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Deuterium concentration in deposited carbon layers in Tore Supra

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Abstract

Deposited carbon layers observed in the tokamak Tore Supra have been sampled in order to quantify their deuterium content using $D(^3He,p)^4He$ nuclear reaction analysis. The results show two trends: the D/C ratio in wetted deposited carbon layers is less than 1% and the D concentration depth profile decreases rapidly from the first micrometers of the plasma facing sub-surface to the rear surface, while the D/C ratio in shadowed deposited carbon layers reaches about 10% and shows a more constant profile along the probed depth. Using the information about D concentrations and of the maximum thickness of the different samples and with the estimated deposited areas, an estimated D inventory is found to be about 1×10^{23}D, which is too low to account for the D retention expected for a whole long plasma discharge campaign.

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1. Introduction

Tore Supra is a fully actively cooled carbon-lined tokamak dedicated to long deuterium plasma discharges; the record is 6 min 18 s with 1.07 GJ of injected/extracted energy from the plasma [1]. Particle balance performed on these discharges shows that a significant fraction (~50%) of the injected deuterium particles is retained in the wall at the end of the shot, i.e. 7×10^{22} D in the discharge #32299, and the wall does never show any sign of saturation. The required gas injection for controlling the density remains constant during the whole discharge and the corresponding retention rate is 2.5×10^{20} D/s [1]. One of the two main processes invoked to explain this retention is co-deposition of deuterium in deposited carbon layers (DCL). This paper presents results of nuclear reaction analysis (NRA) performed on small samples removed from the DCL observed in Tore Supra.

2. Experimental

Fig. 1 represents an internal view of the vacuum vessel of the tokamak Tore Supra showing the plasma-facing components (PFC), which are covered with carbon–fiber composite armor tiles. In operation, the plasma leans on the toroidal pumped limiter (TPL), which defines the last closed flux surface (LCFS). A set of twelve neutralizer baffles located beneath the TPL

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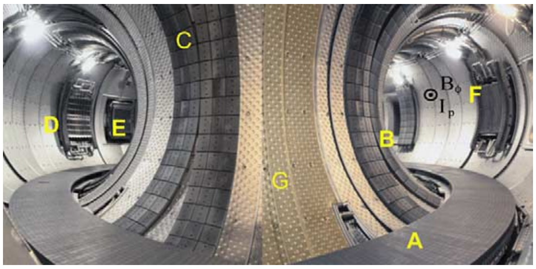

Fig. 1. Plasma facing components of Tore Supra. A: Toroidal pumped limiter, B: Outboard modular limiter, C: Poloidal inner bumpers, D: C3-LH launcher, E: C2-LH launcher, F: ICRH antenna, G: stainless steel panels.

(two per module – A_i and B_i – Tore Supra's vessel being divided in six modules of 60° each) helps to extract particles towards pumped ports (10 of them are pumped, including the B_i ones). Each neutralizer consists of four CFC-clad plates, which form a V-shape. The B-field lines intercept only one of these plates, which is the one that has DCL. In this work, only the DCL easily scraped away using a scalpel were studied. Thus, thin films that were strongly attached to the cooling tubes of the PFCs were not collected nor the DCL on the plasma facing TPL surface. The size of the obtained samples ranges from $20 \times 20\,\mu m^2$, resembling a fine grain powder, up to a few mm^2. In the latter case, we can find solid grains, flakes, and thin films. Fig. 2 represents views corresponding to the analyzed DCL location. The NRA was performed on DCL samples extracted from: the neutralizer plates (leading edge and lateral tiles, i.e. A and B in Fig. 2); the outboard modular limiter (left and right lateral faces of CFC tiles and their cooled copper base, i.e. E and F in Fig. 2); LH launcher carbon heat shields (i.e. D in Fig. 1 and in Fig. 2); underside of the TPL fingers (i.e. C in Fig. 2). A more complete description of the DCL in Tore Supra can be found in Ref. [2]. The maximum thickness of the DCL was estimated using optical microscopy (and scanning electron microscopy for some). The area of the surfaces involved in the deposition process was estimated visually taking into account the area of the different PFC surfaces. The NRA was performed with a nuclear microprobe, which uses a 1.5 MeV ^{3}He beam (beam current: 1 nA and spot size: less than $10 \times 10\,\mu m^2$) to produce $D(^3He,p)^4He$ reactions. The spectra were normalized with respect to a total load current onto the sample of 1 μC. Quantitative results and deuterium depth profiles were obtained using the simulation program SIMNRA [3].

