Transport transitions at high electron cyclotron resonance heating powers at the L-2M stellarator

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Abstract. The experimental results are presented from the experiments on the high-power electron cyclotron resonance heating (ECRH) of the current-free plasma with the power 200–500 kW (the specific power was 0.8–2 MW/m$^3$). The spontaneous transport transitions were observed that resulted in an increase in the plasma density and energy. At the ECRH powers exceeding 150 kW, the processes are observed accompanied by the abrupt changes in the plasma edge parameters, while the core plasma parameters change only slightly. At the ECRH powers exceeding 400 kW, a jump-like increase in the plasma density and energy is observed. At a power of approximately 500 kW, the regime was obtained, in which at time of transition, the plasma energy and lifetime increase by 20%, despite a decrease in the electron temperature. At the same time, at heating powers up to 700 kW, the energy lifetime corresponds on average to the L-2M single-machine stellarator scaling.

1. Introduction

The problem of using current-free methods for high-temperature plasma heating is quite relevant in terms of obtaining the plasma with fusion parameters. The spontaneous dynamic processes that lead to the improved plasma confinement are of particular interest. The experiments on the magnetic confinement of high-temperature plasma are focused on obtaining the highest plasma parameters, primarily the highest plasma energy and energy lifetime, as well as on studying the physics of the processes that may contribute to or impede obtaining the record parameters (for the given facility). After the LH transition was discovered at the ASDEX tokamak [1], many other transport transitions were observed at other tokamaks and stellarators (see, e.g., [2]).

The goal of this work is to study the transport transitions in the current-free plasma in the regimes of the electron cyclotron resonance heating (ECRH) with high specific microwave powers of 0.8–4 MW/m$^3$. The corresponding experiments were performed at the L-2M stellarator (Prokhorov General Physics Institute of the Russian Academy of Science, Moscow). The L-2M stellarator is a classical two-turn stellarator with the major radius $R = 1$ m and the minor radius $a = 0.15$ m. The magnetic field $B_0$ at the chamber axis can be varied in the range of 1–1.4 T, the rotational transformation angles $\iota$ at the axis and separatrix are 0.18 and 0.78, respectively. The detailed description of the facility can be found in [3]. The experiments were carried out in hydrogen plasma, and preliminary boronization of the vacuum chamber walls was performed using the glow discharge in helium with addition of carborane. The facility is equipped with the movable carbon-coated sector limiter. At the relatively...
low plasma pressures ($\beta = 0.2\%$), the plasma is stable relative to the large-scale ideal MHD modes. In the ECRH experiments, the bootstrap current $I_p \sim 1$ kA does not cause the development of the large-scale instabilities. In most experiments on ECRH, the energy lifetimes are $\sim 1$–$2$ ms. The diagnostic complex of the L-2M stellarator allows measuring the following plasma macroparameters: the plasma energy $W$ and absorbed heating power (the diamagnetic measurements), the radial electron temperature distribution (the diagnostics operating in the soft X-ray, cyclotron and visible frequency ranges), and the radial electron density distribution (HCN laser and microwave interferometry). The following microparameters are also measured: the plasma potential and magnetic field fluctuations (the Langmuir and magnetic probes) and plasma density fluctuations (reflectometry and gyrotron radiation scattering). At the L-2M facility, the ECR heating using the high-power pulsed microwave radiation is the main method for the plasma creating and heating. In the presented experiments, two gyrotrons were used: the first gyrotron with a power of up to $P = 0.8$ MW and a frequency of 75 GHz and the second gyrotron with a power of up to 0.7 MW and the frequency tuned to 74.8 GHz [4]. In the most of experiments, the region of microwave power absorption is in the center of the plasma cord cross-section, where the resonance field is maximal $B_0 = 1.34$ T.

2. Experimental results and discussion

In previous experiments, only one gyrotron was used for plasma heating and the ECRH power was 50–250 kW. Based on those experimental results, the database was compiled and analyzed, and the L-2M scaling was written [5]. Since, the profiles of the plasma parameters in the edge region of the L-2M plasma were measured with the resolution insufficient for identifying the transport processes, a drop in the $H_\alpha$ signal and a change in the electric field in the edge plasma region were used as markers that indicate the presence of transport transitions. For the first time, the spontaneous transport transitions at the L-2M stellarator were observed in experiments with the ECRH powers exceeding the threshold power $P = 150$ kW, and simultaneously, sharp changes were observed in the plasma edge electrostatic characteristics that indicated the electric field redistribution in the plasma volume [6].

![Figure 1](image-url)  
Figure 1. Transport transitions at heating powers of (a, b) 200 and (c, d) 450 kW. (a, c) diamagnetic signal, which is proportional to $dW/dt$, and energy $W$, (b, d) central-chord-averaged electron density $n_e$ and floating potential signal $V_f$ measured by the Langmuir probe. The vertical lines indicate the times of transition and switching-off the heating power.
The transport transitions were identified by a small negative drop on the $dW/dt$ signal (Figure 1a), and subsequently, the total plasma energy $W$ quickly increased to its initial value or even became 10% higher. The most considerable changes occurred in the edge region, which were indicated by a decrease in the floating potential $V_f$ measured by the Langmuir probe (Figure 1b). The presented data correspond to the shot with the ECRH power $P = 200$ kW, slightly exceeding the threshold power. Subsequently, the model of local resistive MHD instabilities (peeling modes) was developed theoretically describing these phenomena [7, 8]. Apparently, the instability that develops in the stellarator separatrix region leads to an increase in the plasma density and temperature gradients, and as a result, to the ejection of plasma from this region.

