MODELLING OF PARTICLES COLLECTION BY VENTED LIMITERS

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1 - INTRODUCTION

After more than ten years of experiments, pump limiters with throats have widely demonstrated their capability to control the plasma density. However, the high heat flux deposition on the leading edge just above the throat can result, at least for modular limiters, in an unacceptable surface temperature of this part of the device. Moreover, when operating with strongly radiating plasmas, the pumping efficiency of throat limiters drops correlatively with the strong reduction of the parallel particle flux in the SOL. In order to overcome these limitations, the concept of vented pump limiter has been studied and experimentally developed on Tore Supra [1, 2]. Schematically, its principle is the following : since the cascade of reactions experienced by the recycled flux (dissociation, charge-exchange) yields a nearly isotropic neutrals distribution, almost half the recycled flux comes back towards the limiter. If the limiter head is designed to be semi-transparent to neutrals (slots between tiles), a significant fraction of the backflowing flux can enter the limiter plenum and be extracted. The geometry of the present limiter is shown on fig.1. Two sets of slots (1.2cm × 9.5cm) are worked out in the limiter head, aligned along the toroidal direction. For typical conditions (q_{edge}≈3) the angle between the field lines and the slots is ≈7°. In Section 2, we describe the model developed for experiments interpretation and device optimization. We present in Section 3 a comparison between the simulations and experimental data, and discuss in Section 4 the difference between the deuterium and helium pumping efficiencies and the possible improvements of the device.

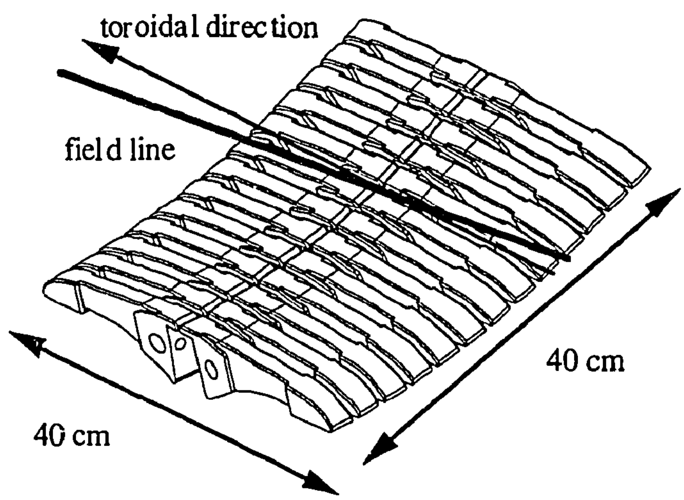

Figure 1 : *The TORE SUPRA vented limiter*

2 - MODEL

The model assumes steady-state conditions and isothermal magnetic surfaces (this last hypothesis reduces the validity domain to regions of temperature ≥10eV). Schematically, three different physical processes can be distinguished, each of them corresponding to one module of the computer code :

(1) Ballistic (ionic) collection : Due to the angle between the slots and the field lines, a fraction of the parallel ion flux (≈15% for the present limiter) enters the slots where it recycles on the lateral faces. Once neutralized, these particles have a significant probability (≈0.20 for the present slots geometry) to directly enter the pumping chamber. The efficiency of this ballistic collection depends strongly on the slots geometry and localization on the limiter head but is independent on the incident ion species (D^+ or He^{++}).

(2) Neutrals collection : The remaining flux (i.e. the part which is not ballistically collected) recycles towards the plasma as atoms or molecules (whose relative ratio and energy distribution are taken from [3]). It experiences several atomic reactions the most important of which are [4] : D_2 dissociation, D ionization and charge-exchange with D^+ for deuterium plasmas ; He 1rst and 2nd ionizations and charge-exchanges with He^+ and He^{++} for helium plasmas. For known plasma characteristics, the SOL ion source, the D, D_2, He and He^+ distributions in front of the limiter head, the flux entering the pumping chamber and the corresponding pressure are determined from multi-1D calculations. The efficiency of this neutrals collection is strongly dependent on the ion species : due to Franck-Condon dissociation, it is much larger for deuterium than for helium, whose atomic flux on the limiter surface is only due to charge-exchange (at low temperature, elastic collisions of He with background plasma ions can increase this backward flux [5]).

(3) SOL density modification : Due to the ion source (ionization of D and He), an electrostatic potential developes in the SOL. This potential induces a reduction of the plasma density, associated with a macroscopic parallel flow for reasons of particles and momentum conservation. This density modification changes the reaction rates experienced by the recycled flux and influences the results of the calculations of module (2). It is determined by a 2D calculation, assuming a sonic flow at the limiter surface and neglecting the contribution of the secondary species (i.e. D, D_2, He and He^+) to the ionic pressure.

