Observation of non–Maxwellian soft X-ray spectra in the L-2M stellarator in experiments with ECR plasma heating

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In recent years, the ECR heating with power in the megawatt range has been used in toroidal magnetic traps [1–3]. At the L-2M stellarator, we also perform experiments on the ECR heating of plasma by high-power microwave radiation P_{ECRH} = (0.5 -0.75) MW and its further confinement [1]. In this case, specific heating power amounts to the record values ever used in toroidal magnetic traps P_{ECRH}/V_P = (2.0 -3.0) MW·m^{-3}, where P_{ECRH} is the ECRH power and V_P is volume of plasma inside the facility. Under these conditions, a number of specific features of plasma heating and confinement were revealed. One of them is the formation of non–Maxwellian electron distribution function over energies.

To measure the distribution functions of electrons over energies, we have used the soft X-ray spectrometer which was recently arranged at the L-2M stellarator. It can measure spectra in the energy range from 1 to 80 keV. A distinctive feature of this spectrometer is its high output count rate $V = 2\cdot10^5$ counts per second. This spectrometer characteristic is very important when we perform experiments on the ECR plasma heating at the L-2M stellarator

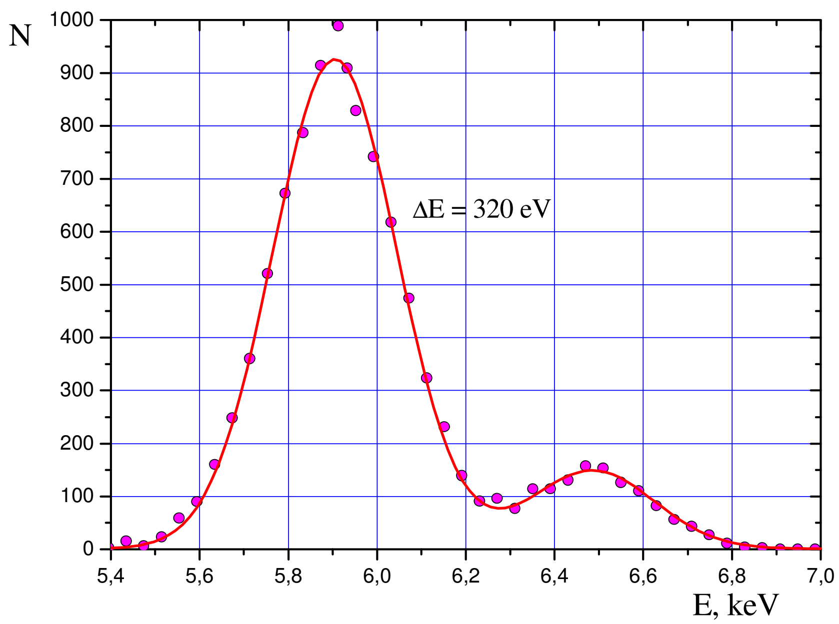

Fig. 1. Experimental emission spectrum of the ^{55}Fe source. Spectral resolution of the spectrometer determined from the spectrum is ΔE = 320 eV.

because the ECRH pulse duration is 12 ms in our experimental conditions and the duration of the quasi-stationary stage of the operation pulse is about 5 ms.

In this spectrometer, achieving of a high counting rate is accompanied by the decrease in its spectral resolution. The measured spectrum of the ^{55}Fe X-ray source is given in Fig. 1. The width at half-height of K_α and K_β lines of manganese makes it possible to determine the spectral resolution of the spectrometer in the energy range in the vicinity of 6 keV and it occurs to be ΔE = 320 eV.

Creating and heating of plasma in the experiment was carried out using two gyrotrons with total power of P = 350–400 kW. The gyrotrons' frequencies were f_1 = 75 GHz and f_2 = 71 GHz. The magnetic field in the center of the plasma column was B_0 = 1.34 T which corresponds to the location of the resonant zone of the first gyrotron in the plasma center and the resonant zone of the second gyrotron was positioned at the half of plasma radius toward the outer side of the torus. The soft X-ray spectrum was measured along the central chord in the equatorial plane of the stellarator. Full spectrum was measured during several pulses of the facility in the quasi-stationary stage of the discharges (Δt = (55–60) ms) when the basic plasma parameters reach their steady values. The mean plasma density measured along the central chord was $n_e = 2.0 \cdot 10^{19}$ m^{-3}. Figure 2 shows time dependences of the basic plasma parameters in one of the operation pulses.

