Density limit in tokamaks with auxiliary edge heating

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1. Introduction

It is well known that radiation losses in tokamaks rise with the periphery plasma density. Radiative losses also have a strong maximum for the temperatures of few eV. If radiation losses from the edge exceed the heat flux from the core thermal equilibrium cannot exist. Cold thermal front moves to the core. It achieves the surface $q = 2$ generating MHD instabilities and the disruption as the sequence [1-3]. As it has been shown theoretically as well as experimentally central ECR heating is able to prevent the disruption [4-6]. Another way of the disruption control is proposed in the present paper. One can heat low z impurity ions appearing in low temperature plasmas. As the consequence electron temperature also rises in the cold region. The density of low z ions decreases together with radiation losses, and the thermal disruption is prevented. The feedback system may be used. For instance the impurity heating may be proportional to highest power of impurity radiation intensity.

2. Qualitative model

Stationary thermal equation in cylindrical tokamaks takes the form

$$-\frac{1}{x}\frac{\partial}{\partial x}(xn\chi_{\perp}\frac{\partial T}{\partial x}) = a^2(P-Q). \tag{1}$$

Here x is the dimensionless minor tokamak radius, $x = \frac{r}{a}$, $n = n_e = n_i$ is the plasma density, χ is the thermal conductivity, P and Q are the thermal sources and sinks respectively, and $T = T_e = T_i$ is the temperature. In order to clarify how the critical density may be increased the qualitative theory is proposed. More accurate theory is developed in the next chapter.

We put $n = const$, $n_I = const$, $Q = nn_I L(T)$, where L is the function of the temperature only. Radiation losses are supposed to be constant in the cold region $T \leq T_1$ where ions with low charges z may exist,

$$L = \begin{cases} L_0, & \text{for } T \leq T_1; \\ 0, & \text{for } T \geq T_1. \end{cases}$$

Heating power may be presented as the sum of Ohmic heating and auxiliary one, $P = P_{OH} + P_{AUX}$,

$$P_{AUX} = \begin{cases} P_A = const, & \text{for } T \leq T_1; \\ 0, & \text{for } T \geq T_1. \end{cases}$$

Ohmic heating is small at the edge. We suppose that it is concentrated in the core. Instead (1) one can use equation in slab geometry for radiative zone:

$$\frac{\partial^2 T}{\partial y^2} = A. \tag{2}$$

Here $y = 1 - x$, $A = a^2 \frac{nn_I L - P_{AUX}}{n\chi_\perp}$. Plasma density achieves its critical value if the total energy impact is reradiated. Hence, $\frac{\partial T}{\partial y}|_{y=0} = 0$. As a consequence, $T = 0$ for $y = 0$. In the simplest case the plasma density as well as the impurity one does not depend on y. The thermal conductivity is proportional to n and does not depend on the temperature, $n\chi_\perp = \kappa = const$. Solution of equation (2) corresponding to the critical density takes the form

$$T = \frac{Ay^2}{2}. \tag{3}$$

The radiation layer thickness is defined as $y_1 = \frac{a^2 P_{OH}}{\kappa A}$. Critical density may be calculated from the condition $T(y_1) = T_1$. One can get

$$nn_I L - P_{AUX} = \frac{(aP_{OH})^2}{2T_1\kappa}. \tag{4}$$

The auxiliary heating power is proportional to the impurity density, $P_{AUX} = \alpha n_I$. Let's analyze three limits.

I. Impurity density does not depend on the main plasma density. Under this condition critical density is proportional to the inverse specific radiation power.

$$n_c = \frac{(aP_{OH})^2 + 2\alpha\kappa T_1 n_I}{2T_1\kappa n_I L}. \tag{5}$$

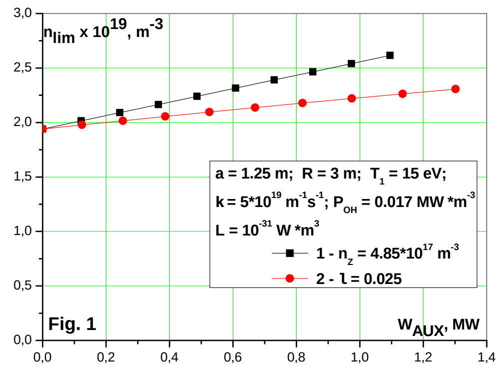
II. If the impurity density is proportional to the main plasma density, $n_I = \lambda n$, the critical density

$$n_c = \frac{\alpha}{2L}\left(1 + \sqrt{1 + \frac{2(aP_{OH})^2 L^2}{\alpha^2 \lambda L \kappa T_1}}\right). \tag{6}$$

