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Improvement of start-up in tokamaks by modulation of ECR source.

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1. Introduction. In order to decrease the loop voltage at the stage of start-up the ECR heating is used in recent tokamaks. It is considered to be used in ITER [1]. Nevertheless, the overcoming of radiation barrier related to the radiation losses maxima requires high power ECR sources. The efficiency of sources may be improved by low frequency modulation. As it shown earlier [2, 3] 20÷30 % temperature oscillations may decrease radiation losses by factor 1.3÷1.5. The reason of the decrease is the strong dependence of ionization rate on the electron temperature. The recombination rate depends on the temperature not so strong. Hence:

- under the temperature oscillations the effective temperature related to ionization-recombination processes is higher than in steady state. Lithium-like ions are stripped more effectively. One can find the shift of the ionization balance [2, 3]. On the other hand, the radiation in lines of lithium-like ion is significantly higher than the helium-like ion radiation and the last is significantly higher than the hydrogen-like one;
- the electron temperature oscillations decrease radiation losses;
- the low frequency modulation of the ECR heating power may decrease the radiation barrier and the averaged ECR heating power required respectively.

2. Elementary model. In order to separate the pure effect the reduced model has been used at the first step of investigations. The electron temperature has been supposed to be determined by the balance of ECR heating and impurity radiation losses.

$$3n\frac{dT}{dt} = S - Q\,. \qquad (1)$$

Here $T_e = T_i \equiv T$ is the temperature, $S = S_0(1+\alpha\cos\omega t)$ is the modulated ECR heating power, $Q = n n_I \sum y_z L_z(T)$ is the power radiated by the impurity in lines, $n = n_e \approx n_i$ is the hydrogen plasma density, n_I is the total impurity density, y_z is the relative concentration of the ions with the ion charge z, $\sum_z y_z = 1$, $L_z(T)$ is the radiation function. The expressions for $L_z(T)$ have been taken from Ref. [4]. Ohmic heating, as well as the energy losses related to the heat conductivity and convection have been ignored. Impurity distribution over ionization states has been supposed to be determined by usual set of equations:

$$\frac{dy_z}{dt} = -n\left(y_z\left(J_z + R_z\right) - R_{z+1}y_{z+1} - J_{z-1}y_{z-1}\right). \qquad (2)$$

Here J_z and R_z are the ionization and recombination rates respectively. Photo- and dielectronic recombinations and ionization by electron impact have been taken into account with expressions taken from [4]. The set of equations (1, 2) has been solved numerically for carbon seeded plasmas. The problem of the breakdown is not examined here. The initial conditions have been chosen as the coronal equilibrium at $T = 3eV$. The results are shown in Fig. 1 for the equal averaged ECR powers and for different values of α. One can see that the temperature is approximately constant at the first stage ($t < \tau$). Then the radiation barrier is overcome. The temperature rises rapidly after $t = \tau$. The time τ may be defined as the time of the radiation barrier overcoming. It depends on the value of α and decreases with the increase of α.

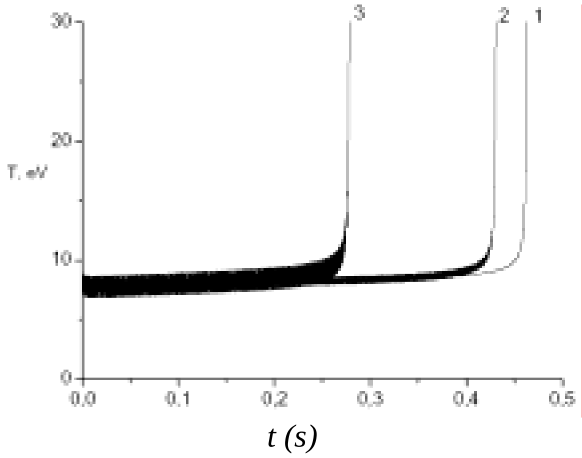


Fig. 1. Temporal temperature evolution in carbon seeded plasmas. Averaged specific ECR *power* $S_0 = 9.8 \cdot 10^{-2}\ W \cdot cm^{-3}$, $n_I / n = 10^{-2}$, $\alpha = 0$,0.1 *and* 0.3 *for curves 1, 2 and 3 respectively.*

Moreover, the radiation barrier may be overcome in modulated regime even if the averaged ECR power is not sufficient for overcoming the barrier in non-modulated regime.

