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Carbon source from the toroidal pumped limiter during long discharge operation in Tore Supra

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1. Introduction

Tore Supra is an actively cooled carbon machine that allows to perform long duration plasma discharges [1]. The particle balance of these long pulses has shown a constant in-vessel deuterium retention rate of $\sim 2\times10^{20}$ at/s, with no sign of saturation. Up to now, measurements of deuterium content in the carbon layers deposited on the plasma-facing components have not allowed the long term deuterium balance to be closed [2]. A better understanding of deuterium retention mechanisms requires the knowledge of carbon sources in the tokamak. The main source of carbon in the vacuum vessel during long discharges is the toroidal pumped limiter (TPL). This work is devoted to the experimental characterisation of the carbon source from the TPL surface during long discharges using a visible spectroscopy diagnostic. Moreover, we present an attempt to perform a carbon balance over a typical campaign and we discuss it with regards to the deuterium in-vessel inventory deduced from particle balance and the deuterium content of the deposited layers.

2. Characterisation of the carbon source from the TPL in Tore Supra

The main diagnostic used for evaluating the carbon source from the TPL is a visible telescope, located in a top part of the torus, allowing a direct view of the TPL. This diagnostic comprises a CCD camera with interchangeable interference filters and four optical fibres connected to a visible Czerny-Turner spectrometer.

Atomic carbon and deuterium fluxes $\Gamma_{C^0}^{in}$ and $\Gamma_{D^0}^{in}$, from the TPL surface towards the plasma, are deduced from the CII (658.1 nm) and Dα (656.3 nm) spectral line brightnesses. Indeed, atomic physics allows an absolute particle flux Γ_A^{in} to be written as [3] :

$\Gamma_A^{in} = 4\pi\, \mathcal{B}_A (S/XB)_A$ where $\mathcal{B}_A$ is the brightness of a spectral line emitted by those particles, S and X are the ionisation and excitation rate coefficients, and B is the branching ratio. The number of ionisation events per photon (S/XB) depends on edge electron density and temperature, which are obtained by fast-scanning Langmuir probes and reflectometry. The (S/XB) calculation for the Dα line takes into account the molecular contribution [4]. Two series of long discharge pulses are studied. The first series (A) is a low power case with LH heating only and low density ($I_p = 0.6\,MA$, $B_T = 3.6\,T$, $V_{loop} \sim 0$, $P_{LH} = 2\,MW$, linear density $nl = 1.9\times10^{19}\,m^{-2}$). The second series (B) is extended towards a higher power ($P_{LH} = 3\,MW + P_{ICRH} = 4\,MW$) and a higher density ($nl \sim 2.6\times10^{19}\,m^{-2}$). The corresponding plasma edge conditions at the last closed flux surface (LCFS) are $n_e^{LCFS} = 5\times10^{18}\ m^{-3}$ and $T_e^{LCFS} = 50\,eV$ for pulses A, $n_e^{LCFS} = 8\times10^{18}\ m^{-3}$ and $T_e^{LCFS} = 70\,eV$ for pulses B. The particle fluxes that we obtain from CII and Dα brightnesses are the following : during discharges A, $\left\langle \Gamma_{C^0}^{in} \right\rangle = 1.5\times10^{20}\ C/m^2/s$ and $\left\langle \Gamma_{D^0}^{in} \right\rangle = 1\times10^{22}\ D/m^2/s$, and during discharges B, $\left\langle \Gamma_{C^0}^{in} \right\rangle = 3.5\times10^{20}\ C/m^2/s$ and $\left\langle \Gamma_{D^0}^{in} \right\rangle = 2\times10^{22}\ D/m^2/s$. These values are estimated to be lower boundaries : first, the fibre views do not exactly correspond to the maximum erosion zone on the TPL; second, the mean free path of eroded carbon atoms can be larger than the field of view of the fibres ($diameter = 10\,cm$) and, therefore, the fibres do not see the CII emission of all the atoms eroded from the viewed zone.

From carbon and deuterium fluxes $\Gamma_{C^0}^{in}$ and $\Gamma_{D^0}^{in}$, we calculate the experimental carbon sputtering yield Y_{exp} for the TPL surface as the ratio of the eroded atomic carbon flux $\Gamma_{C^0}^{in}$ over the incident ionic deuterium flux $\Gamma_{D^+}^{out}$, considering the deuterium recycling equal to unity ($\Gamma_{D^+}^{out} = \Gamma_{D^0}^{in}$). Figure 1 shows the experimental carbon sputtering yields obtained for discharges A and B : $Y_{exp} = 0.016 \pm 0.008$ and 0.018 ± 0.008 respectively. Error bars take into account the uncertainty on edge parameters (electron density and temperature) and on coefficients (S/XB). These experimental yields are compared to theoretical values calculated from Roth formulas [5] for different erosion mechanisms : physical sputtering, self-sputtering and chemical sputtering. We can see that, for these plasma edge conditions, experimental yields on the TPL correspond to physical erosion. Indeed, the mean free path of a carbon atom eroded by physical sputtering is smaller than the diameter of the observed area, when that of a carbon atom eroded by self-sputtering is significantly larger. Therefore,

the emission of atoms eroded by self-sputtering is diluted on the whole TPL surface and self-sputtering only contributes to the background CII emission. Fibres only see a part of the emission of atoms eroded by physical sputtering.

