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Study on Degradation of Energy Confinement on L-2M Stellarator

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Abstract

Power degradation has been observed in ECRH experiments on stellarators[1-5]. In order to find out characteristic features of the degradation phenomenon, experiments of the following three types were run in the L-2M stellarator: (a) Global analysis of stationary phases, which might present evidence of the power degradation of confinement and the incremental confinement time; (b) Study of dynamic phases with stepping the heating power by its relatively small portion; (c) Study of transition from the heating phase to the free-decay phase.

Keywords:

stellarator, degradation of confinement, heating efficiency

1. Introduction

There are at least three phenomena that are observed consistently in plasma experiments. In our opinion, all these phenomena can be of the same origin, specifically, the nonlinear dependence of heat losses on the plasma energy or plasma temperature. First, the plasma energy W depends on the heating power P as $W=\text{const.}P^{\alpha}$. The exponent α decreases with increasing P, leading to a weaker dependence of W on P. Second, the heating efficiency decreases with increasing P. The phenomena of the third group are those occurring during transient phases of discharges when the heating power is stepped up or down. In the present work, we study these phenomena and attempt to find out their common features. Our analysis is based on results of the recent ECRH experiments in the L-2M stellarator.

2. Experimental and Simulation Model Results

The stellarator has a minor plasma radius $a=11.5$ cm and a major plasma radius $R=100$ cm. The characteristic property of the L-2M stellarator is the strong shear: the central/edge rotational transform ratio is $\iota_c/\iota_e=0.2/0.7$. In the ECRH experiments, the magnetic field was $B=1.34$ T, and the heating power was varied from 0.1 to 0.3 MW. We used a 75 GHz gyrotron and a transmission system focusing a gaussian microwave beam on the magnetic axis. A movable carbon limiter was used to decrease the plasma radius and thus prevent the plasma – wall interaction, which allowed us to control the impurity concentration and plasma density. The plasma radius was $a=9$ cm in these experiments. As the heating power was increased, the electron temperature raised from 0.4 to 0.9 keV, and plasma energy

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increased from 170 to 270 J. It should be noted that the heating power was the only parameter governing values of the electron temperature and plasma energy. Other conditions, such as the magnetic field configuration and the time behavior of the density, were kept constant ($n_e = 1\times10^{19}$ m^{-3}).

Figure 1 shows the dependence of the plasma energy on the heating power. One can see that the dependence $W(P)$ is obviously nonlinear: the energy increases from 170 to 270 J as the heating power varies from 0.1 to 0.3 MW. Hence, the energy confinement time $\tau_E = W/P$ decreases with increasing P, which is reflected in the change in the incremental confinement time $\tau_{inc} = \mathrm{d}W/\mathrm{d}P$ (see Fig. 1). Thus, the experimental evidence suggests that the degradation of energy confinement takes place for ECR plasma heating in the L-2M stellarator.

Analysis of the power balance was performed by using the power balance equation in the following form:

$$\mathrm{d}W/\mathrm{d}t = -P_{loss} + P\,,$$

where P is the heating power, and P_{loss} is the overall loss power including losses through thermal conductivity, convection, radiation, charge exchange as well as anomalous losses.

For steady state ($\mathrm{d}W/\mathrm{d}t = 0$)

$$P_{loss} = P$$

For our analysis we take quite a different approach from that used in our previous works. In the coordinates (W, P), the loss power is a function of the plasma energy and is determined by the plasma state (W, P) in accordance with the nonlinear dependence $W(P)$.

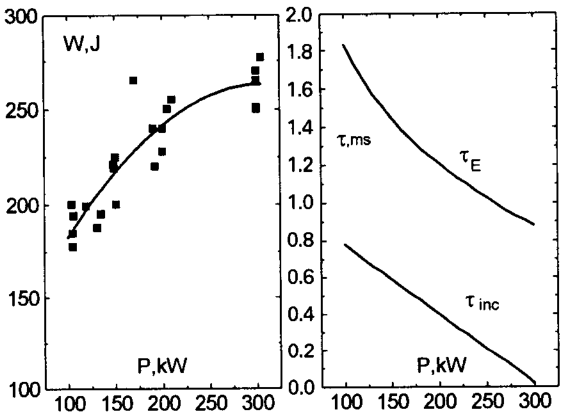

Fig. 1 Plasma energy (W), energy confinement time (τ_E) and incremental confinement time (τ_{inc}) versus heating ECR power (P).