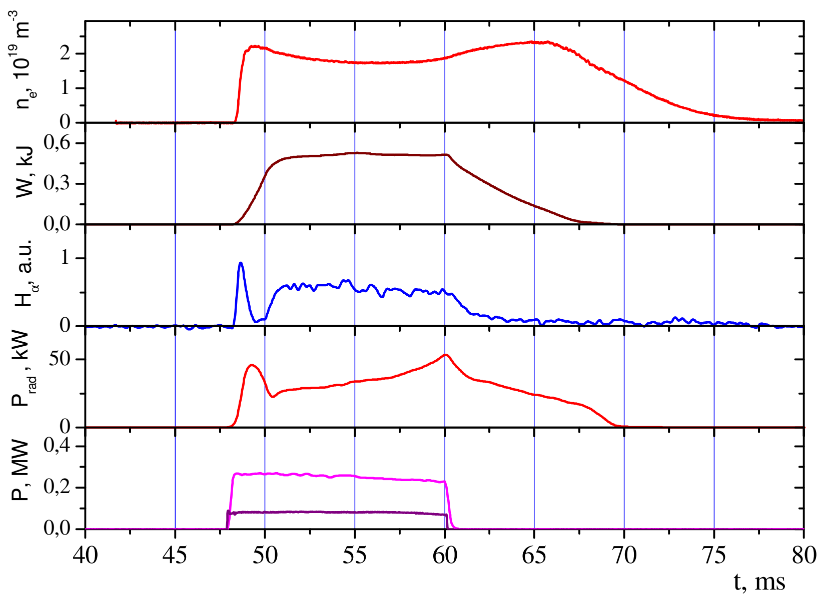

Fig. 2. Temporal development of plasma parameters and the ECRH power during the operation pulse No 18222: (a) mean plasma density measured along the central chord; (b) plasma energy content measured from diamagnetic signals; (c) H_α line intensity; (d) radiation losses; and (e) the output power of the two gyrotrons used for the ECR plasma heating.

The experimentally measured SXR spectrum is given in Fig. 3. Sharp decrease in the intensity of soft X-ray radiation in the energy range of about 2.5 keV occurs due to the presence of input beryllium foil with a thickness of d_{Be} = 800 μm. In this graph, experimental data (dots) are accompanied by the two calculated spectra. The upper and lower curves correspond to the calculated spectra with electron temperatures of T_e = 0.8 and 2.0 keV, respectively. The formation of epithermal tail is clearly seen in the energy range of $E > 5.5$ keV. In this energy range, the experimental spectrum is in good agreement with the spectrum calculated at the temperature T_e = 2.0 keV.

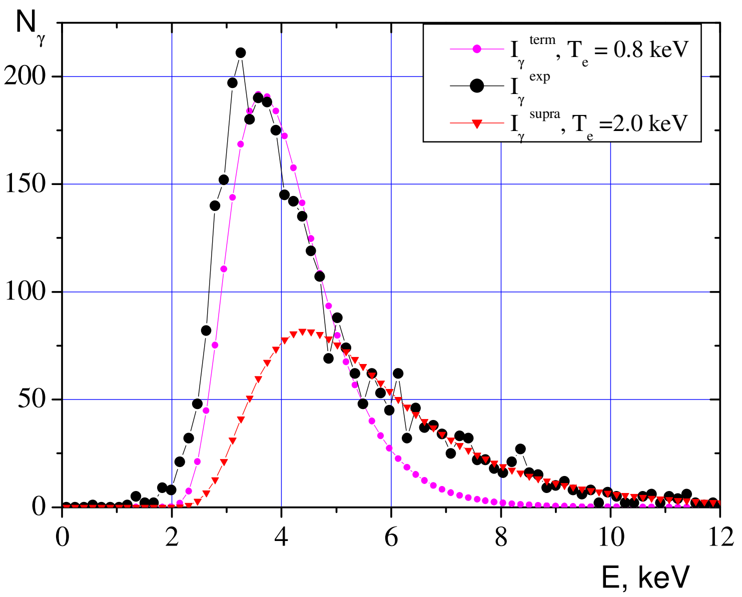

Fig. 3. Experimental SXR emission spectrum (dark dots) and the calculated spectra with T_e = 0.8 and 2.0 keV (upper and lower curves, respectively).

