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Plasma edge characterisation and control in ergodic divertor experiments on Tore Supra

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Abstract

The upgrading of the power handling capability of the Ergodic Divertor of Tore Supra has been accompanied by the installation of a new set of edge plasma diagnostics. The characterisation of the edge plasma (electron density and temperature measured with Langmuir probes) is presented for ohmic shots in deuterium. The edge plasma density exhibits a linear and then a cubic dependence with the plasma density while for larger plasma density, detachment occurs. Two methods of defining detachment are presented: one based on local measurements obtained with the Langmuir probes and one using integrated measurements from edge bolometry. These two different definitions produce very similar values. Active pumping, using a pump limiter inserted in the ergodic layer, is shown to be efficient for both low plasma density and ohmic power. The edge plasma density is shown to be strongly linked to active pumping while the edge electronic temperature is shown to be less sensitive. Experimental evidence of active edge density control is shown when active pumping is applied. Finally, particle exhaust with the vented structure of the ergodic divertor is shown to become efficient for high recycling regime obtained at large plasma density and/or large input power.

Keywords: Tore Supra; Ergodic divertor detached plasma; Particle control; Pumping

1. Introduction

The ergodic divertor (ED) of Tore Supra has been equipped with a set of 42 new vented neutraliser plates [1] as well as a new set of edge diagnostics allowing for a better edge plasma characterisation (14 Langmuir probes, pressure gauges located poloidally and toroidally). In addition to the specific titanium getter pumping dedicated to the D_2/H_2 exhaust, the outboard pump limiter (OPL) may be inserted in the ergodic layer to provide additional turbomolecular pumping. Such a pumping system is particularly useful since the capability for particle collection (and consequently particle exhaust) of the vented structure has been shown to be modest for low plasma density and low input power [2,3]. The turbomolecular pumping also allows for impurity exhaust (e.g.: neon…) used for the highly radiative scenario [4]. Due to the radial extension of the divertor perturbation (<0.16 m) the limiter is generally positioned 0.04 m ahead the divertor front face without introducing significant modification of the edge configuration [5,7].

Edge density regimes (high recycling and detachment) very similar to those produced with axisymmetric divertors [8] have been observed. The dependence of the edge electron density on the volume averaged plasma density is found to be linear for low densities while exhibiting a cubic behaviour in the high recycling regimes obtained for larger plasma density. Finally, as the plasma density is increased, a detachment is observed, i.e. the edge density saturates and then decreases as the gas injection is increased. Such behaviour is shown to depend on the power flux feeding the flux tubes: generally, the more power loaded tubes are the more prompt to detach [7]. The analysis of these regimes can be performed in terms of screening capability, once the link between the characteristic length of the ergodic boundary layer to the mean free path of ionisation. This

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governs the amplification of the particle flux which then imposes the edge electron temperature. The recycling conditions play an important role: active pumping allows higher bulk density to be reached before entering the successive high recycling and detached regimes. The active pumping ensured by the OPL is shown to be efficient for the edge plasma density control. Finally, the vented structure is demonstrated to behave efficiently for the particle exhaust capability as soon as the plasma density becomes larger than about 3.0×10^{19} m^{-3} or when auxiliary heating is applied.

In this paper, for all the reported experiments, the ergodic divertor is at its maximum current ($I_{div} = 45$ kA) with an edge safety factor, q_{edge}, always very close to 3 ensuring the maximum edge perturbation [9]. The first section reports deuterium ohmic experiments where the edge plasma density and temperature have been measured as a function of the volume averaged plasma density. The edge plasma density exhibits a linear and then a cubic dependence with the plasma density while for larger plasma density, detachment occurs. The second section is devoted to the degree of detachment which is defined for deuterium ohmic plasma shots and which can be based on the edge electron density (Langmuir probe) or the edge bolometry measurements. It is shown that these two independent detachment monitoring lead to the remarkably similar trends as the plasma detaches. The effect of active pumping on the edge plasma parameters is reported in the third section. The edge plasma density is shown to be very closely linked to the pumping and is nearly two times lower in the pumped case while the edge temperature is shown to be rather similar. It is shown that the transitions between the three regimes reported above occurs for the same edge plasma density confirming consequently that active pumping allow for larger central plasma density to be reached without any detachment. Finally, the vented structure is shown to be efficient for particle exhaust for high recycling regimes obtained either for high plasma density or for high input power in the plasma.