After the gyrotron complex was upgraded, several series of experiments were performed in order to obtain the maximum plasma parameters (primarily, the maximum plasma energy), in which the inputted ECRH power was gradually increased. In the experiments described, the inputted power was in the range of 200–1000 kW in the single-pulse regime (the rectangular 12-ms-pulse of one gyrotron or two gyrotrons operating simultaneously) that corresponds to the specific powers 0.8–4 MW/m$^3$. In Figures 1c and 1d, the plasma characteristics are presented in shot with the ECRH power $P = 450$ kW. In the stationary discharge stage, there is no clear drop on the $dW/dt$ signal (in contrast to the previous lower-power case), although the strong fluctuations are observed on it before the transition.

![Figure 2](image-url)  
**Figure 2.** Time evolution of plasma parameters in shot with transport transition at $P = 500$ kW: (a) ECRH power $P$ (left axis) and the average electron density of the plasma $n_e$ (right axis); (b) diamagnetic signal $dW/dt$ (left axis) and the plasma energy $W$ (right axis); (c) radiation loss power $P_{\text{rad}}$ (left axis), the intensities of the BII (right axis) and $H_\alpha$ (right axis) emission lines; and (d) electron temperature at the axis of the plasma column and at 0.7 of the plasma radius.

The results from the experiment on plasma heating with the help of two simultaneously operating gyrotrons with the total power of $P = 500$ kW are presented in Figure 2. We note that in this shot, the experimental data on the plasma parameters were obtained immediately after the boronization of the vacuum chamber walls of the L-2M stellarator [9]. After the transition, the plasma density and energy sharply increase by 1.5 times and 20%, respectively. After the transition, the cyclotron emission measurements at different plasma radii also indicated the simultaneous cooling of the entire plasma column. Apparently, this occurred due to the accumulation of impurities in the plasma volume after the transport transition that indicates the improvement of particle confinement after the transition. At the same time, there is a decrease in the intensity of the $H_\alpha$ hydrogen line, an increase in
the intensity of the boron ion line $B_{II}$, and an increase in the radiation losses in a wide wavelength range from UV to XR, which is recorded by the bolometer. These data indicate that at this time, the plasma transition to the H mode occurred in the L-2M stellarator. Such markers of the transport transitions were observed as an increase in the plasma energy and density and a drop in the $H_{a}$ intensity, as well as the 20%-increase in the dynamic energy lifetime. Such transport transitions occur randomly; for example, in the next shot, no transition was observed. We also note that the energies and lifetimes obtained at the high ECRH powers (up to 700 kW) generally correspond to the scaling obtained for the low powers [5].

In the experiments with the ECRH powers in the range from 700 kW to 1 MW (the specific powers are up to 4 MW/m$^{3}$), the transport transitions occur in the larger number of shots, although the energy increase during the transition becomes less (~10%). The transition time is most clearly fixed on the spectroscopic signals. We note that at the time of transition, the intensity of soft X-ray plasma emission also considerably increases and the electron temperature slightly drops. This also indicates an increase in the concentration of impurities and an increase in the radiation losses from the core plasma region that resulted in the plasma cooling. It is important that at ECRH powers higher than 700 kW, the plasma energy no longer corresponds to the L-2M scaling; it becomes lower by 10–15% [10]. The increased plasma instability made it necessary to introduce the graphite-coated limiter into the plasma to a depth of 1 cm, which reduced the plasma volume by means of cutting off its boundary region. As a result, the energy accumulated in the plasma decreased and the transport transitions were suppressed.

3. Summary

The results are presented from the experiments on the ECR heating of the current-free plasma with powers in the range of 200–500 kW (the specific powers were in the range of 0.8–2 MW/m$^{3}$). The spontaneous transport transitions were observed that resulted in an increase in the plasma density and energy. At the ECRH powers exceeding 150 kW, the processes are observed manifesting themselves in sharp changes in the plasma edge parameters, while in the core plasma region, the plasma parameters change only slightly. At the ECRH powers exceeding 400 kW, a jump-like increase in the plasma density and energy is observed. At a heating power of 500 kW, the regime was obtained, in which at the time of transition, the plasma energy and lifetime increase by 20% despite the plasma cooling. At the same time, at higher ECRH powers up to 700 kW, the energy lifetime corresponds on average to the L-2M single-machine stellarator scaling while in shots with ECRH powers in the range of 700–1000 kW, the energy lifetime no longer corresponds to the L-2M scaling and becomes lower by 10–15%.

Acknowledgments

The authors are grateful to the L-2M team for the experimental data provided.

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