ASSESSMENT OF IMPURITY CONTROL BY THE ERGODIC DIVERTOR ON TORE SUPRA.

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1. Introduction, and definition of the screening factor.

The demonstration of an efficient impurity control was one of the first experimental results obtained in Tore Supra with the ergodic divertor (ED). Both the level of metallic impurities, and of the dominant intrinsic carbon and oxygen impurities were found to be significantly reduced in the central confined plasma [1]. Extensive series of impurity seeding experiments in different density regimes have then been performed to investigate the role of the impurity recycling properties and ionisation mean free path (λ_i) in the core contamination [2]. This paper reports our latest analysis of the observed particle screening effect for intrinsic carbon and oxygen impurities, injected nitrogen, and for hydrogenic species. A 0-D particle flux balance is used to derive the relationship between core particle content and incoming particle flux from the divertor target plates. Let Γ_{div} S_{div} $\exp(-\Delta/\lambda_i)$ be the core influx, Γ_{div} being the average ion influx, S_{div} the total wetted surface of the neutralizers, and Δ the radial extent of the screening region with vanishing confinement time. This flux must balance the core plasma outflux : N_p/τ_p, where N_p is the total number of particles in the plasma core, and τ_p the core particle confinement time. We define the screening factor f_{sc} by:

$$f_{sc} \equiv \frac{N_p}{\Gamma_{div} S_{div} \tau_p} = \exp\left(-\frac{\Delta}{\lambda_i}\right) \qquad (1)$$

This 0-D model for particle flux balance is used in the following as a guideline to analyse the experimental data. The aim of the paper is to show that Δ/λ_i is a control parameter of the measured core contamination, and to determine Δ from experimental data.

2. Experimental determination of the effective width of the screening layer

2.a. Experimental scenario. Most of the experiments have been carried out with deuterium gas injection feedback on divertor electron temperature T_e^{div} measured by Langmuir probes[3]. T_e^{div}=50 to 10eV is therefore achieved in the ohmic plasmas analysed here. It corresponds to volume averaged electron densities in the range $1.5 - 3 \times 10^{19} \mathrm{m}^{-3}$. The standard resonant ergodic divertor configuration is used: B_t = 3.1T, I_p = 1.4MA, R = 2.39m, edge safety factor $q_\psi(a) \approx 3$. The effective extent of the low confinement region Δ is changed by varying the magnitude of the divertor perturbation monitored by the divertor current I_{ED}.

2.b. Measurement of the screening factor f_{sc}. For carbon, oxygen and nitrogen, N_p is obtained from the visible bremstrahlung measurement of Z_{eff}, and VUV measurements of the Lymanα line brightnesses. In the case of deuterium, N_p is obtained from the volume averaged electron density corrected by dilution effects. In the present analysis, τ_p is taken constant and equal to 0.2s. S_{div} is computed with the field line tracing code MASTOC [4]. It is $\approx 0.6\text{m}^2$ for the maximum magnetic perturbation, and varies as $I_{ED}^{0.5}$. The neutral influx Γ_{div} is measured from CII (658.1 nm), OII (431.7nm) or Dα (656 nm) line emission, monitored by a visible endoscope viewing a neutraliser plate [5]. In the case of deuterium, two particle sources are measured [6]: a slow neutral population with $E_0 \approx 1.5\text{eV}$, and a faster population, $E_0 \approx 22\text{eV}$. The fractions of slow and fast particle fluxes in the total D particle flux depend on the balance between the atomic physics processes producing the slow D population, and are still under investigation. For the experiments analysed here, $\Gamma_{slow}/\Gamma_{tot}$ is estimated to be 80%. The fast D population is assumed to penetrate entirely in the plasma core, without being screened, whereas the slow population is attenuated over the width Δ_{slow}. This assumption is supported by the large difference between the ionisation mean free paths of fast and slow neutrals ($\lambda_i^{fast} \approx 4\lambda_i^{slow}$), and the large value of λ_i^{fast}.