2. Plasma edge characteristic for deuterium shots

A series of experiments has been performed in deuterium in order to investigate the edge plasma parameter (electron temperature $T_{e\text{-edge}}$ and electron density $n_{e\text{-edge}}$) behaviour as a function of the volume averaged plasma density $\langle n_e \rangle$. Density scans have been realised for ohmic shots ($I_p = 1.5$ MA) using gas injection; a typical plasma discharge including a density ramp up. The maximum $\langle n_e \rangle$ obtained in these experiments has been about 0.45 the Greenwald density limit n_{GW} which was about $8.5 \times 10^{19} m^{-3}$. The edge plasma density, $n_{e\text{-edge}}$, is measured with the set of Langmuir probes installed in the vented structure of the neutraliser plates [1]. $n_{e\text{-edge}}$ is displayed as a function of $\langle n_e \rangle$ on Fig. 1(a) and three phases can be clearly distinguished. A linear dependence of $n_{e\text{-edge}}$ is recorded for $\langle n_e \rangle$ less than about $2.5 \times 10^{19} m^{-3}$. For larger $\langle n_e \rangle$, a more than linear dependence, $n_{e\text{-edge}} \sim \langle n_e \rangle^{3-3.5}$, occurs and corresponds to the high recycling regime which is observed in the range 2.5–3.0 $\times 10^{19} m^{-3}$. Finally, when $\langle n_e \rangle$ becomes larger than about $3.0 \times 10^{19} m^{-3}$ $n_{e\text{-edge}}$ remains roughly constant and finally drops dramatically as the plasma detaches. From the resulting edge temperature corresponding to the edge density displayed on Fig. 1(b), it can be seen that the edge temperature, $T_{e\text{-edge}}$, exhibits a clear drop at the transition from the linear to the high recycling regime. In the linear phase the T_e dependence is proportional to $\langle n_e \rangle^{-1}$ while for the high recycling regime $T_e \propto \langle n_e \rangle^{-2}$. Such an effect is observed for all the deuterium experiments. This suggests

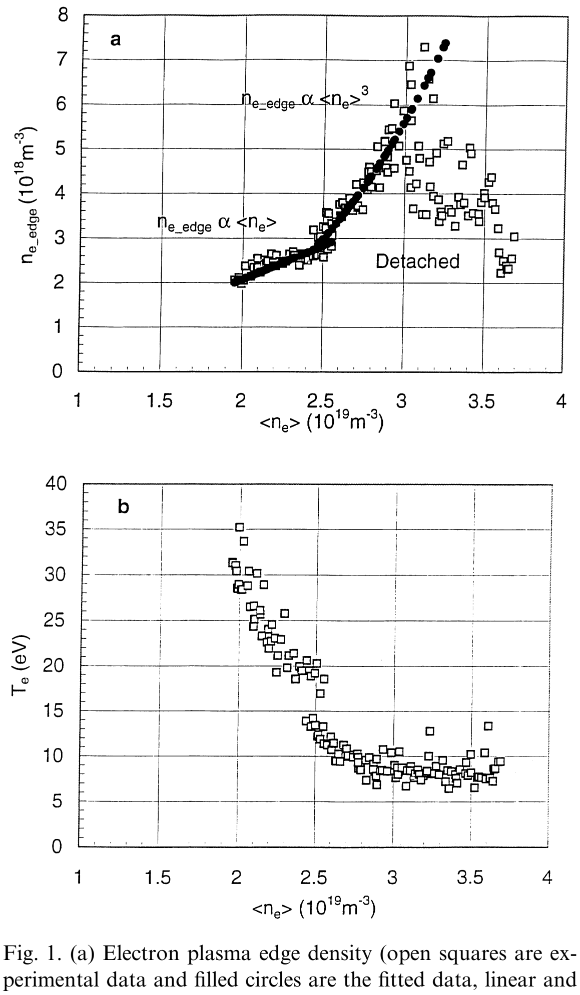

Fig. 1. (a) Electron plasma edge density (open squares are experimental data and filled circles are the fitted data, linear and cubic) and (b) electron temperature (at the same location) as a function of the volume averaged plasma density for deuterium ohmic shots.

