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Particle collection and exhaust in ergodic divertor experiments on Tore Supra

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Abstract

The particle exhaust in ergodic divertor (ED) configuration has been enhanced by inserting the outboard pump limiter (OPL) in the ergodic layer. The influence on the edge parameters (electron density and temperature) induced by the insertion of the OPL at different positions in the ergodic layer is reported in this paper. The additional pumping delivered by the OPL is shown to improve by about 50% the plasma density control while low impurity (carbon) concentration, characteristic of the ED shots, is also obtained for high plasma density in spite of proximity of the OPL to the bulk plasma. © 2001 Published by Elsevier Science B.V.

Keywords: Fuelling; Pumping; Particle exhaust; Particle balance; Screening

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1. Introduction

Previous experiments with the ergodic divertor (ED) in Tore Supra have shown that for deuterium as working gas, the particle exhaust becomes efficient in the high recycling regime obtained at high plasma density and/or auxiliary heating [1,2]. The understanding of the particle exhaust is essential since both the radiation efficiency and good coupling of waves from ion cyclotron resonance heating (ICRH) power in the ED experiments depend on the density in the divertor volume [3]. The particle exhaust can be enhanced by inserting the outboard pump limiter (OPL) in the ergodic layer. In addition to the resulting effects of the enhanced pumping capability on the global particle balance, the additional pumping delivered by the OPL (>30 m^3 s^{-1}) also allows for the investigation of the 'puff and pump' technique [4]. These experiments are also a good reference for the dynamic ergodic divertor (DED) which will be installed on TEXTOR [5].

Section 2 investigates the effects on the edge plasma parameters as a function of the OPL position in the ED layer. The resulting effects on the divertor particle flux and the resulting neutral pressure in the ED plenum are discussed. Section 3 is devoted to the global particle balance and fuelling efficiency. Particle screening at the edge is also discussed in terms of carbon concentration in the plasma with and without the OPL.

In this paper, for all the reported experiments, the ED is at its maximum current ($I_{\rm div} = 45$ kA) with an edge safety factor, $q_{\rm edge}$, always very close to 3 ensuring the maximum edge perturbation [6,7]. The standard resonant ergodic divertor configuration is used: $B_{\rm t} = 3.1$ T, $I_{\rm p} = 1.4$ MA, $R = 2.41$ m.

2. Effects of the introduction of the OPL on edge plasma parameters

The reported experiments have been carried out in ohmic plasma conditions with the OPL inserted at three radial positions in the ergodic layer. The modules of the

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ED are located at a radius of 3.17 m. The ergodic layer has a radial extension of about 15 cm for the experiments considered. The OPL has been located successively at a radius of 3.18, 3.14 and 3.11 m. The influence of the OPL position on the edge electron density, $n_{\mathrm{e\_edge}}$, and temperature, $T_{\mathrm{e\_edge}}$, particle flux measured on the vented structure, I_{sat}, and the corresponding neutral pressure, P, behind the vented neutraliser plate of the ED modules have been investigated over a plasma density scan. The measurements were performed with a set of Langmuir probes located on a vented neutraliser plate [8] of a module which is not magnetically connected to the OPL. Fig. 1(a) displays $n_{\mathrm{e\_edge}}$ and Fig. 1(b) $T_{\mathrm{e\_edge}}$ as a function of the volume-averaged plasma density $\langle n_e \rangle$ for the three radial positions of the OPL. For the three OPL positions, the edge plasma regimes [2] with $\langle n_e \rangle$ (linear, high recycling and detachment) are still obtained except when the OPL is located at 3.11 m ; at this position, no detachment is observed. This is due to a too low plasma density which, in this configuration, corresponds to a larger edge temperature. In Tore Supra the detachment process occurs for $T_{\mathrm{e\_edge}}$ ~8–10 eV. Plasma density higher than $\langle n_e \rangle = 3.8 \times 10^{19}$ m^{-3} is necessary to obtain this threshold for an OPL position of 3.11 m. Moving the OPL from $R = 3.18$ to 3.14 m has little effect on the edge density and temperature, except that the detachment threshold density drops by 10% from $\langle n_e \rangle \sim 3.3 \times 10^{19}$ to $\sim 3.0 \times 10^{19}$ m^{-3}. The ergodic layer (~14–15 cm) consists of a laminar zone (3–4 cm) which extends from the wall to the stochastic zone (10–11 cm) which is itself located between the confined plasma and the laminar zone. The dominant part of the recycling flux takes place in the laminar zone and no modification is observed when the OPL is inserted in this zone. In contrast, when the OPL is located at 3.11 m (7 cm in front of the ED modules) in the stochastic zone, $n_{\mathrm{e\_edge}}$ and $T_{\mathrm{e\_edge}}$ are significantly modified. For the same central plasma density, $n_{\mathrm{e\_edge}}$ is decreased by a factor ~2 while $T_{\mathrm{e\_edge}}$ is increased by about 50%. However, for the three considered shots, the corresponding parallel heat flux $Q// = \gamma n_{\mathrm{e\_edge}} T_{\mathrm{e\_edge}}^{3/2}$ (where γ is the heat transmission factor), remains constant within ±15% over the investigated plasma density range. A higher plasma density before detachment can be obtained by insertion of the OPL in the stochastic zone. The OPL is closer to the confined plasma and this leads to a larger recycling flux on the head of the OPL which is effective for the plasma fuelling. As a result, for a given central plasma density, the required edge density is lower when the OPL is inserted in the stochastic zone.

