SXR spectra from the Maxwellian spectrum are also caused by the longitudinal electric field present in plasma. Then, using the technique described in the previous section, for the ECRH mode, we can determine the longitudinal electric field corresponding to the spectrum shown in Fig. 4. It is equal to $E_{||} = 0.4$ V/m.

Using the L-2M database on the SXR spectra measured in the ECRH mode, we can obtain the dependence of the longitudinal electric field on the plasma density at ECRH power of $P = 100$ kW (Fig. 5, curve 1). It can be seen from the figure that the longitudinal electric field decreases with growing plasma density. The dependence of the total plasma current $I_p$ (measured by the Rogowski belt) on the plasma density looks similarly. The total current flowing through plasma is the difference between the drag currents and the
arising countercurrents (Fig. 5, curve 2). Curves 1 and 2 are close to each other, since both these dependences reflect the fact that the drag currents decrease with growing plasma density.

5. Conclusions
The soft X-ray spectra were measured at the L-2M stellarator in the OH mode. Measurements have shown that the thermal part, the intermediate suprathermal part and the part corresponding to runaway electrons can be distinguished in the SXR spectra. The measured spectra were compared with the model bremsstrahlung spectrum of plasma in the longitudinal electric field. It turned out that, at energies of \( W > 3 \) keV, the SXR spectra considerably deviate not only from the Maxwellian spectrum, but also from the model bremsstrahlung spectrum of plasma in the longitudinal electric field. The spectrum deviations from the model spectrum can occur due to the fact that, under ohmic heating conditions, plasma waves can be excited and absorbed by electrons.

In the ohmic heating mode, the radial distribution of the longitudinal electric field was determined. It turned out that the longitudinal electric field is almost uniformly distributed over the radius, and its strength is consistent with the electric field strength determined from the loop voltage.

The longitudinal electric field occurring in plasma in the ECRH mode due to the drag currents was estimated from the SXR spectra measured in the ECRH mode. The dependence of the electric field on the plasma current was obtained. It was shown that this dependence is consistent with the dependence of the differential current flowing through plasma (the current, which is the difference between the drag currents and countercurrents) on the plasma density. Based on this fact, it was hypothesized that, in the ECRH experiments, the deviations of the measured SXR spectra from the Maxwellian spectrum are also caused by the presence of the longitudinal electric field in plasma.

Acknowledgments
The authors are grateful to the L-2M team for their help in conducting the experiments.
This work was supported by the Russian Foundation for Basic Research (project no. 18-02-00609).

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