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Modelling of plasma conditions for the mirror exposure study in Tore Supra

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1. Introduction

In the 2003-2004 experimental campaign of Tore Supra (TS), solid metal mirror samples (mono-crystalline molybdenum, stainless steel SS316L and copper OHFC) had been installed near the equatorial plane on the inner wall of the vacuum chamber about 140mm outside the last closed flux surface. During this time, the samples were exposed to ~1400 plasma pulses (mainly D_2) of more than Ip = 200 kA (n_{e0} ~2-4 10^{19} m^{-3}) with a total pulse length of ~26000s (7h10). The total energy injected of ~37GJ was composed of ~13GJ ohmic, ~22GJ LHCD and ~2GJ ICRH. With a typical value for the radiated power fraction of about 40% this corresponds to an accumulated average wall load of ~18 kJ/cm². In addition the mirrors were exposed to vessel wall conditioning: glow discharges in He (361h59min), in D_2 (606h8min) and boronisations (13h40min). Baking cycles of the vacuum vessel structure were performed at T~200°C. Besides minor leaks, a major water leak of an actively cooled in-vessel component occurred in September 2003, after 177h of D_2 and 108h of He glows. Minor water leaks on RF antenna structures appeared also during March 2004. The final TS operation before the mirror recovery lasted 2495s of plasma (including long discharges with pulse lengths > 100s), followed by a final 6.5h He glow and only 85s of plasma operation.

2. Experimental results

The optical properties of the mirror samples in the visible and the IR were documented before and after exposure, as well as the surface quality [1,2]. The samples were recovered in April 2004 and subjected to a series of measurements (AFM, confocal microscopy, Zygo interferometry, SEM, EDX, XPS, SIMS, spectra-photometry and ellipsometry) documenting the surface morphology and the optical properties after exposure. For all samples exposure in TS resulted in a net erosion: ~0.12µm for Mo, ~0.22µm for SS312L and ~2.68µm for Cu. Micro-particles, composed mostly of carbon and oxygen, with traces of hydrogen, deuterium, boron and iron, were found in small numbers on the surface of the Mo and SS316L samples, in larger number (and larger sizes up to 1mm) on the copper samples. The optical quality remained nearly unchanged for the Mo and the SS316L samples, but deteriorated severely in the case of the Cu samples with a large decrease of the reflectivity. The existence of a carbon deposit could only be proven on the Mo sample (12nm thickness measured by Ion-TOF-4-SIMS). The surface quality of the other samples or the thickness of a possible layer was not good enough to allow a measurement.

3. Numerical simulations of plasma conditions

Numerical simulations were undertaken to characterize the plasma near the mirror samples and to allow gauging the results in terms of particle fluxes and energies with those expected for the ITER diagnostic ducts. It was expected that two counteracting processes – erosion and deposition – will change the mirror surface and thereby degrade the reflectivity. The effort was divided into two tasks, assuming that erosion will primarily be caused by CXS neutrals, and deposits formed by carbon eroded and re-deposited from the TPL (toroidal pump limiter):

a) Using the Eirene code [3] to calculate the transport in the edge region of the plasma, taking into account the actual configuration of Tore Supra with the inner wall covered by stainless steel panels (T=460K) and the carbon TPL at 920K, the latter being the main particle source. Fictive D+ ions, which originate in the SOL, are followed to the limiter, where atoms and molecules are produced by recycling. The trajectories of these recycled products are followed to calculate the densities and energies of the CXS particles, allowing to calculate the erosion.

b) Using the BBQ 3-D Monte Carlo scrape-off layer impurity transport code coupled to a core radial impurity transport code (ITC / SANCO / MIST) to create a model describing carbon erosion and re-deposition processes in the TS CIEL geometry, allowing to estimate the expected carbon deposition on the mirror samples [4].

A standard TS discharge was defined as input into the codes: TS deuterium discharge with Te,max= 6keV, Te,bord=90eV, Te decay length l_Te=6cm, Ti=Te; ne,max=3e19cm^{-3}, ne,bord=4e18, ne decay length l_ne= 4cm. The profiles shapes were taken to be parabolic, the Shafranov shift to be 10cm and Zeff of the order of 2.