2.c. Determination of the neutral ionisation mean free path. The ionisation mean free path of neutral atoms is obtained from the computed radial ionisation profile. Measured edge electron density and temperature profiles are used. The energy of the incoming neutrals (E_0) is a key parameter in the computation of λ_i. For carbon, physical sputtering is assumed ($E_0 \approx 10\text{eV}$), which gives a good agreement between the calculated λ_i and the measured penetration of C neutrals obtained from a set of 4 optical fibers with lines of sight roughly parallel to the neutralizer plates and observing a CI spectral line [7]. Fig. 1 shows the variation of λ_i for C, in a typical experiment where T_e^{div} is varied between 30 and 50eV. The divertor perturbation is set to its maximum value, I_{ED}=45kA. The divertor electron density is also shown, together with the measured neutral C flux Γ_{div}^{C}, and the total number of C ions in the confined plasma N_C. For the slow deuterium population at 1.5eV, ionisation mean free paths in the range 0.03 to 0.05m are computed, whereas for the fast deuterium population, $\lambda_i^{fast} \approx 0.15 - 0.20\text{m}$. The energy of oxygen neutrals is not measured in our experiments. It is assumed to be the dissociation energy of the H-O binding ($E_0 \approx 2\text{eV}$).

2.d. Determination of Δ. The variation of Δ with I_{ED}, assumed to be of the form $\Delta = \alpha I_{ED}^{\beta}$ is determined experimentally from Eq. (1) by plotting Log(-λ_iLog(f_{sc})) versus Log(I_{ED}), Fig. 2. The effective width of the screening region for carbon neutrals is found to be 0.050m at the maximum magnetic perturbation, varying as I_{ED}^{β} with $\beta \approx 1.0$. For slow D neutrals, $\Delta_{slow} \approx 0.14\text{m}$ for I_{ED}=45kA, and $\beta \approx 1.5$. For oxygen neutrals, the width of the screening region exhibits the same linear increase with I_{ED} as for C neutrals, $\beta \approx 1.0$.

$\Delta^{Ox} \approx 0.027\text{m}$ is found at the maximum magnetic perturbation: however this low value depends on the energy of neutral O atoms, which is a parameter of our analysis. Figure 3 shows the measured screening factor for carbon, oxygen and deuterium versus the corresponding Δ/λ_i. Experiments with I_{ED}=18, 27, 36 and 45kA are included in the plot. For each value of I_{ED}, the variation of λ_i stems from the variation of T_e^{div} and n_e^{div}. This result shows that the value of Δ/λ_i controls the screening of the incoming particle flux.

3. Non uniformity in space of the screening effect

The width Δ is a mean property over the complex 3D pattern of the edge region. This is confirmed by changing the location of the impurity source. Indeed, to reach a given core nitrogen contamination, an injection rate 3 times larger is required when the gas valve is located at the divertor target plate. Moreover in the latter case, the power radiated by nitrogen in the edge is also 3 times higher for a given core nitrogen contamination, Fig. 4. This experiment thus indicates that the screening effect is not uniform in space.

4. **Coherence with the edge structure generated by the ergodic divertor**

The linear increase of Δ with I_{ED} observed for C and O neutrals is characteristic of laminar transport [8], suggesting that the laminar region, with short connection lengths less than one poloidal turn, plays a dominant role in C and O screening mechanism. This is further supported by the small width of the screening region which is found for these species (0.05 and 0.027m).This behaviour indicates that the screening does not stem directly from transport along stochastic fields. Indeed a dragging effect associated to the large values of the Mach number that are measured across the laminar zone appears to be effective. For deuterium neutrals, two particle sources are measured, with neutral energies of $\approx 1.5\text{eV}$ and 20eV, and these two populations are screened over two different characteristic widths. A reasonably good assumption, supported by the values of the ionisation mean free paths, is that Δ_{fast} is small enough to consider that the fast population penetrates entirely in the plasma core. Δ_{slow} is then determined from experimental data to be $\approx 0.14\text{m}$ and varies with $\approx I_{ED}^{1.5}$. These experimental characteristics of the screening layer for slow D neutrals are compatible with that of the stochastic region dominated by diffusive transport and which extends further inside towards the confined plasma.

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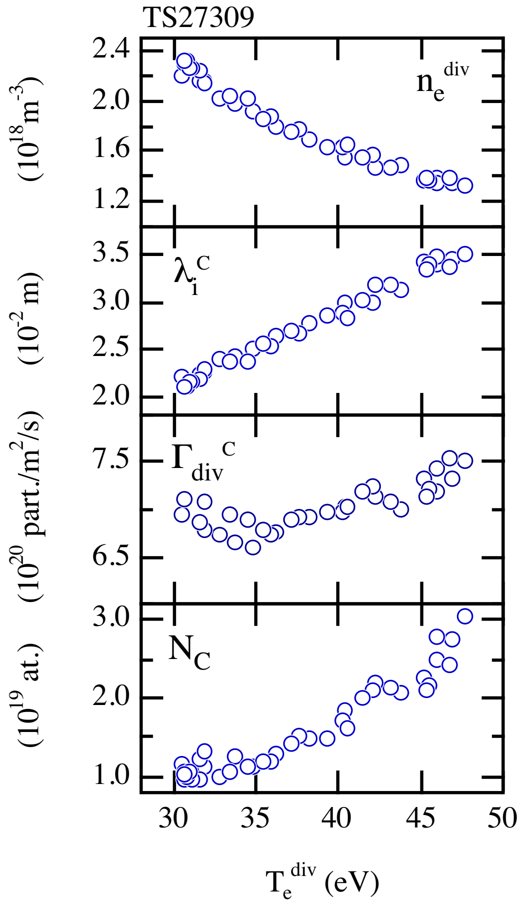