As for $n_{\mathrm{e\_edge}}$ and $T_{\mathrm{e\_edge}}$, the particle flux on the divertor plates ($\propto I_{\mathrm{sat}}$) is not affected when the radial OPL position is greater than 3.14 m ($I_{\mathrm{sat}} \propto n_{\mathrm{e\_edge}}\sqrt{T_{\mathrm{e\_edge}}}$). Since the resulting neutral pressure, P, behind the neutraliser plates of the ED modules is proportional to $n_{\mathrm{e\_edge}}\sqrt{T_{\mathrm{e\_edge}}}$, the best pumping capability is obtained for the largest particle flux which occurs for the high recycling regime as shown on Fig. 2. It has to be noted that the particle collection efficiency does not depend on the three edge density regimes; linear (L), high recycling (HR) and detached (D) [1]. It is also worth noting that there is neither degradation nor improvement of the particle collection with the particle flux intensity. When the plasma detaches, P decreases in the same proportion as I_{sat}. This is in contrast with the axisymmetric divertor where the resulting pressure in the pumping chamber still increases even during the drop of I_{sat} associated to the detachment of the plasma [9].

In terms of particle exhaust capability, the pressure decrease in the plenum of the vented neutraliser plates

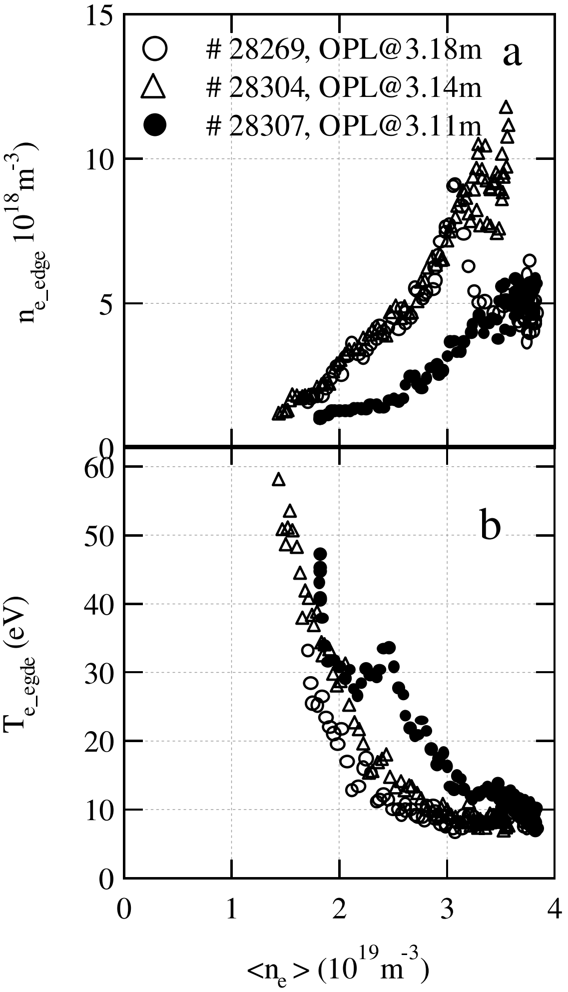

Fig. 1. (a) $n_{\mathrm{e\_edge}}$ and (b) $T_{\mathrm{e\_edge}}$ as a function of the volume-averaged plasma density $\langle n_e \rangle$ for three positions of the OPL inserted in the ergodic layer. When the OPL is located in the laminar zone (open symbols) neither $n_{\mathrm{e\_edge}}$ nor $T_{\mathrm{e\_edge}}$ are modified. This is in contrast to the filled symbols which correspond to an OPL location in the stochastic zone.