Eirene : The D_2 flux near the sample location is ~1.5 10^{20} m^{-2} s^{-1}, the density ~2.5 10^{16} m^{-3} (Fig. 1 &2). Most particles have a low energy (~10eV); nevertheless the energy distribution has a significant high-energy tail, taken into account in the erosion estimations. Assuming physical sputtering only the expected erosion depth is calculated as $\Delta_{erosion} = t_{plasma} \; 1/\rho_{metal} \int_E \Gamma(E) \cdot Y_{metal}(E)\, dE$, with the yields taken from the reference paper by Eckstein [5]. The estimates are shown in Table 1. It was found that the estimated based on plasma operation alone were too small to account for the net erosion measured, and that erosion due to He and D_2 glows had to be taken into account.

This was further investigated exposing reference samples to ex-situ glow discharges. The effect of the D_2 and He glow discharges performed during the mirror exposure were

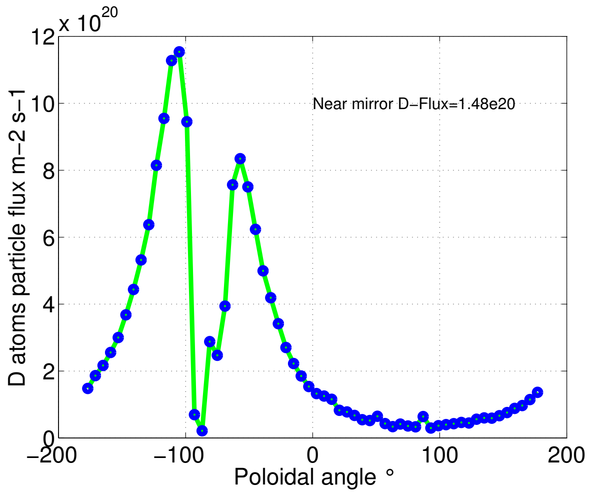

Figure 1: Eirene code: Deuterium flux – the mirrors are positioned at a poloidal angle of –180.

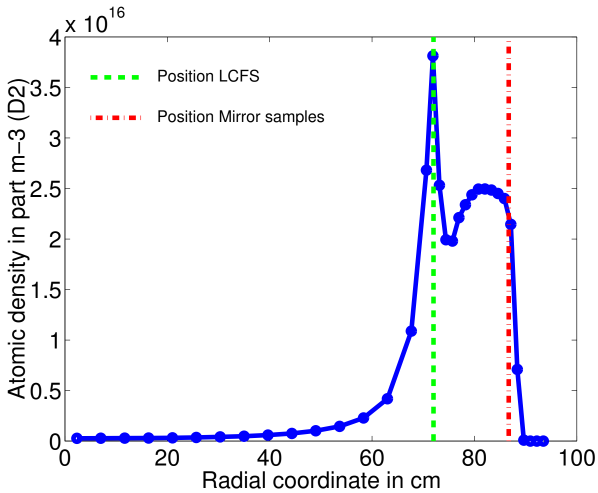

Figure 2: Eirene code: Radial particle distribution. Contributions from two sources at different radial positions (recyling at the CIEL limiter roof and recycling at the main chamber) are superimposed.

estimated as: $\Delta_{erosion} = t_{glow} \; 1/\rho_{metal} \; Y_{glow} \; \Gamma_{glow}$, with Y_{glow} the physical sputtering yields from Eckstein, t_{glow} the total duration of the glow, Γ_{glow} the flux calculated for a current density of $7\mu A/cm^2$ and assuming the energy of the particles to be 250 eV for the D2 glow, and 150 eV for the He glow (which is about the value for the sheath potential for steel). All results are compiled in Table 1.