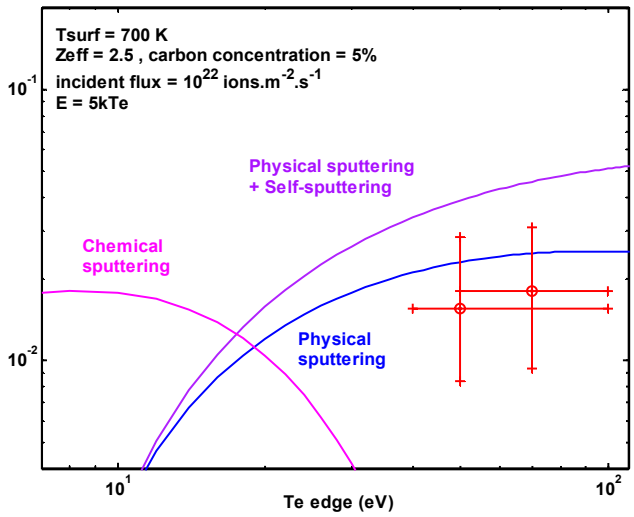

Figure 1 : *Experimental carbon sputtering yields (crosses) compared to theoretical values from Roth formulas (lines) for different sputtering mechanisms as a function of the edge electron temperature.*

3. Tentative carbon balance in Tore Supra long discharges

In order to perform a carbon balance over a typical Tore Supra long discharge campaign, the total quantity of eroded carbon is estimated from CII emission. We make the calculation for the series of pulses A which have been predominant during last campaigns. The effective interaction surface having been estimated to $\sim 1\,\mathrm{m}^2$, we obtain an integrated carbon flux equal to 1.5×10^{20} C/s. For the last campaign, the total plasma duration was about 20000 s. In these conditions, we find a quantity of eroded carbon atoms of 3×10^{24} C, that corresponds to a carbon mass of 60g over one campaign. Since we underestimate the experimental flux values, we make another calculation using the carbon sputtering yield values from Roth formulas : for a carbon concentration of 5% (effective plasma charge $Z_{\mathrm{eff}} = 2.5$), the total sputtering yield (physical sputtering + self-sputtering) is equal to 0.039 for discharges A. Using the previously determined value of 1×10^{22} D/m^2/s for the incident deuterium flux $\Gamma_{D^+}^{out}$, we find a sputtered carbon flux $\Gamma_{C^0}^{in}$ of 4×10^{20} C/m^2/s and an eroded carbon mass of 160g. Therefore, over one campaign, the quantity of eroded carbon ranges between 60 and 160g. Then, we compare this mass to the mass of carbon deposits collected in the vacuum vessel at the end of the last campaign (part of them being accumulated since the TPL installation, i.e. three campaigns). It has been found ~1.5 g on the outboard movable limiter, ~5.5 g on the TPL, ~1 g on LH launchers

and ICRH antennas, ~10 g on neutralizers [6]. Moreover, we estimate that ~20 g maximum are yet in the machine in volumes under the TPL and below the tiles of the inner bumpers. We therefore have ~40 g of carbon deposits for one to three campaigns, i.e. between 15 and 30 g per campaign. If we compare the eroded carbon quantity estimated from spectroscopy with that collected, we can see that 20-50% of the eroded carbon is found in the machine, which is compatible with 80-50% of carbon redeposited locally on the TPL surface. The deuterium quantity that has been lost by retention in the machine during the campaign is estimated to be 4×10^{23} D [2] (8×10^{23} D over a 40000s campaign and 4×10^{23} D over a 20000s campaign). The D/C content of collected deposits ranges between 1% in a less than 1μm layer to ~10% in the whole thickness of the fragment depending on their thermal history. Up to now, 5×10^{22} deuterium atoms have been found in the analysed deposits. Taking into account the 20g of deposits that have not yet been analysed and using the mean value of D/C ~ 0.1, we find that an upper limit of the deuterium inventory in deposits is $\sim1.5\times10^{23}$. This is only a third of the estimated deuterium trapped in the vessel. Thus, in the present state of our knowledge and characterisation of the permanent retention, one has to search for mechanisms other than codeposition to explain the deuterium retention in Tore Supra.

Gross erosion (TPL) from spectroscopy (per campaign)	60 – 160 g $\Gamma_{C^0}^{in} = 1.5\text{-}3.5\times10^{20}$ C/m^2/s
Estimated deposits mass (per campaign)	15 – 30 g
Estimated distant redeposition	20 – 50 %
Estimated local redeposition	80 – 50 %
Integrated D quantity retained in the vessel	4.10^{23} D
Integrated D content in analysed deposits	5.10^{22} D
D/C ratio in the deposits	0.01 – 0.10

Table 1 : *Summary of carbon and deuterium balances for one campaign.*

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