Fig. 2. Location of the analyzed DCL: neutralizers (A: leading edge, B: lateral tiles), C: underside of the TPL fingers, D: lateral faces of C2-launcher and outboard modular limiter (E: CFC and F: copper).

Two steps of in situ sampling were realized: the first one at the end of the 2002 operation campaign (noted α) and the second one (noted β) during the 2003 summer shut down. The NRA was performed on June 3rd 2003 and October 20th 2003.

3. Results

Representative NRA spectra for the different samples are plotted in Fig. 3. Fig. 4 represents typical D/C ratio profiles input into SIMNRA to fit the previous experimental data. They show that, with the 1.5 MeV ^{3}He beam primary energy, the probed depth is limited in this study to ~3.8 μm.

3.1. Neutralizers (N)

(i) *Leading edge tile (N-LE):* Special attention was paid to the neutralizers because very thick deposits

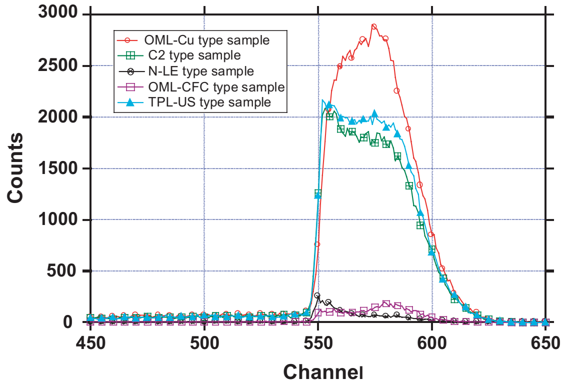

Fig. 3. Representative NRA spectra for different DCL samples.

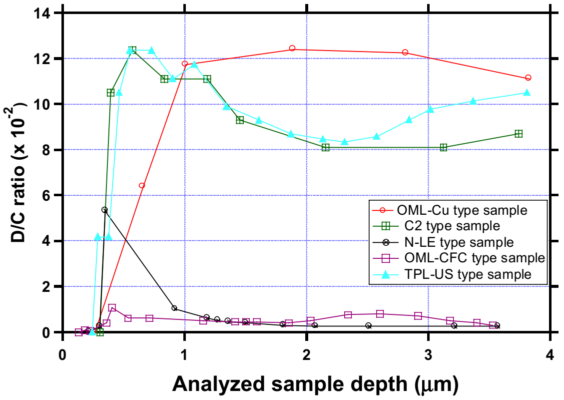

Fig. 4. Representative D/C ratio depth profiles for different DCL samples.

(up to 800 µm after 19600 s of cumulated plasma discharge duration) were observed on their leading edge tiles. All the neutralizers were sampled during the α sampling phase, except for the A_3, which had been removed from the vacuum vessel at that time. The B_i items were analyzed partly in June and partly in October. Some measurements were crosschecked and no influence of the air exposure time between the two measurement steps can be noted. The D concentrations for each B_i are reported in Table 1. The number of measurements does not constitute a good statistical sample and, for some samples, the accuracy of the mean concentration value is low. However, it seems that a clear toroidal asymmetry can be pointed out: concentrations less than 1.0×10^{17} D/cm^2 are found in modules 2 and 3, while in module 5 a concentration around 4.0×10^{17} D/cm^2 is measured. Concentrations for modules 1, 4 and 6 are intermediate. An average value of 2.1×10^{17} D/cm^2 will be considered in the DCL deuterium inventory for the N-LE tiles.

(ii) *Lateral tiles (N-LT):* the dismantling of the A_3 neutralizer plate allowed collecting flakes from the DCL observed on its plasma-facing surface. The mean D concentration is $(1.6 \pm 0.7) \times 10^{17}$ D/cm^2. It is close to the average value calculated for the leading edge tiles (2.1×10^{17} D/cm^2).

