Plasma confinement during ECR heating with a volume power density of 3 mW/m³ at the L-2M stellarator

A I Meshcheryakov¹, G M Batanov¹, V D Borzosekov¹,², S E Grebenshchikov¹, I A Grishina¹, N K Kharchev¹, Yu V Kolnov¹, L V Kolik¹, E M Konchekov¹,², L M Kovrizhnykh¹, A A Letunov¹, V P Logvinenko¹,², D V Malakhov¹,², D, A E Petrov¹,², K A Sarksyan¹, S V Shchepetov¹, N N Skvortsova¹,², V D Stepankin¹,², M A Tereshchenko¹, I Yu Vafin¹ and D G Vasilkov¹,³

¹ Prokhorov General Physics Institute of the Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia
² Pirogov Russian National Research Medical University, ul. Ostrovityanova 1, Moscow, 117997 Russia
³ Bauman Moscow State Technical University, ul. Vtoraya Baumanskaya 5, Moscow, 105005 Russia
⁴ Moscow Technological University (MIREA), pr. Vernadskogo 78, Moscow, 119454 Russia
⁵ RUDN University, Miklukho-Maklaya str. 6, Moscow, 117198 Russia
⁶ E-mail: meshch@flp.gpi.ru

Abstract. The experiments on ECR plasma heating were carried out at the L-2M stellarator at very high volume power density (up to 3.0 MW/m³). Under these conditions, non-monotonous hollow density profiles were measured. At the maximum heating power of \( P = 0.75 \) MW, the concavity in the axial region becomes drastic \( n_e(0)/n_{e,\text{max}} = 0.5 \). In these experiments, plasma temperature profiles measured in the axial plasma region \( r/a < 0.4 \) occur to be rather flat. We have also measured two-slope SXR spectra in the range from 2 to 12 keV. The possible reasons for these observed phenomena were discussed. However, with growing ECRH power up to \( P_{\text{ECRH}} = 0.75 \) MW, we have not observed dramatic deterioration of plasma confinement at the L-2M stellarator. The measured energy lifetime is generally consistent with that determined from the international LHD scaling.

1. Introduction
During several years, the experiments on plasma creation and heating by microwave radiation at the second harmonic of the electron cyclotron frequency were carried out at the L-2M stellarator [1]. A distinctive feature of these experiments is the high volume power density of the ECR plasma heating. Under these conditions, a number of specific features of plasma heating and confinement were revealed at the L-2M stellarator.

The gyrotron complex MIG-3 was used for plasma heating [2]. It consists of two gyrotrons with depressed collector and two quasi-optical channels. One gyrotron operates at a frequency of \( f = 75 \) GHz and has the rated microwave power of \( P = 0.8 \) MW. The second gyrotron can operate at three frequencies of \( f = 71.5, 74.8 \) and 78.2 GHz and has the rated microwave power of \( P = 0.7 \) MW. In these experiments, the maximum total power of microwave radiation launched into the stellarator...
plasma was $P = 0.75$ MW. In this case, power density of plasma heating amounts up to $P/V = 3.0$ MW/m$^3$, where $V = 0.25$ m$^3$ is plasma volume. In all experiments with ECR heating, the walls of the vacuum chamber were covered with boron-carbon film in order to reduce impurity content in plasma [3]. In this report we discuss some effects that occur in plasma due to ECR heating under these conditions.

2. Density pump-out effect during ECRH
The experiments on plasma confinement at the L-2M stellarator were carried out under the experimental conditions when the ECR heating was the only one heating method used. Time dependences of plasma parameters are given in Figure 1, total heating power of the two gyrotrons being $P = 0.4$ MW.

![Figure 1](image_url)

**Figure 1.** Time development of plasma parameters and ECRH power during the operation pulse #18222: (a) mean electron density; (b) plasma energy contents; (c) $H_\alpha$ line intensity; (d) radiation loss; and (e) input power of the two gyrotrons used for the ECR plasma heating.

