Dynamics of plasma confinement during ECR heating in the L-2M stellarator

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Abstract. Dynamics of plasma confinement was considered in the experiments on ECR plasma heating in the L-2M stellarator. It was ascertained that four stages can be distinguished in the process of plasma heating and further cooling. In each stage, plasma confinement has its own distinctive features. In the first stage, plasma confinement is determined by radiation loss. In the second stage, the self-consistent profiles of electron temperature and density form in plasma and the quasi-stationary confinement mode ensues. After ECRH switching off, the third stage begins. The plasma starts cooling and its parameters change in accordance with the scaling of the L-2M stellarator, the self-consistent electron temperature and density profiles being maintained. After the plasma periphery becomes cooled, the fourth stage of plasma confinement starts, and radiation loss becomes a determinative factor again.

1. Introduction
At the L-2M stellarator, the electron cyclotron resonance heating (ECRH) is the basic method for plasma heating. ECRH power is in the range of 100–800 kW at the ECRH pulse duration of 10 ms. In the quasi-stationary stage of the discharge, plasma energy content amounts to 0.8 kJ at a density of $2.5 \times 10^{19} \text{ m}^{-3}$. In this article, we have studied the dynamics of plasma confinement not only in the quasi-stationary stage of the discharge but also in the stages of initial plasma heating and plasma cooling. The last stage occurs after ECRH switching off.

2. Dynamics of plasma confinement
The dynamics of plasma confinement in the L-2M stellarator will be studied by means of analyzing shot #20464. Time evolution of the fundamental plasma parameters in this shot is shown in Figure 1. The figure shows (from top to bottom) the plasma density averaged along the central chord $n_e(t)$, plasma energy content $W(t)$ and its derivative $dW(t)/dt$, intensity of the BII boron ion line $I_{BII}(t)$, power of radiation loss $P_{\text{rad}}(t)$, ECRH power $P_{\text{ECRH}}(t)$ and floating potential of the limiter $U_{\text{LIM}}(t)$. During the first millisecond of heating, the plasma density averaged along the central chord reaches its steady-state value of $2.4 \times 10^{19} \text{ m}^{-3}$, which remains approximately constant until, after ECRH pulse is switched off, the recombination of ions starts. In this shot, the maximum plasma energy content was approximately ~500 J at ECRH power of approximately 200 kW. It can be seen from the figure that, in the course of plasma heating and cooling, four stages of plasma confinement can be distinguished. In the figure, the times of the transitions between the stages are marked by vertical lines. In the first
stage, the creation and initial heating of plasma occur. The energy content of the plasma rapidly increases; the impurities which were initially present in the plasma volume become ionized and the spectral lines of impurity ions with a low degree of ionization disappear. Then a step-wise transition to the second quasi-stationary stage of the plasma confinement occurs which takes time of the order of 200 μs. In Figure 1, the beginning of this stage corresponds to a jump in the dW/dt signal at the 54 ms. This transition is also seen on the waveforms of other signals. The \( I_{\text{eff}}(t) \) signal reaches its minimum and, after a sharp decrease, radiation loss becomes stationary. After ECR heating is switched off at the 60 ms, the plasma cooling starts. It lasts for ~10 ms, which is of the same order as the duration of the heating pulse. Two more stages of the plasma confinement can be distinguished in the course of plasma cooling. At the beginning of the third stage, the plasma energy content starts to decrease and a corresponding jump is observed in the dW/dt signal. The beginning of the fourth stage of plasma confinement corresponds to a certain increase in the radiation loss signal, which occurs in the course of plasma cooling, and a sharp drop to zero of the floating potential on the limiter.

To analyze the dynamics of plasma confinement in the L-2M stellarator and to more accurately differentiate the stages of plasma confinement, we will use the concept of the dynamic energy lifetime which is defined as a ratio of the energy content of plasma \( W(t) \) to the total loss power \( P_{\text{loss}}(t) \) at each time:

\[
\tau_{E,\text{din}}(t) = \frac{W(t)}{P_{\text{loss}}(t)}.
\]

The total loss power was determined from the global equation of energy balance:

\[
dW/dt = P_{\text{ECRH}}(t) - P_{\text{loss}}(t).
\]

The time development of the dynamic energy lifetime in shot #20464 under consideration is shown in Figure 2. The same four stages of plasma confinement discussed above can be seen in the figure, and the times of transition between the stages are more clearly visible. In particular, the transition from the third stage to the fourth one in the stage of plasma cooling is clearly visible. It occurs when an increase in the plasma dynamic energy lifetime is changed by its fall. In the figure, orange, red, green and blue colors correspond to the first, second, third and fourth stages of plasma confinement, respectively. In Figure 2, the times of the transitions between the stages are also marked by vertical lines. We also note that the transition of plasma from the stage of heating to the quasi-stationary stage is accompanied by an abrupt drop in the dynamic energy lifetime by more than a factor of two. Such a change in the energy lifetime is enormously great for stellarators. For example, during L-H transport transitions in stellarators, only a 20–30% change in the energy lifetime is observed [1].
Figure 2. Time development of the dynamic energy lifetime in shot #20464.