3.2. Outboard modular limiter (OML)

Armor of the OML is made of nine CFC-tiles of about 100 mm long in the poloidal direction and three rows of 85 mm wide CFC-tiles in the toroidal direction. These CFC-tiles are attached to actively cooled copper base tiles. The OML is a start-up bumper, which is retracted from the LCFS to a deeper position in the scrape off layer (SOL) 30 s after the plasma break-down at the latest. The lateral face of the CFC-tiles can therefore intercept particle and heat fluxes, in such a magnetic configuration that the B-field lines are nearly perpendicular to the OML lateral surfaces, but only during the beginning of the shot and during a time much shorter than that spent in the SOL where the fluxes are very weak. The copper part of the OML is always 2 cm minimum behind the plasma-facing CFC surface and supposed to stay in the shadowed zone. The samples from the OML-DCL were collected in the β-phase. At that time, the carbon deposits seemed to be more numerous in the upper part of the OML and on the ion side (the side towards which the plasma current is directed). The precise deposit location on a PFC depends on discharge parameters and changes occur from one campaign to the next. The analyses were performed on DCL from tile numbers 1, 2, 3, 5 and 9 from the ion side and a mix of DCL from tiles 2 and 3 from the electron side. Tile 1 is the upper one and the 9th is the lower one. From the results summarized in Table 2, it is impossible to define a clear influence of the toroidal or the poloidal position on D concentration. It is expected that the cartography of magnetic connections and shadowing by nearby PFCs is quite complex. In the future, we plan to make a detailed 3D mapping of the B-field lines in the SOL. On average, the D concentration in the DCL of the outboard limiter is about 2.4×10^{18} D/cm^2 on the copper-tiles and 1.3×10^{18} D/cm^2 on the CFC-tiles. In the latter case, the mean value is dominated by result from tile #1.

3.3. Other locations

(i) The DCL found on the underside surface (TPL-US) of the TPL CFC-fingers are located near the neutralizer plates. The origin of these DCL is not understood. Flakes from them were collected in the β-phase. The mean D concentration is $(3.3 \pm 0.3) \times 10^{18}$ D/cm^2.

(ii) LH launchers: samples were collected (β-phase) from the DCL found on the carbon-heat shields of the LH antennae, on the electron side. It deals with few flakes coming from a small and plasma facing area of the CFC-armor tiles from the

Table 1
Deuterium concentration in the DCL from the leading edge tiles of the neutralizers in function of the toroidal position

N-LE	B1	B2	B3	B4	B5	B6
Deuterium $\times 10^{17}$ D/cm^2	1.9 ± 0.1	0.8 ± 0.4	0.9 ± 0.2	3.1 ± 0.2	4.0 ± 0.9	2.2 ± 0.3

Table 2
Deuterium concentration in the DCL from the lateral face of the outboard modular limiter

D concentration Tile # (D/cm^2)	Ion side		Electron side
	Copper base tile	CFC tile	Copper base tile
1	–	3.3×10^{18}	
2	3.6×10^{18}		$(2.7 \pm 1.3) \times 10^{18}$
3	$(7.5 \pm 2.3) \times 10^{17}$	2.9×10^{17}	
5	$(2.6 \pm 1.5) \times 10^{18}$		
9		$(2.1 \pm 0.2) \times 10^{17}$	

Tile #1 is at the top of the limiter and tile #9 is at the bottom.

C3-launcher and deposits from the lateral side of the graphite armor-tiles from the C2-launcher. In the former case, the mean D concentration is $(2.5 \pm 1.2) \times 10^{17}$ D/cm^2, while in the latter case, the mean D concentration is $(3.5 \pm 0.1) \times 10^{18}$ D/cm^2. It is in agreement with previous OML results, which indicate a higher D retention capability of the DCL when located deeper in the SOL in the shadowed area.

4. Discussion

4.1. Deuterium concentrations

The number of NRA measurements for each sample is unfortunately small and the sampling, which has been done is not complete enough to reproduce the real D retention pattern in the vessel of Tore Supra. However, two trends can be deduced from the results. First, totally exposed PFC surfaces do not contain a high level of deuterium: one can keep in mind an average value of 2.5×10^{17} D/cm^2 and a D/C ratio smaller than 1%. On the other hand, more shadowed surfaces contain a deuterium concentration of an order of magnitude higher: a mean value is 3.0×10^{18} D/cm^2 and a D/C ratio close to 10%. The main reason seems to be the surface temperature reached by the different zones of the PFC during the plasma discharge. Infrared measurements show that the temperature of the leading edges of the neutralizer tiles reaches 1100 °C, even during ohmic discharges. In such conditions, deuterium leaves the DCL via thermal desorption. Langmuir probe measurements show that only weak particle fluxes are incident on the V-shape neutralizer. That can explain that the D concentration found in the N-LT samples is close to that from leading edge tiles even if temperature of the neutralizer lateral tiles is supposed to be lower than leading edge because of weaker incident fluxes on them. It is in accordance with results obtained for the outboard limiter and the other deposits, which show that the higher is the radial position of the DCL in the SOL, the higher is its D concentration. It is also very likely a consequence of the active cooling set-up in Tore Supra.