At ECRH power of $P = 0.1–0.15$ MW, the electron density profiles of plasma measured by the multi-chord HCN laser interferometry diagnostics become flattened in the stationary stage of the discharge. They can be approximated by the parabolic function $n_e = n_o(1 – (r/a_p)^p)$, the exponent being $p \approx 8$. Here, $a_p$ is plasma radius. Further increase in plasma heating power results in the occurrence of non-monotuous hollow density profiles. Figure 2 presents the density profiles measured at different times under the experimental conditions similar to those shown in Figure 1. As seen from Figure 2, the initial density profile is parabolic (Figure 2, curve 1). In the course of the ECRH pulse, it is gradually transformed into non-monotonous hollow density profile (Figure 2, curve 4). After the end of the ECRH pulse, energy content of plasma gradually decreases during 7–8 ms, the mean density remaining almost unchanged, but the density profiles being transformed (see Figure 1). In two milliseconds after the end of ECRH pulse, the density profile becomes monotonous with the maximum at the axis of the plasma column (Figure 2, curve 5). This is the evidence of the fact that hollow density profiles occur as a result of ECR heating of plasma. At the maximum heating power of $P = 0.75$ MW, the concavity factor in the central region becomes drastic: $\zeta = 1 - n_e(0)/n_e^{\text{max}} = 0.5$. 

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Figure 2. Density profiles in the ECRH experiments measured at different times. (1) t = 50 ms; (2) t = 51 ms; (3) t = 52 ms; (4) t = 58 ms; and (5) t = 62 ms (t = 50 and 62 ms correspond to the 2nd ms after the ECRH switching on and the 2nd ms after the ECRH switching off, respectively (see Figure 1)).

To our opinion, the electron flow which is directed outward the heating region (the so-called “density pump-out” effect) has a strong effect on the formation of the density profile during a quasi-stationary stage of the heating pulse. The “density pump-out” effect is observed in the ECRH experiments at various tokamaks and stellarators [4, 5]. At the L-2M stellarator, the electron density pump-out effect the most strongly manifests itself due to the high ECRH power density.

3. Flattening of electron temperature profile

With growing ECRH power density, the axial electron temperature measured by the multi-chord soft X-ray (SXR) and the electron cyclotron emission (ECE) diagnostics gradually increases. According to the measurements, at heating powers of $P_{ECRH} = 0.25–0.75$ MW, radial temperature distributions in the plasma core $r/a_p < 0.4$ become flat (Figure 3, curve 1).

A flat electron temperature profile may occur as a result of non-axial absorption of ECRH power. One of the possible reasons for non-axial absorption of ECRH power is the deflection of microwave beam from the equatorial plane of plasma. The results of ray-tracing calculations performed for experiments with the axial ECR heating at the L-2M stellarator are shown in Figure 4a. Solid ellipses mark the magnetic surfaces and dotted lines correspond to the lines $|B|$ = const. The calculations were performed for the profiles of electron temperature (dashed line) and density (solid lines) shown in Figure 4b. The microwave beam trajectories 1–4 in Figure 4a correspond to the density profiles 1–4 in Figure 4b. Blue segments mark the absorption regions of microwave radiation and red line is the resonance magnetic field line. The calculations prove that, the microwave beams can be considerably deflected from the equatorial plane and some part of microwave radiation can be absorbed not at the plasma axis. In this case, the profiles of the absorbed power and electron temperature can be rather broad.
Figure 3. (1) Flattened radial profile of electron temperature and (2) the corresponding electron density profile measured at the ECR heating power of $P_{ECRH} = 0.45$ MW.

Figure 4. (a) The results of ray-tracing calculations performed for experiments with the axial ECR heating at the L-2M stellarator, (b) the electron temperature (dashed line) and density (solid lines) profiles used in calculations.

4. Observation of non-Maxwellian soft X-ray spectra in experiments on ECR plasma heating
In the experiments on ECR plasma heating with a heating power of $P_{ECRH} = (0.1–0.75)$ MW, the formation of non-Maxwellian electron distribution function over energies was observed.

