Formation of Non-Maxwellian SXR Spectra at Various Plasma Parameters and ECRH Powers at the L-2M Stellarator

A.I. Meshcheryakov, D.G. Vasilkov, A.A. Vasileva, I.Yu. Vaphin, E.V. Voronova, I.A. Grishina, V.P. Logvinenko and V.D. Stepakhin

Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia, e-mail: meshch@fpl.gpi.ru

1. EXPERIMENTAL SETUP

Experiments on plasma creation and heating by microwave radiation of high power density of P_{ECRH}/V_P = (2.0 -4.0) MW/m^{-3} were carried out at the L-2M stellarator [1]. In these experiments, nonmaxwellian SXR spectra were measured.

The L-2M device is a classical two-pole stellarator (l = 2, N = 7) with a major radius of R = 1 m, minor plasma radius of a = 0.115 m, and toroidal magnetic field of B_0 = 1.34 T. The rotational transform varies from ι = 0.18 at the magnetic axis to ι = 0.78 at the plasma edge. A gyrotron with a power of up to 600 kW is used to create and heat plasma at the frequency 75 GHz (the second harmonic of the electron gyrofrequency). The resonance region was in the center of plasma. Microwaves were delivered to the plasma by the waveguide ($\mathbf{k}\perp\mathbf{B}_0$). The section in which heating was performed was spaced at a distance of about 1 m from the section in which the SXR spectrometer was arranged.

Spectral measurements were carried out by the SXR spectrometer which is capable of measuring spectra in the energy range from 1 to 80 keV and has the count rate of $V = 1.7{\cdot}10^5$ photons per second. Such a high counting rate was achieved at the cost of deterioration of the spectral resolution of the instrument which is ΔE = 320 eV at energy of about 6 keV.

SXR radiation was received in the direction of the central chord in the equatorial plane of the stellarator. To obtain one spectrum, spectral data was summed during several pulses of the facility in the quasi-stationary stage of the discharge when the main plasma parameters become steady-state. In all ECRH operation modes, nonmaxwellian SXR spectra with two different slopes in the low and high energy ranges were observed. Typical SXR spectrum is shown in Fig. 1. This spectrum consists of the thermal part and epithermal “tail”. The breaking point of the spectra corresponds to energy of E = 5 keV. To quantitatively estimate the deviation of the measured SXR spectrum from the Maxwellian one, we will use two parameters. The first one is the slope of the spectrum plotted in semilogarithmic coordinate axes. For thermal electrons, the slope of the spectrum is the electron temperature which we denote as T_e^{bulk}. We will conventionally characterize the slope of the epithermal part of the

SXR spectrum by the "tail temperature" T_e^{tail}. The second parameter is electron density. Let us denote as n_e^{bulk} and n_e^{tail} densities of thermal and epithermal electrons, respectively. These parameters can be determined from the measured SXR spectra because, in our case, these spectra plotted in semilogarithmic coordinate axes consist of two straight segments.

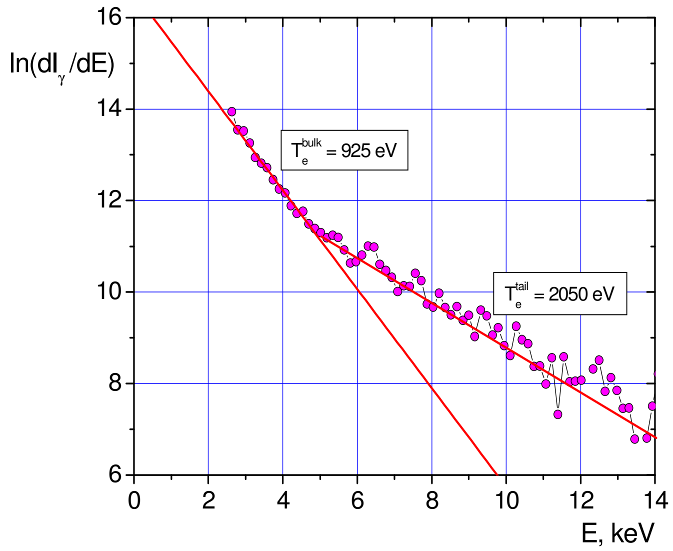

Fig.1. Typical SXR spectrum measured in the ECR heating mode.
P_{ECRH} = 430 kW, and n_e = $1.75*10^{19}m^{-3}$.