that there is a temperature decrease along the magnetic field lines while the loss term in the momentum balance is still low and leads to a minor effect in both the linear and high recycling regimes [7]. Finally, once the plasma detaches T_e remains roughly constant at values around 8 eV. It is worth noting that in the ergodic divertor experiments, the electron temperature at detachment is always larger to what is observed with the axisymmetric divertor which exhibits lower T_e close to 5 eV [10]. These three regimes can be explained in terms of energy transport and momentum balance in the laminar zone (between the stochastic layer and the wall) where the transport is essentially parallel as in the axisymmetric divertor configuration [5,8]. From the linear regime to the high recycling, the strong edge temperature drop associated to the high flux amplification and the screening efficiency, is compensated by an enhancement of the temperature gradient along the field lines. A detailed analysis, in terms of critical temperature, T_e^{Critical}, and temperature gradient along the magnetic field lines, is presented in [7] providing a description of the transitions from one regime to the other.

A second way can be used in order to describe the edge density dependence as a function of $\langle n_e \rangle$. The plasma density behaviour can be described by introducing the screening parameter [6]: $\Delta r/\lambda_i$ where Δr is the width of the radial magnetic perturbation (proportional to the current in the divertor coil I_{div}) and λ_i is the mean free path of ionisation of the neutrals defined as $\lambda_i = v_o/(n_{\text{e-edge}}\langle\sigma v\rangle)$ where v_o is the velocity of the neutrals and $\langle\sigma v\rangle$ the ionisation cross section. $\langle n_e \rangle$ can be written in the form

$$\langle n_e \rangle = n_o + N_o \exp\left(-\frac{\Delta r}{\lambda_i}\right), \tag{1}$$

where n_o is the plasma density fixed by the wall (initial plasma condition defined by the wall saturation) and N_o is the particle density at the edge (injected and recycled) [7].

From Eq. (1), as far as λ_i is of the order of Δr (large edge T_e correlated to a low edge density: $\Delta r/\lambda_i \sim 1$) the exponential term can be supposed constant as the gas injection is increased. The screening efficiency is rather modest and the plasma density can be increased nearly linearly as the gas injection is increased. For an attached plasma, the pressure along the field lines can be assumed constant and as soon as the density increases the corresponding temperature drops. For stronger gas injection, both N_o and $n_{\text{e-edge}}$ increase and since for the deuterium, $\langle\sigma v\rangle$ is nearly constant as long as T_e remains larger than typically 10–15 eV, λ_i becomes significantly smaller than Δr; consequently, the exponential term also increases strongly. This induces an amplification of the particle flux to the wall structure. For a given heat flux flowing along the field lines, T_e slowly decreases. Then a temperature gradient appears in the parallel direction as well as a density gradient opposite to the temperature's one. The edge density is consequently increasing in a non linear way compared to the averaged plasma density. Finally, when T_e becomes lower than typically 10 eV, λ_i increases dramatically (due to a drop of $\langle\sigma v\rangle$) and becomes comparable to Δr. In these conditions, the plasma fuelling by the large amount of particles N_o at the edge plasma becomes larger and is characterised by an abrupt increase of $\langle n_e \rangle$ correlated to a strong drop of the screening efficiency.

3. Degree of detachment

At JET, the concept of the degree of detachment (Dod) has been introduced [10] in order to define a process considered as progressive. Following a similar concept for Tore Supra, a Dod has been defined as the ratio of the extrapolation of the edge density, n_e *Fitted (filled circles on Fig. 1(a))*, to the measured edge density, n_e *Measured (opened squared on Fig. 1(a))*, (Langmuir probes) and is written in the form:

$$\mathrm{Dod} = \frac{n_e\mathrm{Fitted}}{n_e\mathrm{Measured}}. \tag{2}$$

Since T_e is shown to be constant when the detachment occurs, such a definition is equivalent to the JET's one and can be correlated to the pressure drop along the field line between the scrape off layer and the divertor. The Dod for the ohmic plasma discussed in the previous section, is displayed in Fig. 2. The sharp rise of the Dod which occurs when $\langle n_e \rangle$ becomes larger than about 3.0×10^{19} m^{-3} is correlated to a dramatic drop of the power flux deposition on the neutraliser as confirmed by the infrared measurements of the ED neutraliser plates