The experimental SRX spectrum in a semi-logarithmic scale is shown in Fig. 4. It was reconstructed taking into account the absorption of radiation by the beryllium foil. This spectrum deviates from the Maxwellian one in the energy range of $E/T_e > 7$. It can be approximated by the two straight lines with the slope angles corresponding to the temperatures of the main (thermal) and epithermal portions of electrons of T_{e1} = 0.8 keV and T_{e2} = 2.0 keV, respectively. The salient point of the spectrum corresponds to the energy of E = 5 keV or to the sevenfold temperature of the thermal portion of electrons.

In experiments on the ECR plasma heating and current drive at the TCV tokamak, the similar SXR spectra were measured [2, 3]. In these experiments, the heating power was P_{ECRH} = 2.7 MW and the specific heating power amounts to P_{ECRH} / V_p = 2.5 MW/m^{-3}. In [2, 3], the authors performed simulations of the ECRH process using the CQL3D code in which the Fokker-Planck equation was solved for the two coordinates in the velocity space (including relativistic effects) and for one spatial coordinate (minor radius). The simulation results give a non-Maxwellian distribution function of electrons over energies which, however, does not convey the two-temperature shape of the observed SXR spectra.

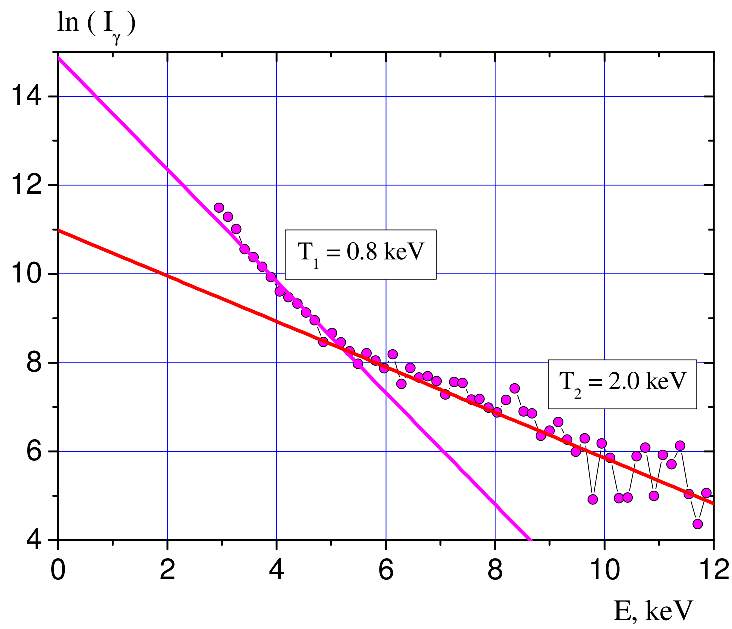

Fig. 4. The experimental SRX spectrum in a semi-logarithmic scale reconstructed taking into account the absorption of radiation by the beryllium foil.

Two-temperature emission spectrum gives grounds to assume the existence of two electron components in plasma having temperatures differing by two and a half times. In this case, the hotter component has much lower density n_{e2} = (0.01–0.03)·n_{e1}. However, there is no reasonable hypothesis of the existence of the two separate ensembles of particles in plasma which do not interact with each other.

Further experiments on the ECR plasma heating at the L-2M stellarator will be focused on determining the functional dependences of the scope angle of the epithermal part of the SXR spectrum and energy at which the SXR spectrum begins to deviate from the Maxwellian one on the heating power and plasma density.

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