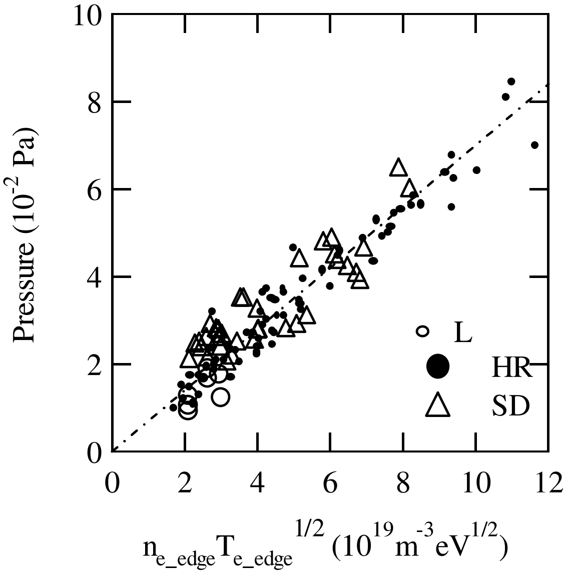

Fig. 2. Resulting neutral pressure behind the vented neutraliser plate as a function of the particle flux for the three edge density regimes; linear (L), high recycling (HR) and detached (D).

resulting from the insertion of the OPL into the ergodic layer is largely compensated by the OPL pumping capability. On the OPL the particle collection is ensured by throats which have been demonstrated to deliver a particle collection efficiency about 4–5 times larger than the vented structure [10,11]. For the reported experiment, the neutral pressure in the OPL plenum of 0.3 Pa is obtained for $\langle n_e \rangle = 3.5 \times 10^{19}$ m^{-3} when the OPL is inserted at a radius of 3.11 m.

3. Particle balance for the two configurations

The reported experiments are the two ohmic shots previously described with: (a) ED alone (the OPL being retracted at 3.18 m) and (b) with the OPL inserted in the ED at a radius of 3.11 m (mixed configuration). The particle fluxes are plotted as a function of time on Fig. 3(a) and (b). With the ED alone, a semi-detached phase occurs at $t \sim 5$ s resulting in a reduction of the gas injection, Φ_{inj}, to about 0.7 Pam^3 s^{-1} for steady-state conditions and compensated by the ED pumping. A feedback on the gas injection is used to control the degree of detachment (Dod) [12]. When the OPL is at 3.11 m, a very strong Φ_{inj} of 6 Pam^3 s^{-1} is required to increase the plasma density. This increment of the injection is nearly compensated by the OPL exhaust (Fig. 3(b)) the ED exhaust representing about 15–20% of the total particles pumped.

The global particle balance, defined by the equilibrium between the injection, exhaust, the plasma and wall (respectively N_{plasma} and N_{wall}) can be expressed as