To measure the distribution functions of electrons over energies, we have used the SXR spectrometer which can measure spectra in the energy range from 1 to 80 keV. A distinctive feature of this spectrometer is its high output count rate $V = 1.7 \times 10^5$ counts per second. This characteristic of the spectrometer is very important because, at the L-2M stellarator, the ECRH pulse duration is 12 ms and
the duration of the quasi-stationary stage of the operation pulse is about 5 ms. In the energy range of 6 keV, the spectral resolution of this spectrometer was $\Delta E = 320$ eV.

In these experiments, creating and heating of plasma was carried out using one gyrotron with a power of $P = 200–600$ kW and a frequency of $f_1 = 75$ GHz. The magnetic field at the axis of the plasma column was $B_0 = 1.34$ T which corresponds to the location of the resonance region at the plasma axis. Total spectrum was measured during several shots of the facility in the quasi-stationary stage of the discharges ($\Delta t = 55–60$ ms) when the basic plasma parameters reach their steady values.

**Figure 5.** The experimental SXR spectrum reconstructed with allowance for absorption of radiation by a beryllium foil (in a semi-logarithmic scale).

The SXR spectrum reconstructed with allowance for the absorption of radiation by the beryllium foil is shown in Figure 5 in a semi-logarithmic scale. The SXR spectrum was measured along the central chord in the equatorial plane of the stellarator. The mean central-chord plasma density was $n_e = 1.5 \times 10^{19}$ m$^{-3}$ and the heating power was $P_{ECRH} = 450$ kW. In the energy range of $E/T_e > 7$, this spectrum deviates from the Maxwellian one. It can be approximated by the two straight lines with the slope angles corresponding to the temperatures of the main (thermal) and supra-thermal portions of electrons of $T_e^1 = 0.85$ keV and $T_e^2 = 2.2$ keV, respectively. The salient point of the spectrum corresponds to the energy of $E = 5$ keV.

The similar two-slope SXR spectra were measured in experiments on the ECR plasma heating and current drive with high specific heating power at several tokamaks, e.g. at the T-10 [6] and TCV [7] tokamaks. Generally, in these experiments, the specific heating power heating power was high. The authors of [6, 7] suggested no explanation for the formation of two-slope spectra.

Experiments intended for determination of the plasma regions which are sources of supra-thermal electron emission were carried out at the L-2M stellarator. It was expected that the plasma heating region (region of absorption of microwave radiation) is the main source of supra-thermal electrons. A scanning system was used to measure SXR spectra along different chords in the vertical section of the plasma column in the range of impact parameters of $-0.45 < r/a < 0.65$ (see Figure 6). The straight line in Figure 6 corresponds to the Maxwellian spectrum with a temperature of $T_e = 550$ eV which corresponds to the thermal portion of the spectrum measured at a radius of $r/a = -0.45$. Negative radii correspond to the chords in the bottom half-plane of the plasma cross section. All the spectra measured along the chords in the bottom half-plane turned out to be almost Maxwellian. In the upper half-plane, a supra-thermal "tail" appears in the spectra. Its temperature and intensity increase with growing distance from the central chord and reach their maximum values at a radius of $r/a = 0.55$ cm. When
the measurements are carried out along this chord, the region in the vicinity of the separatrix X-point falls into the field of view of the spectrometer, where the plasma-wall interaction is the most intense. At longer distances from the plasma axis, the deviations of the measured spectra from the Maxwellian one become slightly smaller. The measurements performed show that, in the experiments on the axial ECR plasma heating, the supra-thermal tail of SXR spectrum is not mainly formed by electrons radiating in the plasma heating region. This issue still remains the subject of further research.

|        | r/aₚ=0.45 | r/aₚ=0 | r/aₚ=0.55 | r/aₚ=0.65 |
|--------|-----------|--------|-----------|-----------|
| ln(I)  |           |        |           |           |
| E, keV |           |        |           |           |

Figure 6. SXR spectra measured along chords with different impact parameters r/a.

