

STUDY AND SIMULATION OF CARBON IMPURITY DYNAMICS NEAR THE ERGODIC DIVERTOR IN TORE SUPRA

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Introduction

In the past few years, effects induced by the ergodic divertor such as impurity screening and transport modifications in the plasma edge have been used to achieve high radiation, low contamination regimes. A crucial issue in understanding these effects is that of impurity generation and propagation across the plasma edge, especially in the vicinity of the Ergodic Divertor (ED) neutraliser plates. A variety of diagnostic tools and techniques are used for this purpose¹. In the case of Tore Supra, interpretation of spectroscopic data is strongly complicated by the complex geometry of the ED, leading among other effects to the total lack of uniformity of the sources. Indeed, due to the specific pattern of impurity sources on the neutralisers and to their particular orientation with respect to the local magnetic field, densities of lowly ionised impurities are deeply modulated on the sub-centimetre scale in both directions perpendicular to the magnetic field. Accurate 3D simulations are therefore essential for the evaluation of experimental signals.

The code

The actual geometry of a few chosen neutralisers, including their fingered structure, the gaps between fingers terminating into V-shaped notches, their actual positions and slight misalignments as deduced from telemetric surveying, have been included in a new adapted version of the Monte Carlo code BBQ². The code follows particles within a cuboid containing a neutraliser plate and generates impurity densities in the same *simulation box* on a 3D grid of 10^6 points. Magnetic field lines are calculated by the Mastoc code³. A suite of post processors then produces and visualises lines emissivities, synthetic endoscope pictures and absolute intensities for the various diagnostics to be compared with experimental data. The analysis presented here refers to the neutraliser PJ1D i.e. the 4th neutraliser down from the top (a D plate) in the divertor module on the machine's JUNCTION PLANE 1 (there are six divertor modules around the torus, from PJ1 to PJ6). D plates are located on the machine's equatorial plane.

Plasma and impurity modelling

The ergodic nature of the magnetic field makes the structure of plasma near the neutraliser quite complex. The path of magnetic lines away from the neutraliser region is affected in an intricate way by the divertor windings and by the discrete structure of the toroidal magnet. Along their way around the torus the field lines explore a region whose radial extension is of the order of several centimetres. Lines leaving the neutralisers from very close positions are suddenly found to step away radially from one another after running in consistently narrow bundles over paths corresponding usually to an integer number of poloidal turns ($2\pi qR \sim 50\text{m}$). So, over a typical length of $2\pi qR$, field lines that are very close near the neutraliser will probe the outer plasma to markedly different radial depths.

Due to the strong electron thermal conductivity, domains that, *within such parallel distances*, are connected to deeper regions in the plasma periphery will be hotter than neighbouring zones. Perpendicular transport cancels out any effects due to longer connection lengths. This effect parts the region close to the divertor plates into a few alternately hotter and colder layers. It is confirmed by the experimental evidence of bands of higher energy flux onto target plates⁴.

Based on these considerations, the 3D electron temperature profile $T_e(x,y,z)$ in the modelling region was generated as a linear function of the field lines penetration depth inside the torus: $T_e = -k * (r_{\min} - c)$, where $r_{\min}(x,y,z)$ is the smallest minor radius attained by the field line passing by the point (x,y,z) over a path length of 1.5 poloidal turns (i.e. approximately 4.5 toroidal turns). A suitable choice of k and c can be made as to have agreement of the temperature values on the neutraliser plates with those given by Langmuir probes that are embedded on several D plates. However data from probes that are situated on the electron side (as all those on D plates) are believed to be affected by the presence of supra-thermal electrons in the pulse analysed in this study. Therefore we reduced the T_e values by 25% with respect to those giving the best reproduction of the probe data. This choice brings the T_e values closer to those measured by probes embedded on C plates that are situated on the ion side. Electron density values as given by the probes on D plates were used in the simulation. $T_i = T_e$ was assumed everywhere.

For the region within the simulation box (see fig. 1) whose points are directly connected by field lines to the neutraliser plate (zone D), we assumed the plasma velocity directed along the field lines towards the neutraliser and with Mach number $M_d = 1$. At smaller radii in the same box, however, there is a region (zone U) that is not connected to PJ1D but to another neutraliser (PJ6B) some 3 m away on the same side (left in fig. 1). For this region (the zone U) the pre-sheath constraint $M \approx 1$ is less stringent due to the longer distance from the solid surface of contact. Indeed experimental data indicate that for the Mach number in this region the condition $M_u = O(0.1)$ is verified (see below).