III. Also, the feedback system is able to provide the auxiliary heating power to be proportional to ${n_I}^2$, $P_{AUX} = \delta {n_I}^2$. Hence, equation (4) yields:

$$n_c = \frac{aP_{OH}}{\sqrt{2\lambda\kappa T_1(L - \delta\lambda)}}. \tag{7}$$

Critical densities (5) and (6) provide the equal dependences on $W_{AUX} = P_{AUX}V_{AUX}$, where $V_{AUX} \approx 2(2\pi R)(\pi a^2)y_1$ is the radiative zone volume (see Fig.1)



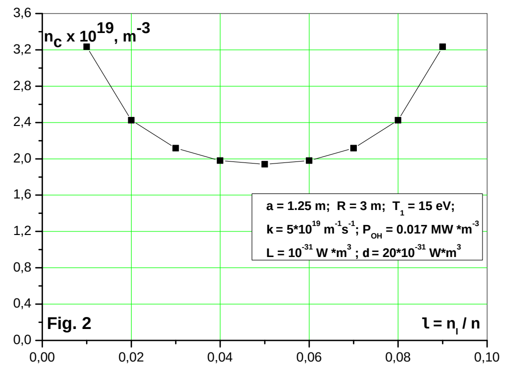


Figure 1: Critical plasma density as a function of auxiliary heating power for cases I and II, i.e. impurity ions density independant and proportional to the main plasma density.

Figure 2: Critical plasma density as a function of the coefficient of proportionality between impurity ions density and main plasma one, for the case III of feedback system usage.

In accordance to expressions (5) and (6) the critical densities decrease with the impurity density. In contrast to both the critical density has the minimum for the case III. In other words, n_c rises with the impurity density for large n_I (Fig. 2)

3. Numerical model

More realistic numerical model is represented in this paragraph. Calculations have been performed using transport code ASTRA [7].

Plasma density as well as impurity one is supposed to be given. Thermal conductivity is supposed to take the Alcator-like form $\chi = \frac{5 \cdot 10^19}{n} m^2 s^- 1$. Steady-state solution for the critical density is found for the auxiliary heating power given. Tokamak parameters approximately equal to JET parameters are chosen. Carbon is chosen as the impurity [8]. First three ions are supposed to be heated with equal intensity. The sum of their relative concentrations may be represented as the function f(T):

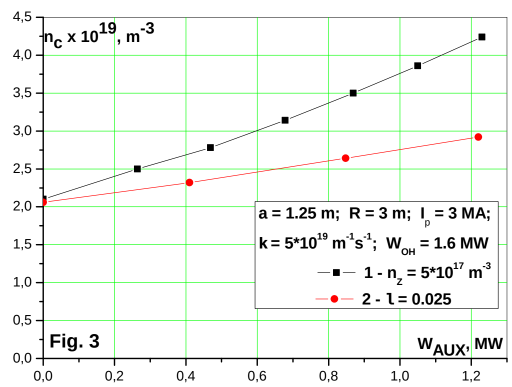


Figure 3: Critical plasma density as a function of auxiliary heating power, ASTRA modeling.

$$f(T) = 0.5(1 - \tanh(\frac{T-15}{5})). \tag{8}$$

In a simplest case the auxiliary heating takes a form $P_{AUX} = P_0 f(T)$. The critical density as a function of auxiliary heating power is presented in Fig.3.

4. Conclusion

Several effects may lead to the density limit in tokamaks. In particular, strong impurity radiation from the edge may lead to the discharge disruptions. As it shown such type of disruptions may be prevented by the ICR heating of low charged impurity ions at the edge, and the density limit may be improved significantly. The heating does not disturb plasma in the core. Especially, the feedback system may be effective if the auxiliary heating rise strongly with the radiated power. We suppose to analyze the influence of neoclassical tearing mode on the density limit.

Acknowledgements

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References

[1] Ohyabu N., Nucl. Fusion **9**, 1491 (1979).

[2] Drake J.F., Phys. Fluids **30**, 2429 (1987).

[3] Connor J.W. and You S., Plasma Phys. Control. Fusion **44**, 121 (2002).

[4] Alikaev V.V., et al., Proc. 13th IAEA Conf. on Plasma Phys. and Controll. Nucl. Fusion, Washigton (USA), 1990. V.1. P.163.

[5] Alikaev V.V., et al., Proc. 17th EPS Conf. on Plasma Phys. and Controll. Fusion, Amsterdam (Holland), 1990. V.14B. Pt. III. P.1080.

[6] Alikaev V.V., et al., Plasma Phys. Rep. **26**, 991 (2000)

[7] Pereverzev G.V., Yushmanov P.N., (2002) Preprint IPP 5/98, Garching

[8] D.E. Post, R.V. Jensen, C.B. Tarter, W.H. Grasberger, W.A. Lokke, et al, Atomic data and Nuclear Data Tables (1977), **20**, 397.