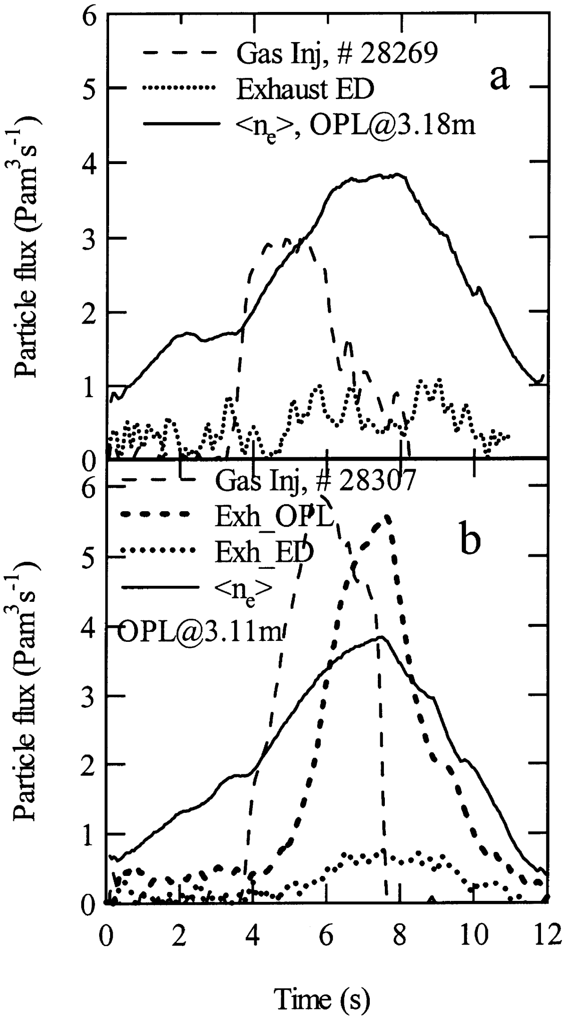

Fig. 3. Particle fluxes as a function of time for a shot: (a) without OPL pumping and (b) with the OPL inserted in the ED layer.

$$\frac{\mathrm{d}N_{\mathrm{wall}}}{\mathrm{d}t} = \Phi_{\mathrm{inj}} - \frac{\mathrm{d}N_{\mathrm{plasma}}}{\mathrm{d}t} - \mathrm{Exhaust},$$

where ‘Exhaust’ is the total pumped particle flux by both the ED and the OPL pumps.

At the end of the plasma ($t \sim 12$ s), the global particle balance exhibits an excess of 5 Pam^3 for N_{wall} with the ED alone while a deficit of 5 Pam^3 is recorded for the mixed configuration, the uncertainty on the exhaust term being about ∼15–20% for the reported experiments. For the medium position of the OPL (3.14 m) the balance is equilibrated. In terms of particle control, the strong additional pumping allows for a significant increase of the plasma density control as well as for a possibility to control the evolution of the wall particle content.

Characterisation of the pumping efficiency can also be performed by the 'classical' global particle balance

$$\frac{\mathrm{d}N_{\mathrm{plasma}}}{\mathrm{d}t} = \Phi_{\mathrm{inj}} - \frac{N_{\mathrm{plasma}}}{\tau_{\mathrm{p}}^{*}},$$

where τ_{p}^{*} is the apparent characteristic particle lifetime defined by $\tau_{\mathrm{p}}^{*} = (\tau_{\mathrm{p}}/1 - R)$ where τ_{p} is the particle confinement time and R is the global recycling coefficient. Such a definition does not allow a separate determination of the wall (passive) and pumping (active) terms, but it allows to quantify a comparison between two shots. Fig. 4 displays the time evolution of $\langle n_{\mathrm{e}} \rangle$ and the corresponding τ_{p}^{*}. There is nearly no variation of the pumping efficiency as a function of time (or $\langle n_{\mathrm{e}} \rangle$ since the density increases with time) for the mixed configuration with $\tau_{\mathrm{p}}^{*} \sim 0.4$–$0.5$ s as far as Φ_{inj} is maintained and an increase up to $\tau_{\mathrm{p}}^{*} \sim 2.0$ s after $t = 7.6$ s when the gas injection is cut off. For the ED alone, $\tau_{\mathrm{p}}^{*} \sim 0.65$ s (~40% larger than for the mixed configuration) as far as the plasma remains attached. When the plasma detaches at $t \sim 5.5$ s, τ_{p}^{*} increases up to about 2 s, indicating a reduction of the plasma density control. The oscillations in τ_{p}^{*} observed at $t \sim 6.4$, 6.8 and 7.6 s are induced by the feedback control on the gas injection for the Dod control. At these times, the gas injection is turned on within a time constant of ~0.1 s which is significantly smaller (about 10 times) than τ_{p}^{*}. Vice versa, the increase of τ_{p}^{*} at $t \sim 6.6$, 7 and 7.6 s correspond to the gas injection cut-off.