Coupling these three modules allows to calculate realistic values for the secondary species distributions, the flux of neutrals entering the slots, the pressure in the pumping chamber and the whole device exhaust efficiency.

3 - EXPERIMENTAL VALIDATION

The input parameters of the model are, in addition to the limiter geometry, the edge temperatures (T_e^a, T_i^a), electron density (n_e^a) and decay lengths in the SOL (λ_T, λ_n). For D plasmas, these quantities have been determined by reflectometry and Langmuir probe measurements on a series of ohmic plasmas (I_p=1÷1.5MA) of volume averaged density $<n_e>$ ranging from 2 10^{19} to 4 $10^{19}m^{-3}$. Typical values are : $T_e^a \approx 50eV$ ($T_i^a=T_e^a$ assumed), n_e^a ranging from 3.5 10^{18} to 1.4 $10^{19}m^{-3}$, $\lambda_T \approx 3.7cm$ and $\lambda_n \approx 3.3cm$. The SOL characteristics are almost similar for He plasmas, but for the edge density, due to a lower flux amplification α for identical $<n_e>$ (one has $\alpha(He)n_e^a(D) \approx \alpha(D)n_e^a(He)$). A comparison between the calculated and measured values of the pressures in the pumping chamber is shown on figure 2. Experimental pressures are displayed as plain symbols : triangles for D plasmas ; squares for He+D plasmas with $<n_e(He)/n_e(He+D)> \approx 0.8 \div 0.9$. The open circles are the calculated values corresponding to the two He+D cases ; simulation results are displayed as full line for D plasmas, as dashed line for pure He plasmas. The calculated pressures in D and He are in a ratio between 2 and 3.5 and are roughly proportional to n_e^a. This is consistent with the experimental behaviour [1] which yields a value of ≈2.7 for the pressures ratio and a square dependence with the average density $<n_e>$ (note that, due to the increase of the SOL opacity with density, one has $n_e^a \propto <n_e>^{2 \div 2.5}$).

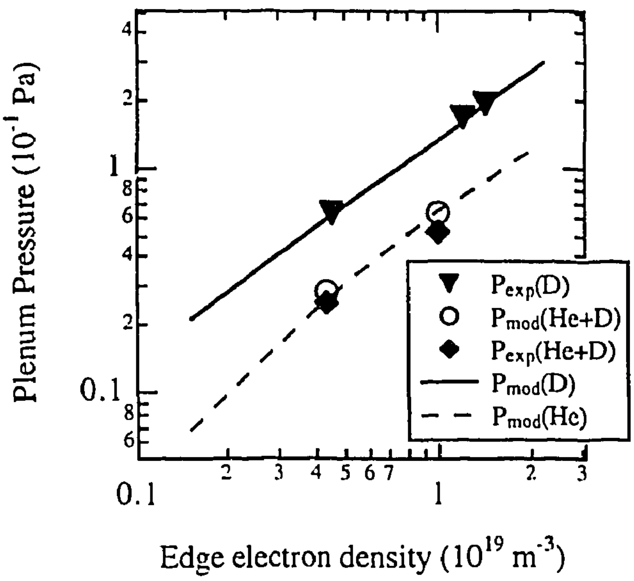

Figure 2 : *Plenum pressure vs. edge density*

4 - DISCUSSION

Due to the differences in the atomic physics of D and He, the neutrals flux towards the limiter head is expected to vary ≈ linearly with D density and ≈ quadratically with He density. As a consequence, the pumping efficiency ε (=[exhausted flux]/[plasma outflux]) is expected to change with He concentration. This is shown on figure 3a where the exhaust efficiencies for both He, ε(He)TS, and D, ε(D)TS, are plotted versus the He ion concentration $n_i(He)/[n_i(He)+n_i(D)]$ for the TORE SUPRA vented limiter. The input parameters of the model are : $T_i^a = T_e^a = 50eV$, $n_e^a = 1\ 10^{19} m^{-3}$, $\lambda_T = 3.7cm$ and $\lambda_n = 3.3cm$ (they correspond to an average density $<n_e>$ between 3 10^{19} and 4 $10^{19} m^{-3}$ depending on the He proportion in the plasma). The pumping speed is assumed to be constant, identical for both He and D, and equal to $8m^3/s$. In this case, ε(He)TS varies from 1.5% to 4% when ε(D)TS remains constant at a value of 8%. For "reactor" conditions (He concentration ≈0.2), one has ε(He)TS/ε(D)TS≈0.3. The corresponding contributions of ballistic collection to the exhaust efficiency, %bal(He)TS and %bal(D)TS, are displayed on figure 3b. The ballistic contribution is moderate for deuterium (20%) but always dominant for He (between 39% and 100%) and, for "reactor" conditions, %bal(He)TS=66%. It appears therefore that, if the pumping of D is dominated by the collection of recycled neutrals, ballistic collection is essential for He pumping. The viability of vented limiters with highly radiating plasmas (reduced SOL parallel flux conditions) depends thus on the ability of elastic collisions with background ions [5] to maintain a sufficient He neutral flux backflowing towards the limiter head.