Figure 3. Total loss power as a function of plasma energy content for the same shot #20464.

The dependence of total loss power on the plasma energy content for the same shot #20464 is shown in Figure 3. Stepwise transitions between the stages of plasma confinement can be also seen in the figure. The stages of plasma confinement in Figure 3 are marked by the same colors as in Figure 2. It can be seen in this diagram, that the $P_{\text{loss}}(W)$ dependences in the stages of plasma heating and cooling are different. There is a hysteresis on the measured dependence. Similar dependences with hysteresis were also obtained in experiments on the modulated ECR heating of plasma at other facilities: at the LHD, TJ-II, and W7-AS stellarators and the DIII-D, JT-6U and KSTAR tokamaks [2, 3, 4]. The dependence in Figure 3 differs from the dependences obtained at the facilities mentioned above. In these facilities, the hysteresis was observed on the dependences of the heat flux on the local temperature gradient at a certain point along the radius, while, in the experiments reported here, the hysteresis was observed on the dependence of the total loss power on the plasma energy content. It can be seen in Figure 3 that, in the second and third stages of plasma confinement, the radiation loss power is much less than the total loss power, that is, the power loss due to the thermal conductivity in the electron component is the main part of the total loss power $P_{\text{loss}}$. Obviously, an increase in the plasma energy content inevitably results in an increase in the temperature gradient. Therefore, the dependence in Figure 3 describes the same phenomenon as the dependences with hysteresis obtained at the other facilities.

Let us consider the processes occurring in plasma in different stages of its confinement. In the first stage, the plasma is created and heated. Heating starts in the core region (the region of the resonant absorption of ECR radiation). Then heat spreads from the axis to the periphery. During the entire first stage, the plasma periphery remains cold. It follows from the absence of the signal of the floating potential of the Langmuir probe which is installed to the depth of 5 mm inside plasma. As a result, the heat flux power transferred to the wall due to thermal conductivity and diffusion is low and the total loss power $P_{\text{loss}}$ is mainly determined by radiation loss. The low values of particle flux to the wall are confirmed by the absence of the floating potential on the diaphragm installed outside plasma (see Figure 1). The gradual ionization of the impurity ions occurs and the spectral lines of impurity ions with a low degree of ionization disappear. For example, Figure 1 demonstrates the disappearance of the BII line which occurs in the absence of particle flux from the wall. It can be seen in Figure 3, that the specific feature of the first stage consist in the fact that, during this stage, the total loss power remains approximately constant, while the plasma energy content increases by several times, and all this power loss occurs due to the plasma radiation (radiation loss). The first stage ends when the plasma periphery gets warm (the signal of the floating potential appears at the Langmuir probe), and its temperature rises up to the values at which an intensive plasma-wall interaction becomes possible, and the heat flux to the wall becomes considerable. The process of establishing considerable heat and
particle fluxes lasts for a very short time (approximately 200 µs). This just corresponds to the fast transition to the second quasi-stationary stage of plasma confinement.

In the second stage, an additional loss channel is opened in plasma which is associated with the appearance of intense particle and energy fluxes to the wall (thermal conductivity and diffusion). The appearance of the negative floating potential on the limiter confirms this. As a result of the appearance of an additional loss channel, in the course of transition to the second stage, a twofold drop in the dynamic energy lifetime of plasma occurs (see Figure 2). During the second stage, the dynamic energy lifetime remains constant, despite the fact that the plasma energy content increases by ~30% (see Figures 1 and 2). This is due to the fact that, during of the second stage, the transformation of the electron density and temperature profiles occurs. The self-consistent profiles are established, in the presence of which the losses due to thermal conductivity and diffusion become optimal. As a result, by the end of the second stage, a quasi-stationary state of plasma confinement is established, for which a single-facility scaling for the L-2M stellarator is determined in the following form [5, 6]:

\[ \tau_{E}^{L-2M}[s] = A \cdot n_{e}^{0.71} \cdot (\frac{P_{ECRH}}{W})^{0.69} [MW], \]  

(1)

where \( \tau_{E}^{L-2M} = \frac{W}{P_{ECRH}} \) is plasma energy lifetime in the quasi-stationary stage of the discharge, \( n_{e} \) is electron density averaged along the central chord, and \( A = 2.32 \cdot 10^{-3} \). It slightly differs from the LHD scaling [7]; especially different is the dependence of the energy lifetime on the heating power.