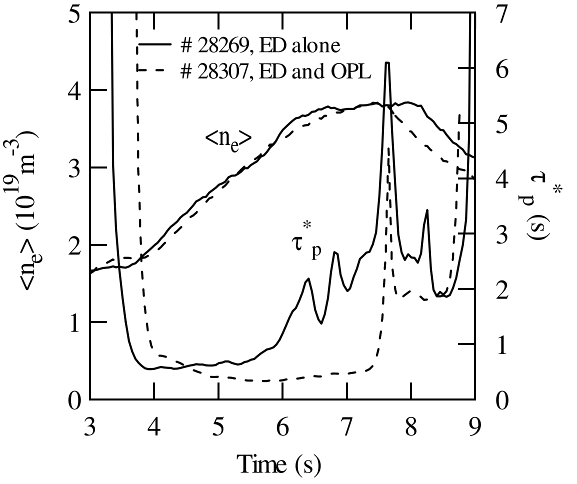

Fig. 4. Evolution of the volume-averaged plasma density $\langle n_{\mathrm{e}} \rangle$ as a function of time and the corresponding τ_{p}^{*} for a shot without OPL and with the OPL inserted (and pumping) and in the ED layer.

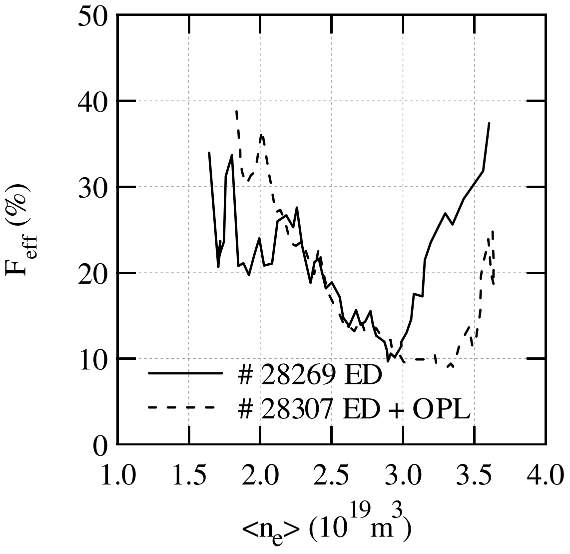

Fig. 5. Evolution of the fuelling efficiency, F_{eff}, a function of volume averaged plasma density $\langle n_{\mathrm{e}} \rangle$ for a shot without OPL pumping and a shot with the OPL inserted in the ED layer.

The fuelling efficiency, F_{eff}, is also a parameter which allows one to characterise the particle screening for a given plasma configuration. F_{eff} is defined as

$$F_{\mathrm{eff}} = \frac{\mathrm{d}N_{\mathrm{plasma}}/\mathrm{d}t}{\Phi_{\mathrm{inj}} - \Phi_{\mathrm{pump}}},$$

where Φ_{pump} is the pumped flux. Fig. 5 displays F_{eff} as a function of $\langle n_{\mathrm{e}} \rangle$ for the two shots; three phases can be distinguished. For density lower than 2.0×10^{19} m^{-3}, F_{eff} is significantly lower for the ED configuration suggesting a better screening of the particles at the edge (Fig. 1(a)). The OPL at 3.11 m represents a dominant source for the plasma fuelling via the recycling flux on the OPL's head. A second phase is observed between 2.2 and 3.0×10^{19} m^{-3} where F_{eff} exhibits the same behaviour for both configurations. This shows that the gas injection has to become much larger than the strong exhaust in order to increase the plasma density. Finally, the third phase corresponds to the detachment for the ED case; F_{eff} increases very abruptly while for the mixed configuration the plasma remains attached with a constant F_{eff} around ~10%.

A low F_{eff} for D_2 can also be interpreted in terms of effective particle screening [13] (D_2 and impurities) at the edge plasma and characterised by the effective charge of the plasma Z_{eff}. Indeed, F_{eff} and Z_{eff} exhibit the same dependence as a function of $\langle n_{\mathrm{e}} \rangle$ with the three phases reported for F_{eff}. On Fig. 6 the carbon concentration in the bulk plasma (CVI) is displayed as a function of $T_{\mathrm{e\_edge}}$ for the two considered shots. It can be seen that the carbon concentration in the discharge depends strongly on the OPL position particularly at large $T_{\mathrm{e\_edge}}$ (low density). However, it is worth noting that for the mixed configuration there is a very strong decrease of the carbon concentration in the plasma as a function of