Changes in surface morphology are also observed between the different DCL sources [2]. As stated in Ref. [2], depending on the way the DCL interacts with the plasma, the DCL surface is characterized by a columnar structure or a much smoother surface. In order to go deeper in correlation between structure and D retention, X-ray diffraction, XANES and Raman spectroscopy were carried out. The results are reported in Refs. [4,5].

4.2. Deuterium inventory in Tore Supra

Using the information about D concentrations and of the maximum thickness of the different samples and with the estimated deposited areas, an estimate of the upper limit for D inventory in the analyzed DCL is given in Table 3. The experimental D/C depth profiles (Fig. 4) show clearly that, above a few micrometers in the bulk, the contributions of neutralizers and CFC-tiles from the outboard limiter to the total D content are negligible.

Table 3
Estimation of the deuterium inventory in the DCL collected in Tore Supra

DCL location	Mean D concentration (D/cm^2)	DCL area (cm^2)	DCL thickness (μm)	D inventory
LH-C2 launcher	3.5×10^{18}	~140	~50	6.4×10^{21}
TPL-US	3.3×10^{18}	~600	~20	1.0×10^{22}
OML-Cu	2.4×10^{18}	~400	<100	2.5×10^{22}
OML-CFC	1.3×10^{18}	~400	<300	4.0×10^{22}
N-LE	2.1×10^{17}	~430	<800	1.9×10^{22}
N-LT	1.6×10^{17}	~1390	<100	5.8×10^{21}
LH-C3 launcher	2.5×10^{17}	<100	<20	1.3×10^{20}

In these conditions, the D inventory in the DCL in Tore Supra is dominated by the retention capability of weak plasma exposure and cold surfaces. Obviously, on very long plasma discharge durations (>hours) DCL thickness plays also an important role and can compensate for a low deuterium concentration. That gives a D inventory of about 1×10^{23} D for an entire campaign (∼7760 s of plasma discharge before the β-sampling phase) for the analyzed DCL. Since particle balance for the single 378 s long plasma discharge (#32299) shows that 7×10^{22} D remain trapped in the vessel at the end of the shot and since long term particle balance, including TPL pumping during discharge, recovering between discharges and He-glow discharges, shows that the wall behaves like an infinite sink of particles [2], the present estimated D inventory does not at all account for the D retention expected for a whole long plasma discharge campaign by at least one order of magnitude.

5. Conclusion

NRA was carried out to quantify the deuterium retention capability of the deposited carbon layers in the tokamak Tore Supra. It was shown that the highest D/C ratio is about 10%. It is found in regions where the DCLs are the thinnest one, giving an estimated total deuterium inventory in Tore Supra of about 1×10^{23} D. The deposition surfaces which interact strongly with the plasma fluxes have low deuterium concentrations, around 1%, and their D depth profile decreases rapidly within a few micrometers. The main lesson from this work is that D inventory in the analyzed DCL does not account for the D retention expected for a long plasma discharge campaign in Tore Supra. This could mean that the major part of the missing deuterium is trapped in a large reservoir which has still to be identified. One of the candidates is the carbon deposits located in the gaps between the 576 fingers of the TPL. Unfortunately, they are in a place that cannot be easily reached without removing the actively cooled high heat flux elements of the TPL.

References

[1] D. Van Houtte, G. Martin, A. Becoulet, et al., Nucl. Fus. 44 (2004) L11.
[2] B. Pégourié, C. Brosset, E. Delchambre, et al., Phys. Scr. T 111 (2004) 23.
[3] M. Mayer, SIMNRA user's guide. Technical Report IPP 9/113, Max-Planck-Institut für Plasmaphysik, Garching, 1997.
[4] C. Arnas et al., these Proceedings, doi:10.1016/j.jnucmat.2004.09.026.
[5] P. Roubin et al., these Proceedings, doi:10.1016/j.jnucmat.2004.10.036.