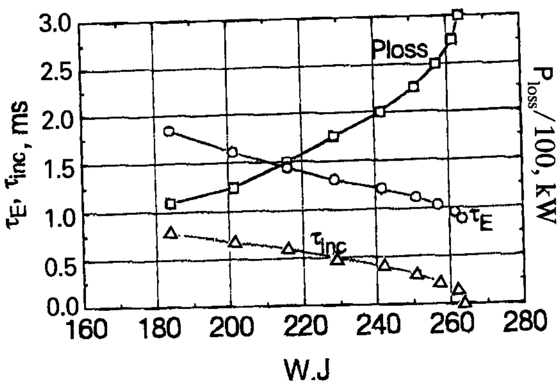

Fig. 2 Dependence of the P_{loss}, τ_E, τ_{inc} on the plasma energy.

Making use of $P(W)$ we can perform analysis of temporal processes occurring in various plasma experiments. The validity of this approach can be determined by comparison of the calculated dependencies $W(t)$ to the experimental data. Then we can estimate the applicability limits of such a simple model involving the function $P_{loss}(W)$ determined from the quasisteady state of plasma. The dependence $P_{loss}(W)$, $\tau_E(W)$, $\tau_{inc}(W)$ for the set of ECRH experiments is shown in Fig. 2

The absorbed power was obtained, in the usual fashion, from analysis of the power balance equation at time t_0 of switching-off the heating power. In our case, this equation is written as

$$P_{ab} = \mathrm{d}W/\mathrm{d}t(t_1) - \mathrm{d}W/\mathrm{d}t(t_2) + P_{loss}(t_1) - P_{loss}(t_2)\,,$$

where $t_1 < t_0 < t_2$.

In determining P_{ab}, a ground rule is to choose the time interval $\Delta t = t_2 - t_1$ such that variation in P_{loss} is negligible. The change in $\mathrm{d}W/\mathrm{d}t$ can be determined from diamagnetic measurements and otherwise from local measurements of T_e and n_e by Thomson scattering. The diamagnetic measurements has the advantage that these measurements provide the high time resolution (10 μs); for this reason we used the diamagnetic data in our analysis of the power balance.

Figure 3(a) shows the time behavior of $\mathrm{d}W/\mathrm{d}t$ during free decay for two initial values of the heating power: 100 and 300 kW. As is seen in the figure, $\mathrm{d}W/\mathrm{d}t$ varies more rapidly in the case $P = 300$ kW, in which case Δt should be shorter than 0.1 ms. With preliminary determined function $P_{loss}(W)$ we calculated the time bahavior of $\mathrm{d}W/\mathrm{d}t$ during free decay. The results of our calculations are shown in Fig. 3(b) for comparison. In both cases (100 and 300 kW) the heating efficiency $\eta = P_{ab}/P$ was close to unity in these experiments. In

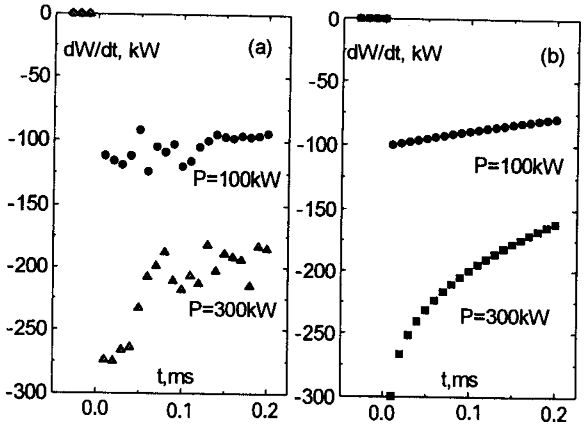

Fig. 3 Temporal evolution of dW/dt during transition to the free decay phase ($t_0 = 0$) for two values of the initial P (100 and 300 kW).
(a) experimental data, (b) data of calculations.