However, the value of α is not arbitrary. It is limited by the temperature of the ECR heating source. If the cathode temperature exceeds some value determined by the construction of the machine the latest may be destroyed. The equation for the cathode temperature takes the form:

$$MC \frac{dT_{cd}}{dt} = S_0 \eta (1 + \alpha \cos \omega t) - P . \qquad (3)$$

Here M is the cathode mass, C is the specific heat capacity, η is the ratio of the power absorbed in the cathode to the output power, and P is the power brought out by the cooler. For the non-modulated regime one can write:

$$S\eta = P . \qquad (4)$$

Ignoring the T-dependence of P one can get the upper estimation for the amplitude of temperature oscillations:

$$\tilde{T}_{\max} = \frac{S_0 \eta}{MC} \cdot \frac{\alpha}{\omega} . \qquad (5)$$

Hence, one has to compare the regimes with equal ratios α / ω. The value of the ratio α / ω depends on technical details of the source. The ratio has been assumed to be the arbitrary parameter in the present paper. The dependence of the radiation barrier overcoming time τ on the modulation frequency $\nu = \omega / 2\pi$ is shown in Fig. 2. One can see that the modulation may reduce the value of τ by factor 10 or more for $\alpha / \omega = 10^{-3}$.

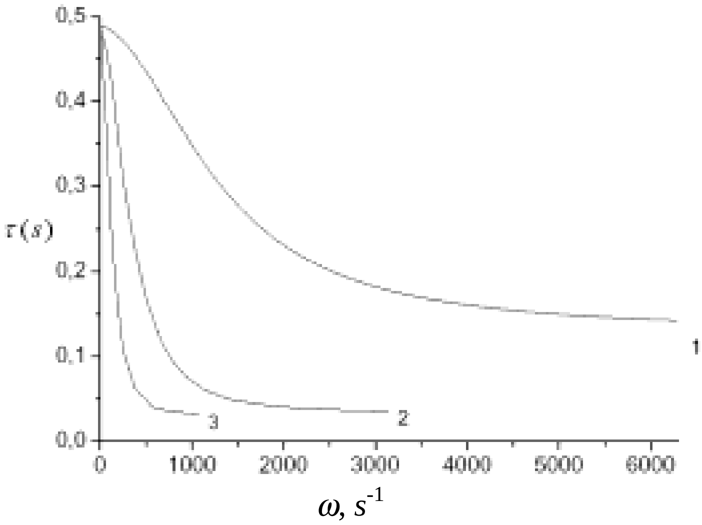
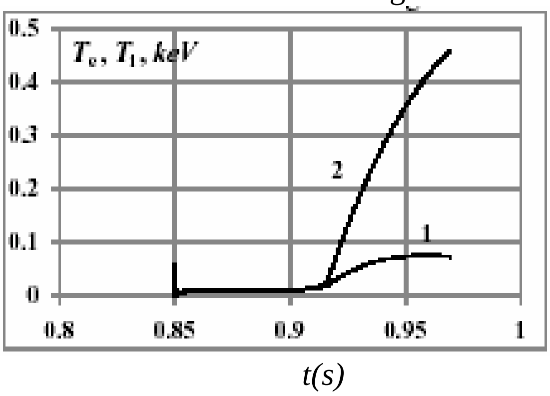


Fig. 2. The radiation barrier overcoming time τ as a function of the modulation frequency $\nu = \omega / 2\pi$. $S_0 = 9.8 \cdot 10^{-2}\ W \cdot cm^{-3}$. Curves 1, 2, and 3 correspond to the ratios $\alpha / \omega = 10^{-4}, 4 \cdot 10^{-4}$, and 10^{-3}, respectively.

3. ITER simulations. More realistic model for ITER simulation has been used. Ohmic heating, heat conductivity losses, difference of electron and in temperatures, and all types of radiation have been taken into account in code SCENPLINT accepted by ITER team for start-up simulations [5, 6]. The effect has been confirmed completely. The simulation was performed for ITER parameters at the stage of plasma initiation: R = 6.68 m, a = 1.6 m, and elongation $k = 1$. Carbon concentration is chosen to be equal to 2 %. Electron and ion temperature as well as the energy balance are shown for the regime without and with modulations in Figs. 3 and 4 respectively. The ECR power is standard one for the ITER scenario, $Q_0 = S_0 V_P$ = 2 *MW* for non-modulated regime.