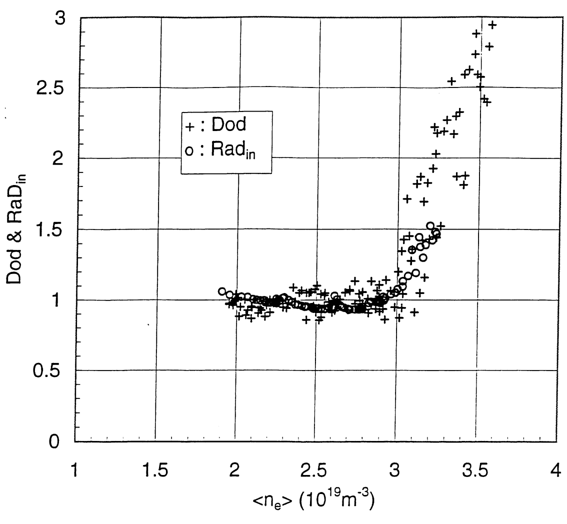

Fig. 2. Degree of detachment (Dod) and $\mathrm{RaD_{in}}$ ratio versus the volume averaged plasma density.

on which an abrupt power deposition drop is recorded as soon as the plasma detaches. The detachment is also correlated to a dramatic change of the edge radiation pattern. Tore Supra is equipped with bolometer cameras viewing from the top of the machine with 16 equally spaced channels as schematically described in Fig. 3. The ratio of the signals of the most external (in minor radius) bolometer chords to the respective adjacent ones, RaD_{in}, characterises the modification of the radiation pattern [5] and is written as

$$RaD_{in} = \frac{(b_2 + b_{15})}{(b_1 + b_{16})}, \tag{3}$$

where b_1, b_2, b_{15} and b_{16} are the signals from the bolometer channels number 1, 2, 15 and 16, respectively.

A shift of the radiation pattern from the outermost location (high recycling regime to detachment) to a lower minor plasma radius is evidenced by an increase of the ratio RaD_{in}. This ratio is also plotted on Fig. 2 and it can be seen that for the linear and high recycling regimes, that the RaD_{in} remains very close to 1. At the time of detachment, a weak decrease with the plasma density can be clearly distinguished which is likely linked to an increase of the edge radiation as the high recycling regime occurs and is correlated to an increase of both the neutral and electron densities. As soon as the plasma detaches, there is a very clear increase of RaD_{in} correlated to an inward shift in minor radius of the radiation pattern and linked to a drop of the screening efficiency ($\lambda_i \sim \Delta r$). As a consequence, the fuelling efficiency increases and as a signature, the plasma density exhibits an abrupt increase. It is worth noting that in spite of the fact that these calculations are totally independent, they both exhibit exactly the same trend. It should be noticed that the RaD_{in} is based on non intrusive measurements as well as on integrated measurements over the channel length while the Langmuir probes deliver local data which can be compared to edge modelling [7]. Finally, both the Dod and RaD_{in} clearly appear to be particularly very useful for the feedback system related to the detachment control [11].

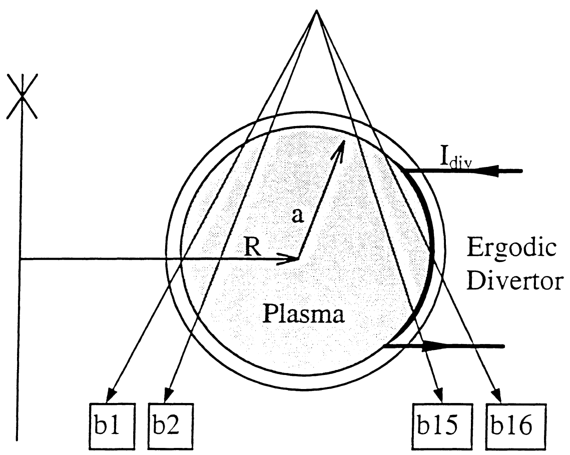

Fig. 3. Cross section of Tore Supra showing the most external bolometer channels and the ergodic divertor.

