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# MODELING OF PARTICLE COLLECTION BY THE ERGODIC DIVERTOR OF TORE SUPRA

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## 1. Introduction

In Ergodic Divertor (ED) configuration plasmas, peripheral field lines are connected to the wall on neutralizers located between the divertor bars (7 neutralizers and 2 pumps per module - 6 modules for the divertor). These neutralizers are vented structures, semi-transparent to neutrals, which can be used for particle pumping (5 neutralizers per module are pumped). A comprehensive set of diagnostics has been installed for a better characterization of the edge plasma: 14 Langmuir probes poloidally and toroidally distributed, pressure gauges in the modules plena and in the titanium getters and  $D_\alpha$  measurements along the neutralizer located in the equatorial plane. A series of experiments has been performed in deuterium with volume averaged densities scaling from 2 to 4  $10^{19} \text{ m}^{-3}$  and additional power (ICRH) up to 5 MW. The edge parameters ranged from 10 to 35eV for the electron temperature and from 4  $10^{18}$  to 2  $10^{19} \text{ m}^{-3}$  for the density. The pressure measured in the modules plena ranged from 0.02 to 0.1 Pa for a pumping speed of  $\approx 5 \text{ m}^3/\text{s}$ . Experimentally, the scaling of the pressure in the modules with averaged density and total power was  $\approx \langle n_e \rangle^2 P_{\text{tot}}^{1/3}$ , identical to what was obtained in limiter configuration [1]. In this paper, we present a modeling of the pumping and neutral recirculation around the neutralizer plates. The simulated pressures and  $D_\alpha$  distributions are compared with measurements. The corresponding exhaust efficiencies are given and, on the basis of these results, an optimized design is proposed for the neutralizers.

## 2. Model

A multi-1D model, extrapolated from the JONAS code [2], has been developed to interpret the experiments. Steady-state conditions are assumed. Due to 1D calculations, the poloidally inhomogeneous flux pattern [3] on each neutralizer cannot be simulated and only averaged gradients are considered. The electron temperature and density profiles are therefore assumed to vary smoothly in the toroidal direction along each neutralizer (routinely, 8 calculations per neutralizer, corresponding to a space resolution of  $\approx 5 \text{ cm}$ ). According to Langmuir probe measurements, the profiles can vary from one neutralizer to the other. At every points where a calculation is performed, the inclination of the field lines with respect to the neutralizer (which determines the incident particle flux) is calculated with the MASTOC code [4]. The proportions of incident ions reflected as fast neutrals or thermal molecules (at wall temperature) are determined through the reflection coefficients for energy and density given in Ref. [5]. The molecule and neutral distributions in front of each neutralizer are then calculated taking into account molecular dissociation, ionization and charge exchange. The  $D_\alpha$  emission distribution is estimated from the ionization and charge exchange rate coefficients, since the molecular ions contribution can be neglected for the plasma conditions investigated in the present work [6]. To calculate the flux entering the plenum two

phenomena are considered: ballistic collection (the part of the ions which recycles on the lateral faces of the slots has a significant probability to directly enter the plenum) and neutral collection (for each molecular dissociation and charge exchange reaction, the outgoing neutral has a probability  $\approx 1/2$  to come back towards the neutralizer and to enter the plenum according to the relative surface of the slots). Summing over the different neutralizers contribution yields, for the whole module, the flux pumped or backflowing through the neutralizers slots and the pressures in the plenum and in the titanium getters. The backflowing flux is included as an additional contribution to the molecular part of the recycling flux, allowing for an equilibrated particle balance.

### 3. Experimental Validation

In addition to Langmuir probe data, the electron density profile in front of the neutralizers is measured by FIR interferometry and reflectometry, the electron temperature profile by Thomson scattering. For the series of discharges presented here,  $Z_{\text{eff}}$  ranges from 1.5 to 1.8, yielding  $n_D/n_e = 0.95$  to 0.9, assuming that CIII and CIV are the dominant impurities at the edge. The pumping speed ( $5 \pm 1 \text{ m}^3 \text{ s}^{-1}$  in the plenum) is determined from the ratio between the pressures measured in the plenum and in the titanium getters. The two quantities of importance for a simulation/experiment comparison are the pressure in the plenum, which depends essentially on the flux entering the slots, and the  $D_{\alpha}$  emission, which characterizes the neutral distribution in front of the neutralizer. The simulated pressure in the plenum is plotted versus the experimental value in Figure 1, showing a satisfactory agreement.