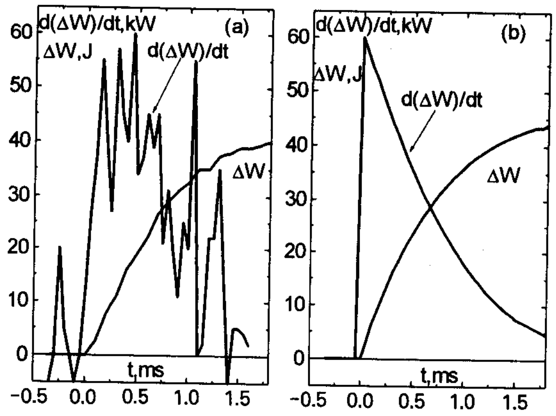

Fig. 4 Temporal evolution of $d(\Delta W)/dt$ and ΔW during transition phase from the state ($W_1 = 160$ J, $P_1 = 110$ kW) to the state ($W_2 = 200$ J, $P_2 = 170$ kW).
(a) experimental data, (b) data of calculations.

connection with this, caution is required in the conclusion about the degradation of the ECR heating efficiency in toroidal magnetic confinement systems.

In the experiments with stepping the heating power from one level to another, our aim was to study degradation of the energy confinement during transition from one plasma energy level (W_1) to another (W_2); $\Delta W = W_2 - W_1$ was smaller than W_1, W_2. The results of the stepping experiment are represented in Fig. 4(a). It is seen that the quantity ΔW reaches its steady level for a time $\delta t = 1.4$ ms, whereas the energy confinement time is $\tau_E = 1.5-1.6$ ms. In this case, the time interval δt is several times larger than the incremental confinement time: $\delta t = 2.5\tau_{inc}$. With the power balance equation and the preliminary determined function $P_{loss}(W)$, we calculated the time dependencies of ΔW and $d(\Delta W)/dt$; these are shown in Fig. 4(b). The calculated and experimental dependencies show fairly good agreement. This lends support to the validity of our simple model used to simulate the plasma behavior during the dynamic phase. It should be noted that this simulation model by which the function $P_{loss}(W)$ describing the quasisteady state of plasma is applied to the dynamic phases may be used when the plasma energy varies by at least no more than 0.2 of its initial level.

If $P = P(0) + p$, $W = W(0) + w$ ($w \ll W(0)$, $p \ll P(0)$), the power balance equation can be written as

$$d(W(0) + w)/dt = -P_{loss}(0) - dP_{loss}/dW(0)^* w + P(0) + p$$

or

$$dw/dt = -w/\tau_{inc} + p$$

The solution for stepping heating power is

$$w = p^* \tau_{inc}{}^* (1 - \exp(-t/\tau_{inc}))$$

and for power modulation ($p(t) = p^* \sin(\omega^* t)$) is

$$w = p^* \sin(\omega^* \tau - \varphi)/(1 + (\omega^* \tau_{inc})^2)^{0.5},$$

$$\tan(\varphi) = \omega^* \tau_{inc}$$

Phase shift (φ) determines time delay of heat wave.

It means that incremental confinement time determines the time evolution of plasma energy for stepping of heating power and the time delay of heat wave for power modulation.

3. Conclusion

(1) The phenomenon of nonlinear dependence of the plasma energy on the heating power, which leads to quasi-saturation of the plasma energy at high values of the heating power, is accompanied by an increase in the plasma heat losses.

(2) The temporal evolution of the plasma energy during transition from one quasi-steady state of plasma to another (corresponding to another level of the plasma energy) and during the free-decay phase of the discharge is described well with the power balance equation and the heat loss power function $P_{loss}(W)$ describing heat losses for the quasi-steady state (W, P).

(3) The ECR heating efficiency was found to be close to unity in the L-2M experiments. However, we would like to see these unique findings verified also in other devices.

(4) The nonlinear dependence $P_{loss}(W)$ leads to quasi-saturation of the plasma energy for high values of the

heating power and to decrease in τ_E and τ_{inc}, and determines the temporal evolution of the plasma during the dynamic and free-decay phases.

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