5. Plasma confinement and energy lifetime data

In experiments with the maximum power density of $P/V = 3.0 \text{ MW/m}^3$, plasma density and radiation loss temporally increase during the operation shot. As the gas pufing into the L-2M chamber is switched off 30 ms before the plasma formation, this increase is a result of intensification of the plasma-wall interaction. But this fact does not negatively affect the plasma confinement. Figure 7 shows the comparison between the energy lifetime data measured in experiments with ECRH power of up to $P_{\text{ECRH}} = 0.75 \text{ MW}$ at the L-2M stellarator and the energy lifetime data calculated according to the LHD scaling. White and black points correspond to the experimental data obtained in the shots with microwave power up to $P_{\text{ECRH}} = 0.4 \text{ MW}$ and $0.4 \text{ MW} < P_{\text{ECRH}} < 0.75 \text{ MW}$, respectively. The red line corresponds to the scaling obtained previously basing on the experimental data of the L-2M stellarator [8]:

$$\tau_E^{L-2M}[s] = A n_e^{0.71}[10^{20} \text{ m}^{-3}] P^{-0.69}[\text{MW}],$$

where $A = 2.32 \times 10^{-3}$. It slightly differs from the LHD scaling (black line in Figure 7) [9]:

$$\tau_E^{LHD}[s] = 0.17 \ R^{0.34}[\text{T}] \ a^{2.0}[\text{m}] \ R^{0.75}[\text{m}] \ n_e^{0.69}[10^{20} \text{ m}^{-3}] \ P^{0.50}[\text{MW}],$$

particularly, the dependences on the heating power are different. The energy lifetimes measured at the L-2M stellarator are consistent with those determined from the LHD scaling within 15%.
Despite the increasing plasma-wall interaction, we have not observed the dramatic deterioration of plasma confinement at the L-2M stellarator when the ECRH power grows up to $P_{\text{ECRH}} = 0.75$ MW (ECRH power density increases up to 3.0 MW/m$^3$). As seen in Figure 8, there is no difference in experimental energy lifetimes in shots with low ($P_{\text{ECRH}} < 0.4$ MW) and high ($0.4$ MW $< P_{\text{ECRH}} < 0.75$ MW) heating powers.

6. Conclusions

The experiments on ECR plasma heating were carried out at the L-2M stellarator at high volume power density (up to 3.0 MW/m$^3$). Under these conditions, non-monotonous hollow density profiles were measured. At a maximum heating power density of 3.0 MW/m$^3$, the concavity in the axial region becomes drastic $n_e(0)/n_e^{\text{max}} = 0.5$. The formation of hollow density profiles can be associated with “density-pump-out” effect which the most strongly manifests itself at the L-2M stellarator due to high ECRH power density.

In these experiments, plasma temperature profiles measured in the core plasma region $r/a_p < 0.4$ occur to be rather flat. A flat electron temperature profile may occur as a result of non-axial absorption of ECRH power.

Two-slope SXR spectra were also measured in the energy range from 2 to 12 keV. In the energy range of $E/T_e > 7$, the formation of supra-thermal tails was observed in the spectra. Experiments intended for determination of the plasma regions which are sources of supra-thermal electron emission were carried out. It was revealed that the supra-thermal tails of SXR spectra are not mainly formed by electrons radiating in the plasma heating region.

Studies of plasma confinement at high ECRH power densities were carried out. With ECRH volume power density growing up to 3.0 MW/m$^3$, we have not observed dramatic deterioration of plasma confinement at the L-2M stellarator. The measured energy lifetime is generally consistent with that determined from the LHD scaling.

Further we plan to continue studies on plasma confinement in experiments on ECR plasma heating using two gyrotrons with total microwave power up to $P_{\text{ECRH}} = 1.0$ MW and study the plasma confinement at still higher power densities.
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