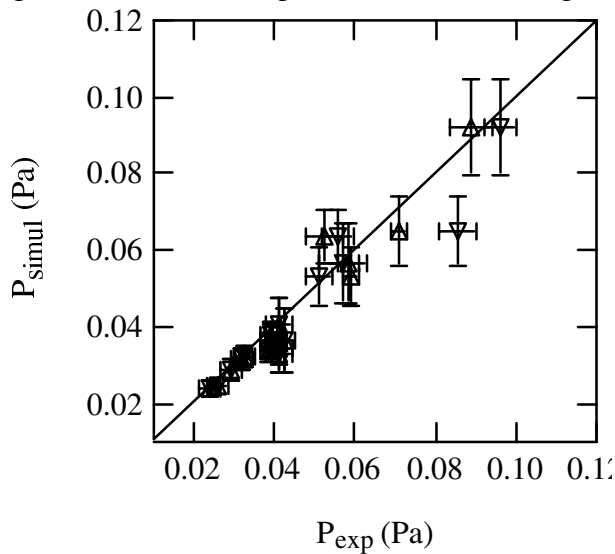


Fig.1: Pressure in the plenum.  
Simulation vs. Experiment.

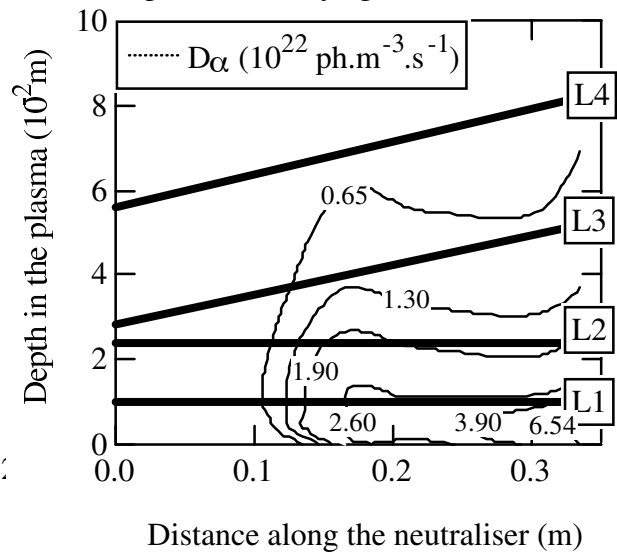


Fig.2: Geometry of the lines of sight  
for  $D_{\alpha}$  emission.

The horizontal and vertical error bars are the standard deviations of the pressure signal and of the saturation current of the Langmuir probes, respectively (one has  $\Delta P_{\text{simul}}/P_{\text{simul}} \approx \Delta J_{\text{sat}}/J_{\text{sat}}$ ). The absolute brightness of the  $D_{\alpha}$  line is measured along four lines of sight, the geometry of which in the equatorial plane is shown on Figure 2, superimposed over a contour plot of the calculated  $D_{\alpha}$  intensity. The simulated and experimental values are compared on Figure 3. The shapes show a satisfactory agreement, although the calculation leads to values  $\approx 30\%$  lower than what is measured. This is probably due to the part of the plasma outflux which recycles on the ED front face (about half the total plasma outflux), the emission of

which is not accounted for in the present calculation. Finally, the  $D_\alpha$  profile along one neutralizer needle (in arbitrary units) as measured by a CCD camera is compared with the calculation on Figure 4.