4. Effect of active pumping on the edge plasma parameters

Experiments with and without active pumping have been realised in order to investigate the effect of active pumping on both the bulk plasma density as well as on the edge plasma. The reported experiments concern two ohmic shots ($I_p = 1.5$ MA) with the same plasma characteristics. A density ramp up, using gas injection, was programmed for these two shots which were performed consecutively in order to avoid significant wall particle content modification. For the pumped shot, the OPL is inserted in the ergodic layer, the set of turbo pumps (total pumping speed $\sim$5 m^3 s^{-1}) allowing for particle exhaust [6]. The plasma densities are very similar for the two shots and the increase of the gas injection for the pumped shot, compared to the non pumped one, is attributed to the exhaust (Fig. 4). Fig. 5 displays the resulting edge electron density as a function of the volume averaged plasma density for both shots. A very strong difference between the pumped case and the non pumped one appears particularly on the edge density where the active pumping allows a dramatic drop by nearly a factor 2. For both cases, the three regimes of the edge density can still be distinguished as a function of $\langle n_e \rangle$. However, it appears also very clearly that for the non pumped case, the high recycling regime occurs for lower

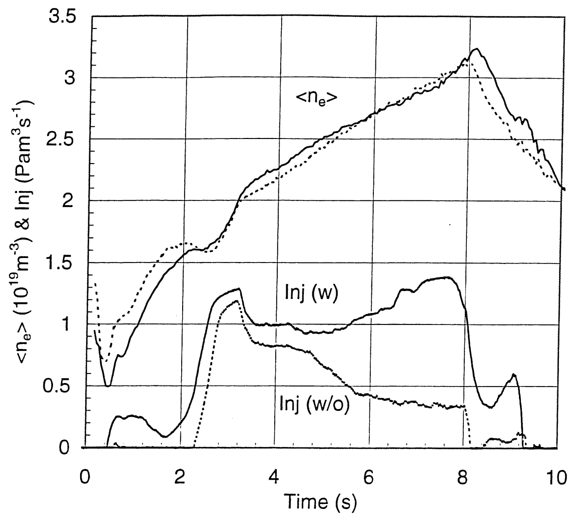

Fig. 4. Time evolution of the volume averaged plasma density and gas injection for two consecutive shots without (*w/o*: dashed line) and with active pumping (*w*: plain line).

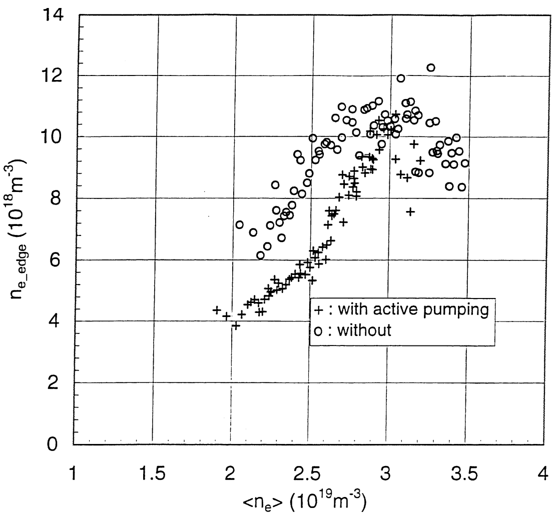

Fig. 5. Electron plasma edge density as a function of $\langle n_e \rangle$ for two deuterium ohmic shots, with and without active pumping.

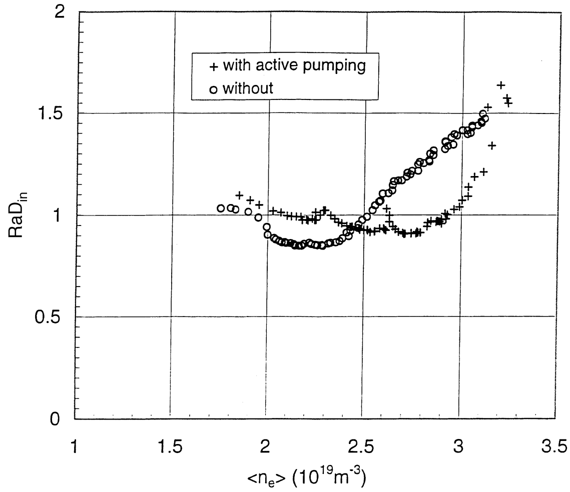

Fig. 6. RaD_{in} as a function of the volume averaged plasma density for two deuterium shots with and without active pumping.

plasma density as well as the detachment phase. Even if for the non-pumped case the high recycling regime appears nearly immediately, the linear phase can still be observed. Also, the transition from the linear regime to the high recycling one still occurs for roughly the same edge plasma density and also exhibit the same temperature drop. All the edge plasma densities deduced from Langmuir probe measurements give the same result, showing that the edge density decrease is not a local effect but is observed on all the neutraliser plates of the ED. The edge temperature exhibits a smaller difference (on all the probes) but the temperature drop is still observed for the linear-high recycling transition as shown on Fig. 1(b). As a consequence, the detachment occurs for a larger plasma density for the pumped shot as monitored by the RaD_{in} ratio (Fig. 6) as well as the infrared camera viewing the neutraliser plates. For the reported experiments, active pumping allows for a reduction of the edge plasma and therefore a shift of about 0.5×10^{19}m^{-3} to larger central plasma density before the detachment. It is worth noting that no difference is recorded on the edge plasma density at JET [10] without and with active pumping.