Carbon impurities production at the neutraliser is calculated by using different models for physical sputtering (including that by Garcia Rosales and Roth of 1993⁵ and that by Roth of 1998⁶) as well as chemical sputtering (including those from ref. [6] and those from B. Mech *et al.* of 1997⁷). The physical sputtering models lead to results that are quite close to one another (within 40%) and the chemical models appear to imply *for our case* carbon densities that are, close to the neutraliser, typically 10 times or more smaller than that due to physical sputtering. Self-sputtering of carbon, which is probably not important for low power pulses, as the one presented in this study, has not yet been included in the model.

The propagation of carbon ions in the plasma is determined in the simulation by the pre-sheath parallel electric field, by friction with the background plasma, as well as by parallel and perpendicular diffusion. The friction effect turns out to be of crucial importance even at plasma velocities much lower than the plasma sound speed (see below), while the effects of parallel diffusion and of the electric field appear of lower importance in determining the carbon ion distribution. For perpendicular diffusion $D_{\perp} = 1 \text{ m}^2/\text{s}$ was used in the simulations. On this effect we must observe that, the role of D_{\perp} being primarily that of determining the radial extent of the

impurity plume in front of the divertor plate, no clear-cut test against experimental data appears feasible when the impurity plumes are long in the magnetic field direction (as confirmed by endoscope pictures). In these cases the orientation of the existing telescopes is not sufficiently well aligned with the field to distinguish this feature from the parallel length of the plume (see fig 1).

Comparison with experimental data

In fig. 1 we present a simulated distribution of C^{+1} ions near the PJ1D plate in a side view. Light straight lines represent the viewing cones' axes of 4 telescopes located at the base of the neutraliser. A prominent feature in the picture is the long plume extending along the magnetic field in the direction contrary to that of the plasma flow, in the zone D, to the neutraliser PJ1D (the thick white line in the figure). The systematic existence of this plume is confirmed by data from an endoscope looking at another D plate, although the quality of its data for the pulse presented here is not good enough to allow a detailed quantitative comparison with synthetic pictures based on the simulations. Our analysis, however, shows that this feature would be totally suppressed if the plasma velocity were everywhere in our simulation box of the order of sound speed and in the same direction as in the zone D. Indeed a plume in the opposite direction would appear. The absolute values of CII intensities from the 4 telescopes would also be lower by ~ 50 -200 relative to measurements. Furthermore ratios between signals from different telescopes would be far from being reproduced.

Such a stark discrepancy with the experimental observations seems clearly to exclude the existence in the zone U of a significant plasma velocity field directed towards the PJ6B neutraliser (i.e. say with $M_u \geq 0.01$). The carbon distribution presented in fig. 1 was obtained with the assumption of $M_u = -0.03$ (i.e. plasma velocity towards the right in fig. 1). It is useful in this context to record that Doppler shift measurements made in the same region with the same telescopes on D_α line emission indicate plasma velocities directed away from PJ6B⁸.

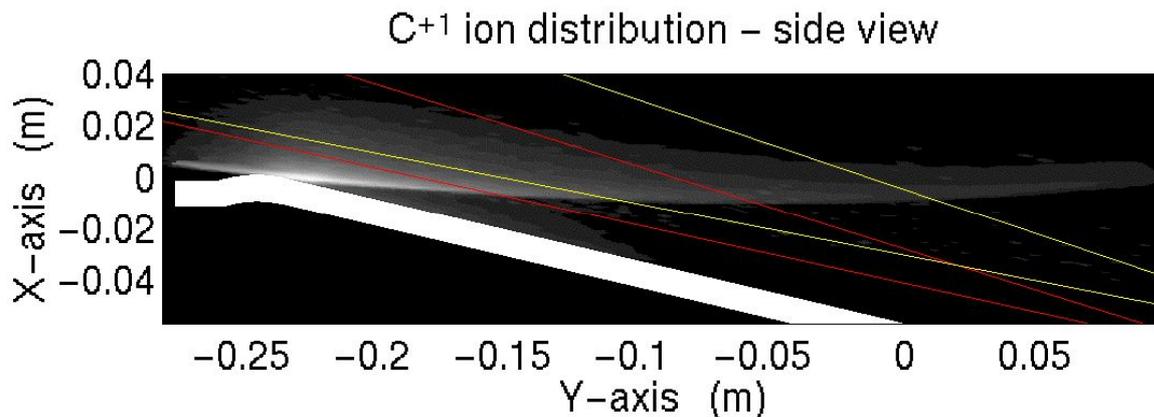


Fig.1. The margin, tangent to the neutraliser's top, between the lower and higher carbon density regions marks the edge between the domain that is directly connected to the neutraliser (zone D) and the domain (zone U) that is connected to another neutraliser some 3 m away on the left side. The y-axis is roughly parallel to the magnetic field and the x-axis, directed towards the plasma core, parallel to the local major radius.