The present vented limiter can be improved on both collection aspects while keeping the thermal constraints on secondary leading edges at an acceptable level. (1) Ballistic collection : The slots section can be optimized for ballistic collection : opening the slots towards the pumping chamber (trapezoidal section) with an angle of ≈15° for each lateral face increases the probability an incident ion has to directly enter the chamber from 0.2 (present geometry) to 0.5. (2) Neutrals collection : The slots can be prolongated up to the top of the limiter, where the neutrals density is maximum. The results of these modifications are shown on figure 3a (curves ε(He, D)opt and %bal(He, D)opt). The pumping efficiencies are multiplied by a factor ≈2, for D as well as for He. Nevertheless, the contribution of ballistic collection remains unchanged (figure 3b) : a particular shaping of the slots section cannot be used to equilibrate the D and He collection efficiencies.

Finally, the relative independence of vented structure performances with SOL characteristics must be noted. A change from 3 to 1.7cm of λ_Γ, the decay-length of the parallel flux in the SOL, yields a reduction of a factor of 0.65 for the proportion of the ion flux intercepted by the slots, when the vented limiter collection efficiency (≈[flux entering the slots]/[SOL parallel flux]), decreases only by a factor of 0.8 for deuterium, and 0.9 for helium.

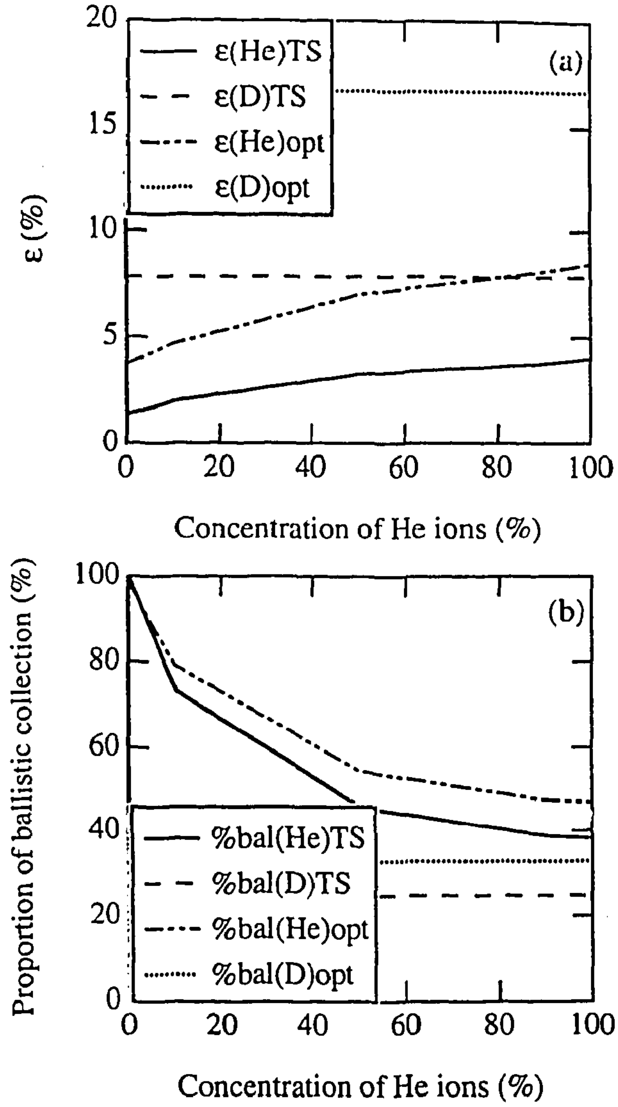

Figure 3 : *Exhaust efficiency* (**a**) *and proportio[n] of ballistic collection* (**b**) *vs. He concentration.*

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