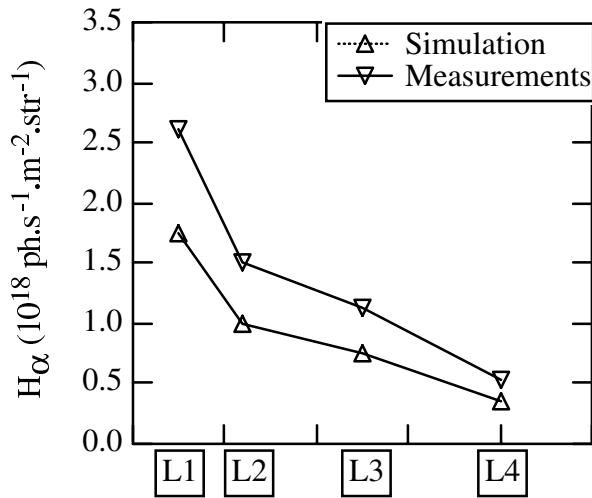


Fig.3: Integrated  $D_\alpha$  emission

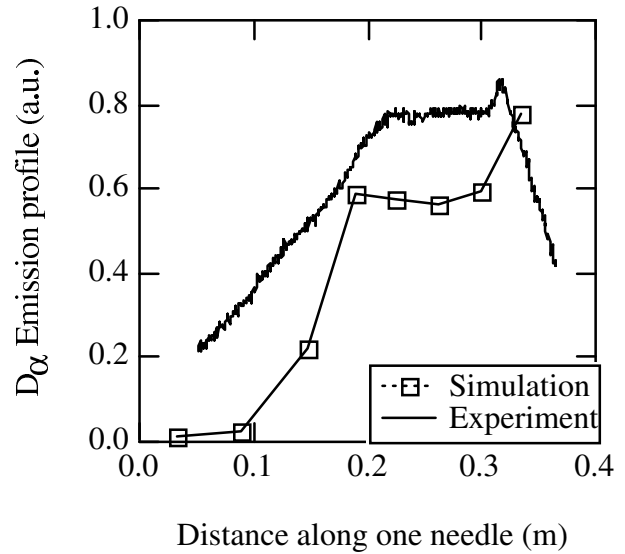


Fig.4:  $D_\alpha$  profile along one needle.

The good agreement between data and simulations for pressure and  $D_\alpha$  emission validates the approximations of the model and shows that the dynamics of the neutrals is correctly described.

#### 4. Discussion

As long as  $T_{\text{edge}} \approx 10 \text{ eV}$ , ballistic collection is significant and its contribution to the incoming flux depends on the location along the neutralizer. This is shown on Figure 5 where the flux entering the plenum due to ionic (ballistic), neutral (atomic physics) collections and the flux backflowing through the slots are displayed for the five pumped neutralizers, labelled from B to F. The backflowing flux depends only on the conductance of the slots. When moving along one neutralizer, the inclination of the field lines varies and thus the contribution of ballistic collection, until the point where the neutralizer is shadowed by the ED front face, for which the entering flux vanishes. This latter part of the slots does not contribute to particle collection but allows a significant leak of the gas (its length is almost half the total length of the slots). Thus, without changing the coils design (i.e. with the same magnetic perturbation), the collection capability can be improved by adapting the length of the slots to the wetted part of the neutralizer and opening the slots towards the plenum (trapezoidal section) with an angle of  $\approx 15^\circ$  for each lateral face [2] (this optimizes ballistic collection while keeping thermal constraints on secondary leading edges at an acceptable level). The key parameter characterizing a tool to control the density is the pumping efficiency  $\epsilon_p$ , defined as the ratio between the exhausted flux integrated over the 6 modules and the total plasma outflux [1]. Its behaviour with  $\langle n_e \rangle^2 P_{\text{tot}}^{1/3}$  is displayed on Figure 6. For deuterium, values between 1.5 and 2.3% have been obtained. This corresponds to  $10^{19}$  to  $10^{20} \text{ mol./s}$  exhausted for the whole ED. Using optimized neutralizers would increase this value by  $\approx 1.5 \div 1.7$ , and faster pumping speeds by  $\approx 1.2 \div 1.5$ . The symbols correspond to the actual pumping speed ( $5 \text{ m}^3/\text{s}$ ), the lines to 10 and  $15 \text{ m}^3/\text{s}$ .