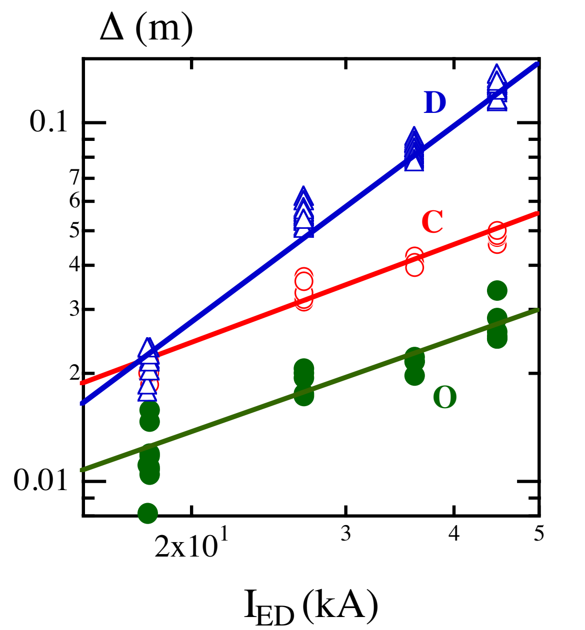

Fig. 2 : Determination of Δ from Eq. (1). For D neutrals, $\Gamma_{slow}/\Gamma_{tot}$=0.8.

Fig. 1 : Variation with divertor electron temperature of the divertor electron density, calculated ionisation length of carbon neutrals, measured carbon flux produced at the target plates, and total number of carbon ions inside the confined plasma. I_{ED}=45kA.

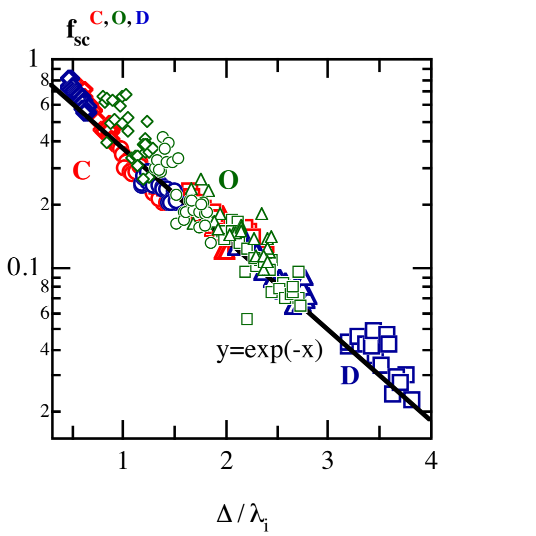

Fig. 3 : Measured screening factor for C, O and D versus the control parameter Δ/λ_i.

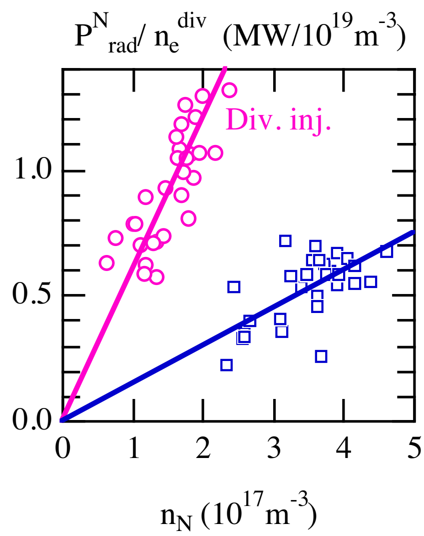

Fig. 4: Power radiated by nitrogen normalized to edge electron density, versus nitrogen density in the plasma core, for an injection valve located at the target plate (circles) or at the bottom of the vessel.