These experimental results show the key role of active pumping on the edge plasma density and therefore on its control. Recent experiments have been performed with larger plasma densities as well as with auxiliary heating (ICRH) in order to investigate the global exhaust capability of the vented structure. Measuring the neutral pressure behind the vented neutraliser plates and knowing that for these experiments, the total pumping speed delivered by the titanium getters is at least 5 m^3 s^{-1} per ED module, the resulting exhausted flux is displayed on Fig. 7 as a function of $\langle n_e \rangle$ [12]. Shots without and with auxiliary heating (P_{aux} up to 5.9 MW) are included in this figure but it can be seen very clearly that for densities lower than 3×10^{19} m^{-3}, the exhausted flux by the vented structure is very low. However, for the largest density, for ohmic shots a total exhaust of nearly 1 Pam^3 s^{-1} (D_2 molecules and assuming a total pumping speed for the six modules of 30 m^3 s^{-1}) is obtained while for the same density and with 5.9 MW of auxiliary heating the exhausted flux increases to about 2.7 Pa m^3 s^{-1}. Such an exhaust, performed by the vented structure alone, corresponds to the exhaust obtained with the pump

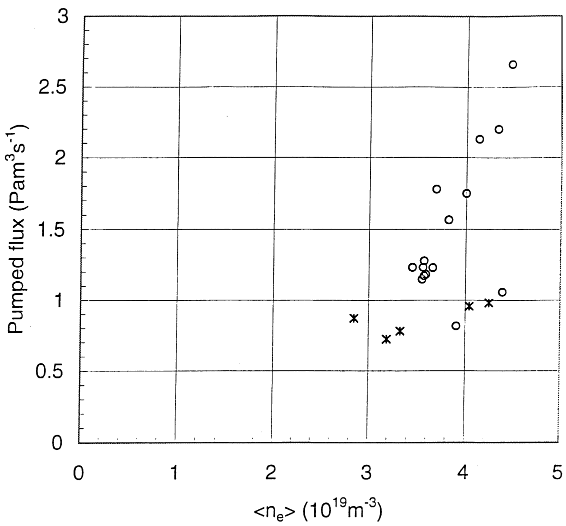

Fig. 7. Total particle flux (D_2 molecules) exhausted by the vented neutraliser plates of the ergodic divertor as a function of $\langle n_e \rangle$. *: ohmic shots, o: with auxiliary heating (ICRH).

limiter for similar plasma conditions [3] and is therefore satisfactory in order to control the plasma density. Knowing that the pumping efficiency of the OPL also increases with both $\langle n_e \rangle$ and P_{aux}, the association of both pumping systems would allow for a better plasma density control.

5. Conclusion

The upgrading of the power handling capability of the Ergodic Divertor of Tore Supra has allowed for the characterisation of the edge plasma (T_e and n_e) in ohmic conditions. The edge plasma density exhibits a linear and then a cubic dependence with the plasma density while for larger plasma density, detachment occurs. The transitions from the linear phase to the high recycling one has been linked to an increase of the screening efficiency and the edge flux amplification correlated to a strong drop of T_e while for larger plasma densities, the plasma detaches. It has been shown that the detachment can be defined either by local measurements, obtained with the Langmuir probes, or by using integrated measurements from edge bolometry. As the plasma detaches, very similar trends are obtained with these two definitions which consequently both appear to be particularly useful for the feedback related to the detachment control. The reported experiments have demonstrated that the edge plasma density is to be strongly linked to active pumping while the edge electronic temperature is shown to be less sensitive. Pumping effect on the edge plasma allows for larger central plasma density and a shift of 0.5×10^{19} m^{-3} towards larger density has been recorded before the detachment. Finally, particle exhaust with only the vented structure of the ergodic divertor is shown to be comparable to the limiter efficiency, and therefore large enough, at large plasma density and/or large input power in order to control the plasma density.

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