Fig.2 shows that the experimental signal levels are nearly matched by simulations, the discrepancy in the overall level being very easily accountable by the uncertainty on density and temperature alone. The shape of the experimental curve profile is only very weakly sensitive to the

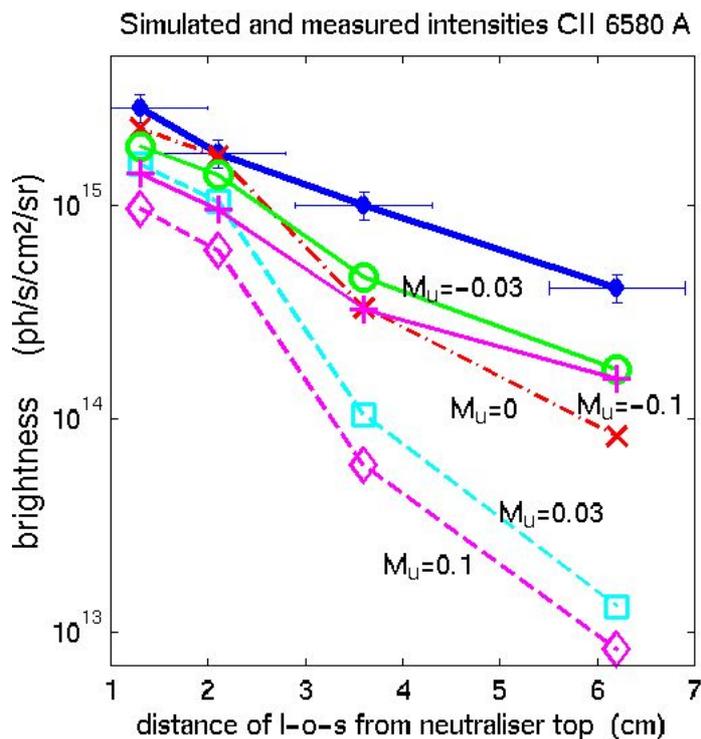


Fig. 2. Simulated data presented here were obtained with the physical sputtering model of ref. [5]

re-scaling method we estimate the total carbon extraction from the PJ1D neutraliser plate to around 1 to $2 \cdot 10^{18}$ atoms/s; the immediately re-deposited fraction around 40% to 50%.

Conclusions

- We verified the substantial quantitative consistency of the present day models for production, edge propagation and radiation of impurities with experimental data from Tore Supra.
- Our modelling tool is a versatile instrument to analyse physical phenomena occurring in the plasma. It is also useful for estimating important unmeasured parameters from the actual measurements such as radiated powers, particle extraction and re-deposition.
- The initial analysis reported in this paper suggests that the plasma state of motion in the region just clear of the divertor neutraliser is sharply different from that existing in the region directly connected to it and that possibly a (mild) flow reversal occurs in that place.

¹ L. Cherigier *et al.* 24th EPS Conf. on Contr. Fus. and Plasma Phys., Berchtesgaden, 1997 Vol. 1 p. 201. R. Guirlet *et al.* Journ. Nucl. Mat. **266-269** (1999) 513

² J. Hogan *et al.* 16th IAEA Conf. On Contr. Nucl. Fusion, Montreal, 1996, Vienna, 1997, Vol. 2 p. 625.

³ P. Ghendrih *et al.* Plasma Phys. and Contr. Fusion **38** (1996) 1653.

⁴ P. Ghendrih and A. Grosman Journ. Nucl. Mat. **241-243** (1997) 527.

⁵ J. Roth and C. Garcia-Rosales Nucl. Fus. **36** (1996) 1647; with corrigendum Nucl. Fus. (1997) 897

⁶ J. Roth Journ. Nucl. Mater. **266-269** (1999) 51

⁷ B. V. Mech *et al.*, Journ. Nucl. Mater **255** (1998) 153.

⁸ M. Koubiti *et al.* Line Shape Modelling for Tokamak Edge Plasma Conditions *This Conference*

source distribution and to the emitted particle energy for physically sputtered particles. The fact that it is matched best by the cases with $M_U < 0$, clearly implies that the plasma flow in zone U is directed away from the neutraliser PJ6B and that a reversal of flow direction takes place at the top edge of the D plate.

For the case analysed here, the total power radiated by C in the close vicinity of neutralisers is mostly due to low ionisation states and amounts to a minor fraction of the total radiation: between 0.2 and 0.4 kW from the simulation box shown in fig. 1. These values are obtained by re-scaling the simulation data by the factor needed to match the intensity measurements. Using the same re-