Soft X-ray spectra in regimes with low plasma density and temperature at the L-2M stellarator

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Abstract. Soft X-ray plasma emission spectra were measured at the L-2M stellarator in the OH regime with low plasma density \(n_e \sim 10^{19} \text{ m}^{-3}\) and temperature \(\sim 200-400 \text{ eV}\). It is demonstrated that on the X-ray spectra, there is no dip in the energy range corresponding to several thermal energies of electrons or higher. This means that at the L-2M stellarator, the “X-ray dip” phenomenon is not observed, as it was at the T-11M tokamak. In the axial ECRH regime at the heating power \(P_{\text{ECRH}} = 250 \text{ kW}\), the soft X-ray spectra of plasma emission were also measured. In this case, the X-ray dip phenomenon was not observed too.

1. Introduction

In [1], the appearance of the X-ray dip was described on the soft X-ray (SXR) spectra measured at the T-11M tokamak. The term X-ray dip was used to describe the phenomenon of anomalously strong absorption of the SXR plasma emission as it passes through the 90-\(\mu\)m beryllium foil as compared to that passed through the 30-\(\mu\)m beryllium foil. This phenomenon was observed in the OH regime under conditions of relatively low electron temperature of the plasma \(\sim 200-400 \text{ eV}\) and low electron density \(n_e \sim 10^{19} \text{ m}^{-3}\). In this article, the intensities are presented of SXR plasma emission passed through the beryllium foils with thicknesses of 30 and 90 \(\mu\)m as functions of the electron density. According to these dependences, at the electron densities \(n_e < 1.4 \times 10^{19} \text{ m}^{-3}\), the intensity corresponding to the SXR radiation passed through the 90-\(\mu\)m beryllium foil becomes disproportionally lower than that passed through the 30-\(\mu\)m beryllium foil.

To explain this phenomenon, S.V. Mirnov had hypothesized that the Maxwell electron energy distribution function (EEDF) becomes “depleted” in the energy range corresponding to the electrons, the energies of which exceed several times the thermal energy. As a probable mechanism for such “depletion”, the author suggested the anomalous transport of the charged particles along the fluctuating toroidal magnetic field (the magnetic flutter model [2]). Such a process of the EEDF depletion in a certain energy range should inevitably result in changes in the shape of the SXR plasma emission spectrum: a dip should appear on the spectrum. It is just the formation of this dip on the SXR spectrum that is a reason for a considerable decrease in the SXR signal passed through the 90-\(\mu\)m beryllium as compared to that passed through the 30-\(\mu\)m foil. However, in [1], the SXR spectra measured in the corresponding experiments were not presented that could visually demonstrate the presence of the dip on the SXR spectra and, accordingly, directly indicate the observation of the X-ray dip phenomenon at the T-11M tokamak.
In this regard, the authors of this article attempted to detect the X-ray dip phenomenon by means of the direct measurements of the SXR emission spectra and intensity. The experiments were performed at the L-2M stellarator in the OH [3] and ECRH [4] regimes of plasma heating. The point is that in the OH regime, the L-2M plasma parameters, such as the electron density and electron temperature, are close to the corresponding parameters of the T-11M plasma [5]. In these two facilities, the longitudinal magnetic fields also coincide: $B_0 = 1.2$ T. The L-2M facility is a classical two-turn stellarator ($l = 2, N = 7$) with the major radius $R = 1$ m and the plasma radius $a = 0.115$ m. In the experiments described, the scanning SXR spectrometer was used [6] with a resolution of 320 eV and a maximal counting rate of $1.5 \times 10^5$ pulses per second. It can be used for the SXR spectra recording in the energy range from 1 to 80 keV. Beryllium filters were used in the spectrometer. The SXR intensity was measured using the multichord SXR diagnostics [7], which allows continuous measuring the radial distributions of the SXR intensity and electron temperature during facility shot.