The transition from the second stage of plasma confinement to the third one occurs when the ECR plasma heating is switched off. This transition occurs stepwise (see Figure 3) and, hypothetically, it has the same nature as the abrupt decrease in the heat flux to the wall carried by the electron component which occurs at time when the ECR heating is switched off. It was observed at the fusion facilities mentioned above [8]. In [2], the authors associate an abrupt decrease in the heat flux with a sharp decrease in the plasma turbulence which occurs at time of the transition. The third stage is characterized by a decrease in the plasma energy content which occurs at the constant mean density and radiation loss power \( P_{rad} \) (Figure 1). In this stage, the losses due to thermal conductivity considerably exceed the radiation loss. It turned out that, in the third stage, the dependences of the dynamic energy lifetime on the electron density and total loss power are the same as those described by scaling (1) which was written for the quasi-stationary stage of the discharge. For the third stage, this dependence can be obtained from formula (1), if we take into account that, after ECRH is switched off, in formula (1), the heating power \( P_{ECRH} \) should be replaced by the total loss power \( P_{loss} \) calculated from the global equation of energy balance. It can be seen from Figure 2 that, in the third stage, the dynamic energy lifetime increases linearly with time. The linear dependence \( \tau_{din}^{L-2M}(t) \) can be obtained from the energy balance equation by substituting into it the dependence \( P_{loss}(W) = P_{0}(W/W_{0})^{3.3} \) which is an approximation of the experimental data (Figure 3, curve 1). Here \( P_{0} \) and \( W_{0} \) are numerical coefficients. We note that the dependence \( P_{loss}(W) \) obtained experimentally for the third stage is a fundamental dependence for the L-2M stellarator, since it characterizes the plasma confinement which can be achieved with the help of the magnetic system of this facility.

The transition from the third stage of plasma confinement to the fourth one occurs due to the fact that the plasma energy content continues to decrease, and the losses due to thermal conductivity also decrease and become much less than the radiation loss. In other words, there occurs a change of the main mechanism that determines the energy loss. In the fourth stage, the radiation loss becomes determinative again. This conclusion can be drawn on the basis of Figure 3, which shows powers of the total and radiation losses, including those for the fourth stage. The transition from the third stage to the fourth one is clearly visible in Figure 2. It occurs when the growth of the dynamic energy lifetime changes to its fall. The plasma periphery becomes cool and the interaction with the wall almost disappears. In this stage, cooling of the plasma periphery is confirmed by the decrease to nearly zero in the ion saturation current of the Langmuir probe installed to a depth of 5 mm inside plasma. The presence of the cold periphery is the general property that characterizes plasma confinement in the first and fourth stages. In the fourth stage, the total loss power is somewhat lower than in the first stage (see Figure 3) since the radiation loss is higher than in the first stage. Apparently, this is due to a decrease in the amount of impurities in plasma which occurs during the ECRH pulse.
3. Conclusions

Thus, in experiments on ECR plasma heating in the L-2M stellarator, four stages can be defined in the process of plasma heating and cooling. In each stage, plasma confinement has its own characteristic features. In the first and fourth stages, the total thermal loss of plasma is mainly determined by the radiation loss. The plasma periphery remains cold which provides low losses due to thermal conductivity and diffusion. In the second confinement stage, there occurs a transformation of the electron temperature and density profiles in plasma. The self-consistent temperature and density profiles are formed with which the losses for thermal conductivity and diffusion become optimal. After the ECRH pulse is switched off, the plasma starts cooling at a constant density. Two more stages of plasma confinement can be defined. In the third stage, the plasma-wall interaction still remains considerable, and the self-consistent temperature and density profiles still survive in plasma. At the same time, the dynamic energy lifetime increases linearly with time which is in accordance with the scaling law of the L-2M stellarator which is valid for the quasi-stationary stage of the discharge. When the plasma edge becomes cool, the third stage smoothly passes into the fourth stage which is characterized by the constant total thermal loss mainly determined by the radiation loss.

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