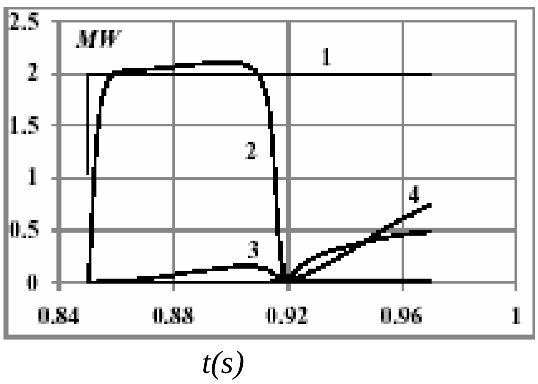
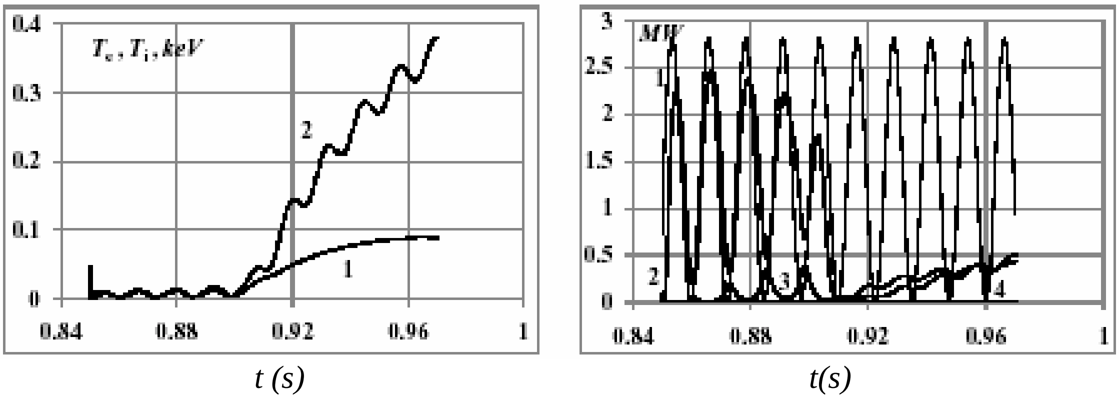


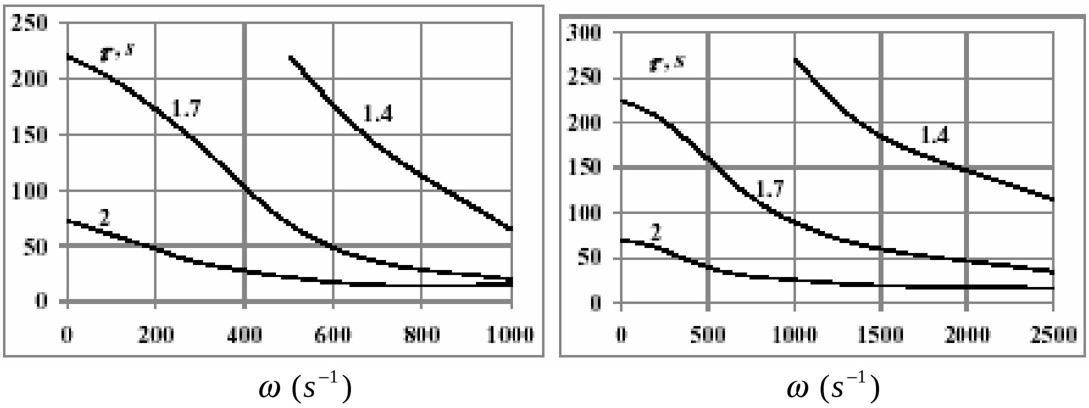
Fig. 3a Temporal evolution of electron (1) and ion (2) temperatures (KeV)

Fig. 3b. ECR power (1), radiation losses (2), Ohmic heating power (3), and heat conductivity losses (4) (MW).

One can see that the barrier overcoming time is approximately the same as for non-modulated case, but the averaged ECP heating power Q_0 = 1.4 *MW* is significantly lower. The frequency dependence of τ is shown in Figs 5a and 5b for $\alpha / \omega = 10^{-3}$ and α/ω = 4 10^{-4} respectively. The simulation with SCENPLINT code demonstrate the dependence similar to the dependence obtained with the reduced model.



Figs. 4a(left) and 4b. The same as in Figs 3 but with modulation, $\alpha = 1$, $\omega = 500\,s^{-1}$.



Figs 5a (left) and 5b. Radiation barrier overcoming time τ *(s) vs frequency* ω. *Numbers near the curves show the averaged ECR heating power in MW.*

4. Summary. It has been shown that low frequency modulation of ECR heating power decrease the power threshold of the radiation barrier overcoming or the overcoming time significantly at the stage of the start-up in tokamaks. The effect is based on the strong nonlinear dependence of the ionization rate on the electron temperature.

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