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1. INTRODUCTION

In order do trigger the transition to the high confinement mode (H-mode), the power lost through the separatrix into the Scrape-Off Layer (SOL), P_L, estimated as the sum of the Ohmic and auxiliary heating power from which the time derivative of the plasma stored energy is substructed, should exceed some threshold value P_{th}. A simple scaling for P_{th} has been deduced from the experimental data collected on several tokamaks with divertors [1],

$$\mathrm{P_{th}} = 0.042\ \bar{\mathrm{n}}_\mathrm{e}^{0.64}\ \mathrm{B}^{0.78}\ \mathrm{S}^{0.94} \tag{1}$$

where $\bar{n}_e$ is the line averaged electron density in $10^{20}\mathrm{m}^{-3}$, S is the plasma surface area in m^2, and B is the toroidal magnetic field in T.

At the same time, there are many experimental situations where the conditions for the H-mode onset can not be described by the Eq.(1) [2-4]. In the present contribution the mechanisms of such deviations will be analyzed by means of predictive transport modelling for the cases of the L-H transition at low plasma densities and in limiter configurations. In both situations the power required to establish the H-mode is significantly larger than the one predicted by the multi-machine scaling (1). As an example, Figure 1 shows the variation of P_L normalized to the value predicted by Eq.(1) with the edge density measured in JET discharges with MKIIGB septum divertor [4]. When the density is below a limit value of $1.3\times10^{13}\ \mathrm{cm}^{-3}$, the H-mode power threshold exceeds the scaling prediction by a factor up to 2.The existence of the minimum in the L-H power threshold at low density is a phenomenon observed in many tokamaks. The low density limit below which the power threshold increases with decreasing density can be related to the condition when the penetration depth of neutrals recycling from divertor plates is of the order of $0.1^*\kappa a$, where κ is the elongation and a is the plasma minor radius [5]. This constraint can be rewritten a condition on the plasma density at the edge:

$$\mathrm{n_e\,(cm^{-3}) > n_{crit} \sim 10^{15}((cm))^{-1}} \tag{2}$$

If $n_e < n_{crit}$ neutrals penetrate freely into the confined plasma volume. The same takes place in a limiter configuration where the distance, which neutrals have to pass in the SOL, is normally much smaller than in a divertor one.

On the basis of numerical computations with 1-D transport code RITM [6], in the the present contribution we interpret the interrelation between the neutral penetration into the confined plasma and the increase of the power threshold for the L-H transition above the value prescribed by the Eq.(1). The present transport model [7-9], includes contributions from the most important core and edge micro-instabilities e.g., ion temperature gradient, trapped electron, Drift Resistive B0xallooning (DRB) and Drift Alfvén (DA) modes. In particularly, the turbulent transport at the edge is dominated by the combination of DA and DRB modes, which are stabilized by increasing pressure gradient and reducing collisionality when plasma warms up. This allows to reproduce self-consistently the formation of the Edge Transport Barrier (ETB) if the total heating power exceeds some critical level.

In addition to radiation, the energy is lost from the plasma trough two channels: due to heat conduction proportional to the temperature gradient, $-\chi_\perp n\nabla T$, and with convection associated with the particleflow, $-3TD_\perp \nabla n$. Here $\chi_\perp$ and $D_\perp$ are the heat and particle diffusion coefficients. At the Last Closed Magnetic Surface (LCMS), the fraction of theconvective loss in the total is given by the expression: $Q_{conv}/Q_{tot} = \left(1 + \frac{\chi_\perp}{3D_\perp} \frac{\delta_n}{\delta_T}\right)$, where $\delta_n -n/\nabla n$ and $\delta_T = -T/\nabla T$ are the density and the temperature e-folding lengths. The prescribed values of δ_n and δ_T taken normally from experimental data are imposed in RITM computations as boundary conditions at the LCMS. Thus, by varying the ratio δ_n/δ_T, Q_{conv}/Q_{tot} can be changed from 0 to 1. Figure 2 compares the power threshold for the L-H transition obtained in computations (black symbols) with the one given by the scaling law (white symbols), for different values of the Q_{conv}/Q_{tot} ratio obtained by varying δ_n (points) and δ_T (boxes), respectively. At a low fraction of convective heat losses, the computed power coincides with the scaling predictions. An increase of Q_{conv}/Q_{tot} above 50% leads to a strong increase of the computed threshold power with respect to the scaling predictions.This can be interpreted as follows.The transport model used in RITM computations [7,8] prescribes that under the L-mode conditions the anomalous transport at the plasma edge is mostly due to drift Alfvén unstable modes driven by collisions and current perturbations. These modes are stabilized when the pressure gradient, driven mostly by the temperature gradient, increases and the plasma collisionality reduces when the heating power grows up. An increase of the convective channel for heat losses results in a reduction of the temperature and its gradient. This prohibits the suppression of the turbulent transport and postpones the L to H-mode transition to a higher heating power.