2. EXPERIMENTAL RESULTS

To clarify the reasons for occurrence of epithermal tails in SXR spectra, we carried out the SXR spectra measurements at various plasma parameters and ECRH powers. Plasma electron density and ECRH power were varied in the ranges of $n_e = 0.7\cdot10^{19}$м$^{-3}$ - $2.5\cdot10^{19}$м$^{-3}$ and P_{ECRH} = 200 - 600 kW, respectively.

Figure 2 shows the temperatures of the bulk of thermal electrons T_e^{bulk} (triangles) and the "tail temperatures" T_e^{tail} (black dots) depending on the heating power normalized to the electron density of $n_e = 10^{19}$ m^{-3}. The temperature of the thermal part of the spectrum (lower curve) considerably increases with growing normalized power and that is quite reasonable. At the same time, the epithermal tail "temperature" T_e^{tail} (upper curve) remains practically constant within the measurement errors.

The dependences of the T_e^{bulk} and T_e^{tail} temperatures on the electron density of plasma measured at the constant heating power are shown in Fig. 3. Curves 1 and 2 are the dependences of the thermal temperature T_e^{bulk} on the electron density corresponding to heating powers of 200 and 400 kW, respectively. Curve 3 shows the dependence of the "temperature" of epithermal electrons on the electron density for both heating powers.

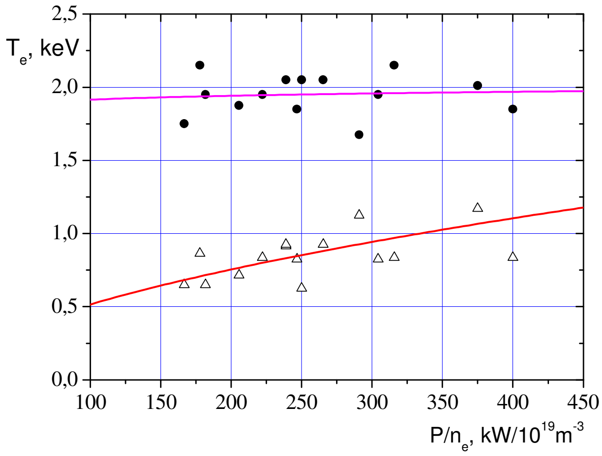

Fig.2. Dependence of the two SXR spectrum slopes T_e^{bulk} and T_e^{tail} on the normalized ECRH power P_{ECRH} / n_e.

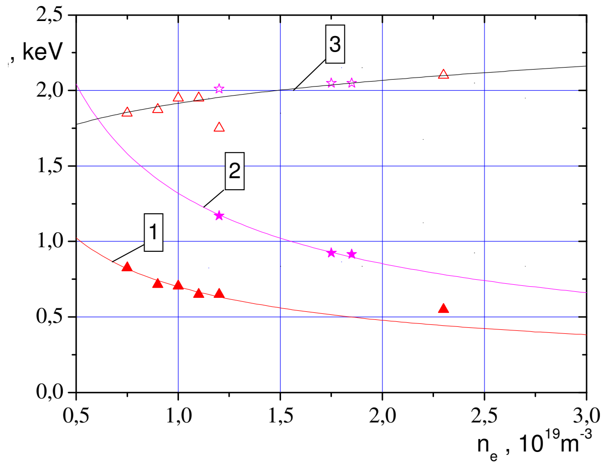

Fig.3. Dependences of the T_e^{bulk} and T_e^{tail} temperatures on the electron density of plasma at two ECRH powers 200 kW (curve 1) and 400 kW (curve 2).

As seen from the figure, the temperature of thermal electrons T_e^{bulk} decreases with growing electron density since the heating power per one electron becomes lower. In contrast, the "tail temperature" T_e^{tail} slightly increases with growing electron density and it does not depend on the heating power.