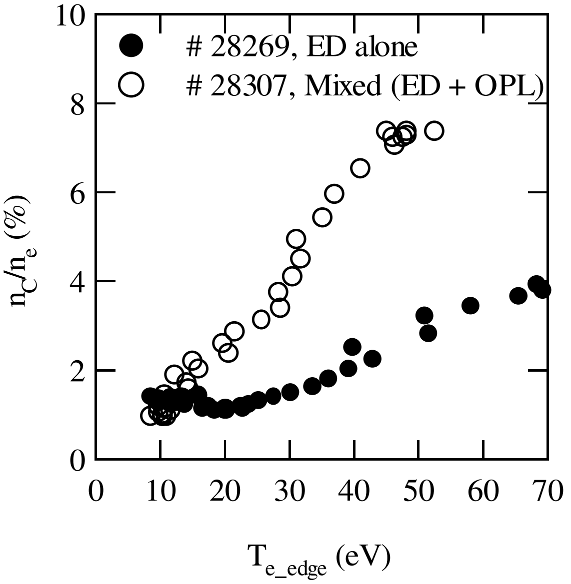

Fig. 6. Evolution of the carbon concentration $(CVI/\langle n_e \rangle)$ as a function of T_{e_edge} for two shots with and without the OPL pumping inserted in the ED layer.

T_{e_edge}. For the lower T_{e_edge} the same concentration as without the OPL is obtained. Such an effect cannot be attributed to the screening of the ergodic divertor and the associated low generation of carbon ions only. Indeed, this is also likely to be the result of the strong additional pumping by the OPL, equivalent to the 'puff and pump' already performed in other machines like DIII-D [3].

4. Conclusion

The investigation of the impact of the insertion of the OPL in the ergodic layer has shown that when the OPL is located inside the laminar zone (~3–4 cm), there is nearly no modification of the edge ergodic layer. In contrast, when the OPL is located in the stochastic zone of the ergodic layer (~7 cm in front of the ED modules), the edge plasma parameters (n_{e_edge}, T_{e_edge} as well as fuelling screening efficiencies) are significantly modified. For the same central plasma density, n_{e_edge} is decreased by a factor ~2 while T_{e_edge} is increased by about 50%. However, at this radial location, the additional pumping delivered by the OPL allows to increase significantly (by ~50%) the pumping efficiency, the exhaust being ensured by both the ED and the OPL with a contribution of 20% and 80%, respectively. Finally, the additional pumping, associated to the low generation of carbon ions, contributes significantly to recover the carbon screening initially obtained with the ED alone.

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References

[1] A. Azéroual, B. Pégourié, E. Chareyre et al., Nucl. Fus. 40 (2000) 16511.
[2] B. Meslin, T. Loarer, Ph. Ghendrih et al., J. Nucl. Mater. 266–269 (1999) 318.
[3] Ph. Ghendrih, A. Azéroual, M. Bécoulet et al., these Proceedings.
[4] M.R. Wade, W.P. West, R.D. Wood et al., J. Nucl. Mater. 266–269 (1999) 44.
[5] K.H. Finken (Guest Ed.), Dynamic Ergodic Divertor (special issue), Fus. Eng. Des.
[6] Ph. Ghendrih, A. Grosman, H. Capes, Plasma Phys. Control Fus. 38 (1996) 1653.
[7] Ph. Ghendrih, A. Grosman, H. Capes, Plasma Phys. Control Fus. 37 (1997).
[8] B. Meslin, Ph. Ghendrih, A. Grosman et al., in: Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics, vol. 1, Berchtesgaden, 1997, p. 197.
[9] W. Zhang, T. Fall, B. Terreault et al., J. Nucl. Mater. 244 (1997) 44.
[10] T. Loarer, E. Tsitrone, B. Pégourié et al., Nucl. Fus. 36 (1996) 225.
[11] B. Pégourié, T. Loarer, E. Tsitrone et al., J. Nucl. Mater. 241–243 (1997) 494.
[12] J.P. Gunn, A. Azéroual, M. Bécoulet et al., Plasma Phys. Control Fus. 41 (B243) (1999).
[13] C. Grisolia, Ph. Ghendrih, J.P. Gunn et al., these Proceedings.