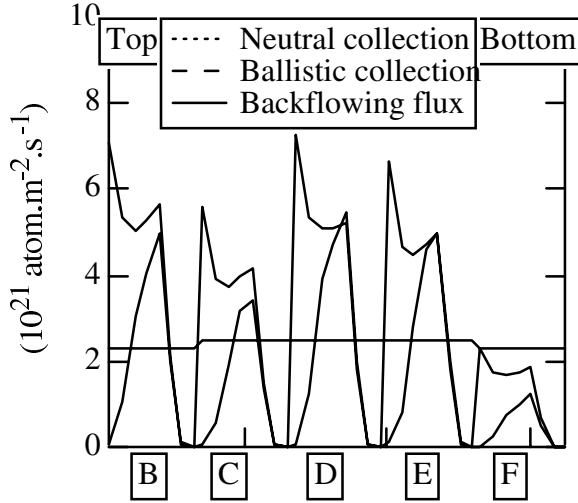


Fig.5: Flux balance for the 5 pumped neutralisers of a module.

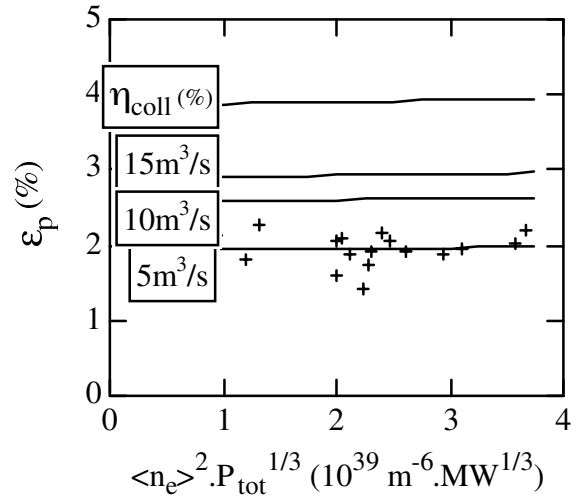


Fig.6: Pumping efficiency (5, 10 & 15 m<sup>3</sup>.s<sup>-1</sup>) collection efficiency.

The collection efficiency,  $\eta_{coll}$ , defined as the ratio between the collected flux and the plasma outflux, is also shown. Its value is  $\approx 4\%$ , identical to what was obtained for the vented limiter [1]. To maintain the ash concentration at the required level in an ITER-like plasma ( $\approx 15\%$ ), a pumping efficiency of  $\approx 2\%$  in helium is required [7]. In these conditions, one has  $\varepsilon_p(D,T)/\varepsilon_p(He) \approx 3$  for vented structures [8]. From the discussion above, it follows that even with a pumping speed of  $\approx 15 \text{ m}^3/\text{s}$  and optimized neutralizers, the required performances are not reached (one has  $\varepsilon_p(He) \approx 1.5\%$ ). To improve further the pumping efficiency would require to modify the coils to reduce the shadowing of the neutralizers by the ED front face.

## 5. Conclusion

A series of experiments ( $\langle n_e \rangle = 2 \div 4 \cdot 10^{19} \text{ m}^{-3}$ ;  $P_{ICRH}$  up to 5 MW) has been performed to investigate the capability of the Ergodic Divertor of Tore Supra to control the density. Pressures from 0.02 to 0.1 Pa have been measured, corresponding to pumping efficiencies from 1.5 to 2.3% ( $10^{19}$  to  $10^{20} \text{ mol./s}$  exhausted). The results of the model developed to interpret the measurements show a satisfactory agreement with experimental values for both the pressure and  $D_\alpha$  distribution. An optimized design is proposed for the neutralizers, improving the collection efficiency by  $\approx 1.5$ . With optimized neutralizers and a pumping speed of  $15 \text{ m}^3/\text{s}$ , the expected pumping efficiency in helium is  $\approx 1.5\%$  for a helium concentration of  $\approx 15\%$ .

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