2. Simulations of the X-ray dip phenomenon

Before the experiments, the X-ray dip phenomenon was simulated in order to determine the energy range, in which we can expect to find a dip on the SXR spectrum. The model spectrum of the SXR plasma emission was specified in the form shown in Figure 1. The model SXR spectrum was terminated at a certain critical energy $E_{cr}$, and in the energy range $E < E_{cr}$, it was set to be the Maxwellian one. Then the SXR emission intensities were calculated, which would be detected by two sensors of the multichord SXR diagnostics covered with the beryllium foils with thicknesses of 30 and 90 $\mu$m. The simulations were performed in the electron density and temperature ranges $n_e \sim (0.8–4.5) \times 10^{19}$ m$^{-3}$ and $T_e \sim 300–400$ eV, respectively. The plasma parameters, at which the anomalously strong absorption of SXR plasma emission was measured by the detector covered with the 90-$\mu$m-foil at the T11-M tokamak, fall within these ranges. The simulations have shown that, under conditions of the experiment described at the T11-M tokamak, the dip on the SXR spectrum should be searched for in the energy range $E = (5–7)T_e$.

Figure 1. SXR spectrum used in simulations of X-ray dip phenomenon.

Figure 2. SXR spectrum measured at the L-2M stellarator in OH regime with $T_e = 320$ eV and $n_e = 1.1 \times 10^{19}$ m$^{-3}$. Straight line corresponds to the Maxwellian spectrum.
3. SXR spectra measured in OH regime

It was already mentioned that, in the OH regime, the typical plasma parameters at the L-2M stellarator are close to the corresponding parameters at the T-11M tokamak: $T_e = 250–350$ eV and $n_e = (0.8–2.5) \times 10^{19}$ m$^{-3}$. The SXR spectra were measured along the central chord. The SXR spectrum measured at $T_e = 320$ eV and $n_e = 1.1 \times 10^{19}$ m$^{-3}$ is shown in Figure 2. The discharge parameters were as follows: the plasma current was $I_p = 20$ kA, the loop voltage was $U_{loop} = 2.5$ V, and the OH power was $P_{on} = 50$ kW. According to Figure 2, in the energy range $E = (5–7)T_e$, no decrease in the emission intensity is observed. On the contrary, the SXR spectrum begins deviating from the Maxwellian spectrum so that at high energies, the emission intensity becomes higher than that in the corresponding Maxwellian spectrum. This deviation caused by the acceleration of electrons in the longitudinal electric field, observed in the OH regime at the L-2M stellarator, was studied in detail by the authors in [8].

4. SXR spectra measured in ECRH regime

In the ECRH regime, the authors also attempted to detect a dip on the SXR spectra of plasma emission. The spectra were measured along the chord passing through the plasma heating region [9]. The spectral data was collected during several facility shots. Typical SXR spectrum measured in the axial ECRH regime at the heating power $P_{ECRH} = 250$ kW is shown in Figure 3. The plasma parameters were as follows: $n_e = 1.7 \times 10^{19}$ m$^{-3}$ and $T_e = 750$ eV. In the energy range $E = (5–7)T_e$, no decrease in the emission intensity in the SXR spectrum was detected, similarly to the OH regime. The SXR spectrum has a curved shape in the energy range from 2 to 12 keV, and in the high-energy range, the spectral intensities are higher than those in the corresponding Maxwellian spectrum. This means that under these experimental conditions the X-ray dip phenomenon is also not observed.

4. Conclusions

In this paper, the spectra of soft X-ray plasma emission were studied in different operating regimes of the L-2M stellarator. We tried to detect the X-ray dip, which occurs at other facilities in the regimes with low plasma density and temperature. Based on the results of modeling the X-ray dip phenomenon, it was found that a decrease in the SXR spectrum intensity is expected to be found in the energy range $E = (5–7)T_e$, corresponding to several electron temperatures.

In the OH regime, in the energy range $E = (5–7)T_e$, a decrease in the emission intensity in the SXR spectrum was not observed. In this energy range, the experimental SXR spectra begin deviating from the Maxwellian spectrum with the same temperature so that the experimental intensities exceed the Maxwellian ones. This deviation is associated with the acceleration of electrons in the longitudinal vortex electric field creating the OH current.
In the ECRH regime, in the energy range $E = (5-7)T_e$ of the SXR spectra measured along the chord intersecting the heating region, a decrease in the emission intensity in the SXR spectrum was also not observed. The SXR spectrum has a curved shape in the entire energy range from 2 to 12 keV, and in the high-energy range, including the range corresponding to several temperatures of thermal electrons, the experimental spectrum lies above the Maxwellian spectrum.

Thus, we have failed to observe the X-ray dip phenomenon at the L-2M stellarator both in the OH and ECRH operating regimes. It is possible that the experiments at the T-11M tokamak were performed under some specific conditions that were not reproduced in the experiments at the L-2M stellarator.

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