Normally, the change of the dominant mechanism for the heat losses from conductive to convective takes place by switching from a divertor to a limiter configuration, when the distance between the confined plasma and plasma facing components increases, or by the reduction of the density below some critical value. In both situations the ratio of the distance travelled by neutrals in the SOL, δ_{SOL}, to their mean free path length before ionization decreases. Therefore a larger fraction of neutrals, recycling from the limiter surface or divertor plate, penetrate inside the LCMS, the charged particle flux in the confined region increases and the heat losses associated with particle convection enhance. This can be demonstrated by using the improved two-point model [10]. Figure 3 shows the variation of the Q_{conv}/Q_{tot} ratio with the edge density computed for two different values of the distance travelled by neutralsin the SOL before entering the confined plasma, d_{SOL} = 10cm and d_{SOL} = 30cm. The reduction of convective contribution to heat flux with increasing density and increasing δ_{SOL} can be understood as follows. The flux of neutrals recycling from the limiter or divertor plate, Γ_R, is attenuated in the SOL due to ionization and charge-exchange processes. This attenuation increases with increasing density and increasing distance, which neutrals should travel in the SOL and the influx of neutrals into confined plasma can be roughly estimated as

$$\Gamma_{LCMS} = \Gamma_R \exp\left(-n\sigma_* d_{SOL}\right), \tag{3}$$

with σ_* being the effective cross-section for the neutral losses due to ionization and charge-exchange. In a steady state, the influx of neutrals should be balanced by the outflow of charged particles, $D_\perp/n\ \delta_n$. Thus, the reduction of the edge density or d_{SOL} would lead to the stronger density gradient or shorter δ_n. For the given heat source, the increase of convective losses, caused by stronger particle flux, leads to a corresponding reduction of the conductive heat flux component. The latter leads to the reduction of the temperature and its gradient, and, as it is mentioned above, hinders the ETB formation.

The radial profiles of the density scale-length for two values of the edge density, measured by the lithium beam diagnostic, for two JET discharges from the sequence plotted in fig.1, are shown in fig.4. The discharge with the higher edge density (solid curve) is characterized by larger δ_n in the vicinity of the separatrix. The reduction of density results in the steeping of the density profile (dashed curve) and, therefore, in increase of heat losses due to charged particle convection. Unfortunately, for extremely low density, where the measured power deviates from the scaling predictions, no data from the lithium beam diagnostic are available. Such measurements are a subject for further experiments. Nevertheless, the tendency shown in fig.4 is in agreement with that obtained from improved two-point model, see fig.3.

SUMMARY

Calculations done with 1-D transport code RITM show the strong dependence of the L-H threshold power on the dominant mechanism for the heat losses at the edge. Whereas, in the situation when the fraction of the convective heat losses in the total one does not exceed 50%, the computed threshold power coincides with the scaling prediction. An increase of heat losses due to charged particle convection leads to the increase of the threshold power by several times compared to the multi-machine scaling. Under these conditions, corresponding to the low density discharges or to the limiter configuration, the heating power required to establish the ETB is up to a few MW larger than it is predicted by the scaling.

The analysis done with two-point model demonstrated that, the relative contributions of convective and conductive heat losses are determined by the transport of neutrals recycling from neutralizing plates and, in particular, by the ratio of the distance which they should pass in the SOL before entering the confined plasma to their mean free path. The decrease of the edge density or the distance traveled by neutrals before entering the confined plasma, which occurs in the switch fromdivertor to limiter tokamak, leads to a lager fraction of particles penetrating through the LCMS and, therefore, changes the heat flux balance to the convection dominated one.

Measurements of edge profiles in JET discharges with MKIIGB septum divertor demonstrate that, the discharges with lower density are characterized by steeper edge density profile and, therefore, by stronger heat losses due to charged particle convection, in agreement with analysis done with improved two point model.