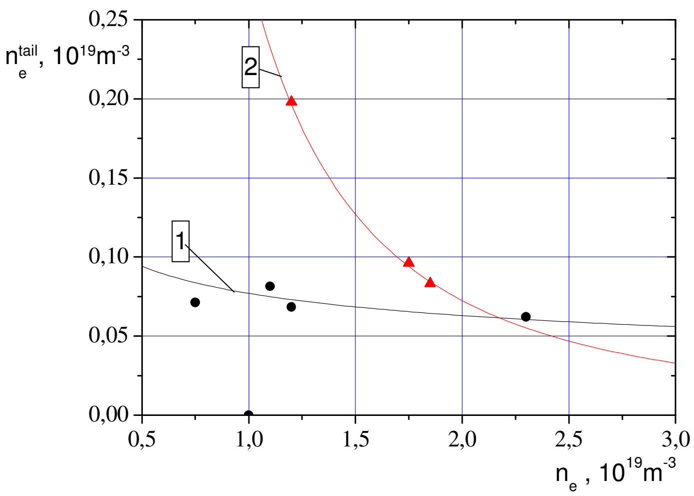

Fig. 4. Dependence of density of epithermal electrons on electron density of plasma at two ECRH powers 200 kW (curve 1) and 400 kW (curve 2).

Figure 4 shows the dependence of density of epithermal electrons n_e^{tail} on the total electron density of plasma at two ECRH powers 200 and 400 kW. The density of epithermal electrons decreases with growing electron density of plasma and, for a higher power of 400 kW, it decreases sharper.

Explanation of the experimental dependences (Figs. 2 – 4) requires understanding of the mechanism of generation of epithermal electrons in these experiments which is not yet clear.

3. DISCUSSION

SXR spectra with two slopes were previously observed at the T-10 [2] and TCV [3] tokamaks in experiments on current drive. In [2], the occurrence of epithermal electrons was associated with the generation of drag currents caused by changes in the distribution function of electrons over energies. In both papers, the authors were unable to give satisfactory explanation of the “two-temperature” shape of the measured SXR spectra.

We also can not suggest the well-studied explanation of the shape of the measured SXR spectra consisting of two straight sections. We can only hypothesize that the observed shape of the SXR spectra occurs due to the geometry of microwaves’ absorption. In [4], it was shown that, in our experiments, radial width of the area of microwaves’ absorption is about 0.5-0.7 cm. Apparently, the temperature profile is very sharp within the absorption area. The SXR spectrometer received radiation coming along the central chord of plasma section. Radiation from both the area of plasma heating and the colder areas of plasma fall into its field of view. Tentative simulations of X-ray flux from plasma carried out at various given profiles of plasma density and temperature showed that, in some cases, “two-temperature” spectra can occur in plasma. The studies in this field are in progress.

Thus, in the ECRH experiments at the L-2M stellarator, the SXR spectra with two “temperatures” were observed. It was found that, with growing heating power and with decreasing density, the temperature of the thermal part of the spectrum increases and the epithermal tail “temperature” remains practically constant within the measurement errors. The mechanism of generation of the epithermal part of the electron distribution function over energies is not yet clear.

The work was supported by the Russian Fund for Basic Research (project no. 15-02-09192).

References

[1]. G.M. Batanov, V.I. Belousov, Yu.F. Bondar et al, A New MIG-3 Gyrotron Complex for Creation and Heating of Plasma in the L-2M Stellarator and the First Experimental Results, Plasma Physics Reports, V.39, No 13, p. 1088 (2013)

[2]. Yu. V. Esipchuk, N.A. Kirneva, A.A. Martynov, V.M. Trukhin, Suprathermal SXR emission in ECCD experiments at the T-10 tokamak, Plasma Physics Reports, (1995), V. 21, No 7,

[3]. P.Blanchard, S.Alberti, S.Coda, H. Weisen, P. Nikkola, and I. Klimanov, Hight field side measuraments of non-thermal electron cyclotron emission on TCV plasmas with ECH and ECCD, Plasma Phys. and Control. Fussion 44 (2002) pp.2231-2249.

[4]. A. S. Sakharov and M. A. Tereshchenko, Kinetic Simulation of EC Plasma Heating and Current Drive in the L-2M Stellarator, Plasma Physics Report, (2002), Vol.28, No. 7, pp. 539-548.