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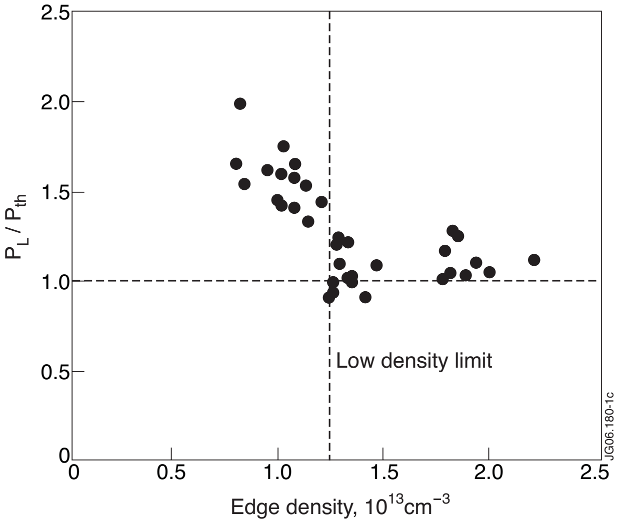

Figure 1: Increase of the L-H threshold above the scaling predictions at low densities (JET measurements)

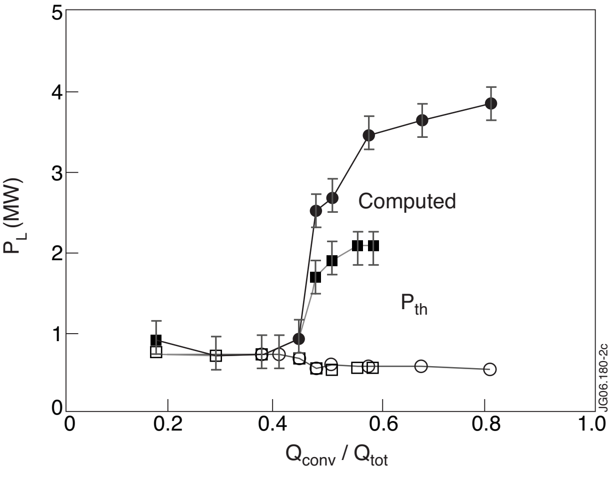

Figure 2: Comparison between computed H-mode power threshold in TEXTOR and the one predicted by Eq.(1) at different fraction of convective heat losses

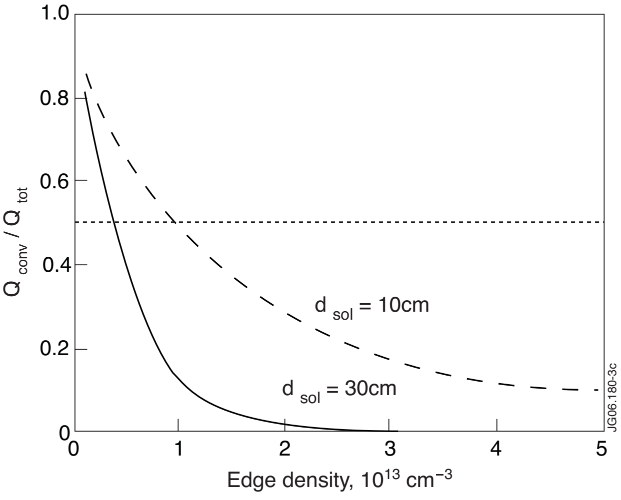

Figure 3: Fraction of convective energy loss versus the edge plasma density

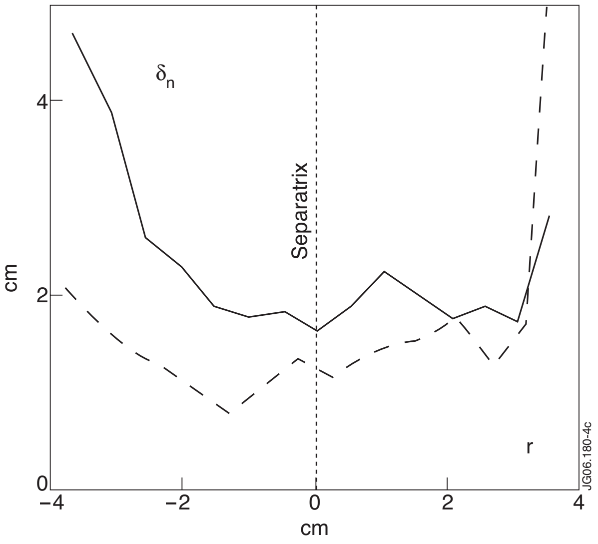

Figure 4: Variation of the density e-folding length at the edge of JET tokamak measured prior to the L-H transition for two discharges from the data set shown in fig.1 (solid – n_e~$2*10^{13}cm^{-3}$, dashed – n_e~$1.2*10^{13}cm^{-3}$)