BBQ: After determining the 3D incident D^+ deposition profile, the spatial and velocity-space distribution of emitted C fluxes due to the physical, chemical, and radiation enhanced sublimation (RES) processes driven by the D^+ source is calculated following the resulting C evolution in 3-D until final disposition taking into account self-sputtering. Fig. 3 shows the convergence of sample BBQ/ITC iteration for cases with (a) low impurity generation = rapid convergence, (b) moderate impurity generation = transition and (c) high impurity generation = production of runaway due to self-sputtering arising from hot spot sources on plasma-facing components in the far scrape-off layer. Calculations excluding the effect of localized hot spots indicate that less than 1% of the carbon generated at the TPL structure is deposited on the inner wall mirror locations. Assuming a moderate impurity generation with no hot spot sources the total deposit is expected to be only 86nm for the whole of the exposure time. This

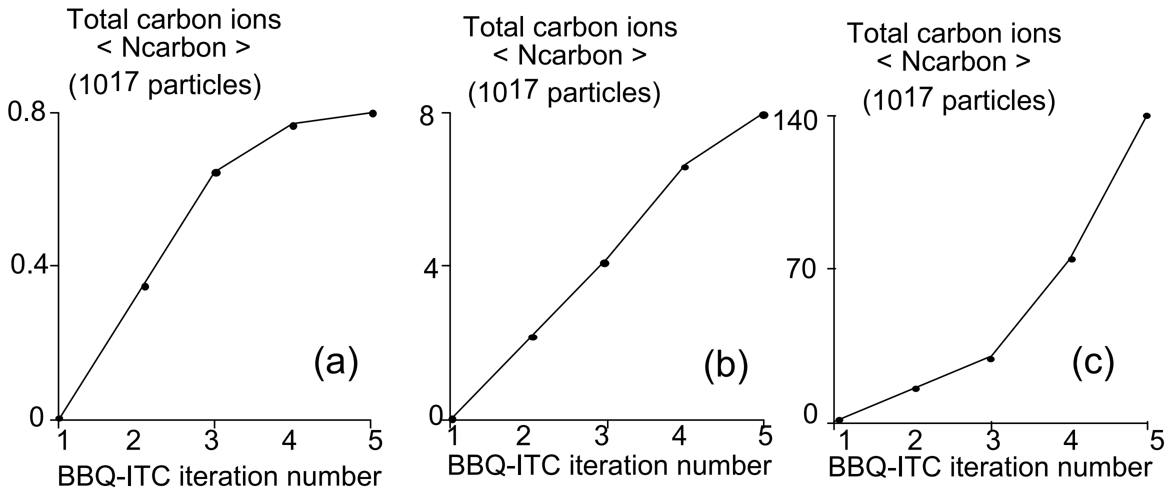

Figure 3: BBQ/IRTC: Code calculations for various assumptions about hot spot sources in the SOL. (a) No hot spots, (b) low localized SOL source, (c) maximum SOL source.3

low value is due to the positioning of the samples near the equatorial plane on the inner wall, where carbon fluxes, as well as CXS fluxes are small.

Mirror	Net-erosion TS (μm)	**Erosion simulation***			He + D_2 ex-situ glow norm. to exposure (μm)	Deposit meas. (μm)	Carbon Deposit (μm)
		Plasma	glows (μm)	total			
Mo	**~0.12**	**0.0317**	**0.0753**	**0.1070**	**0.061+ 0.25 = 0.31**	**0.012**	**0.086**
SS316L	**~0.22**	**0.0379**	**0.4806**	**0.5185**	**0.3 + 0.17 = 0.47**	**-------**	**0.086**
Cu OFHC	**~2.68**	**0.0685**	**0.9400**	**1.0085**	**0.31 + 2.53 = 2.84**	**-------**	**0.086**

*** Erosion due to physical sputtering**

Table 1: *Measured and calculated erosion and deposition.*

4. Discussion

It is evident that the glow discharges contributed significantly to the erosion process. The positioning of the samples near the equatorial plane was unfortunate as at this position both the flux of CXS atoms as well as the flux of carbon atoms is minimized, thus also minimizing the effect of erosion and deposition during plasma operation. The exposure of samples in TS clearly demonstrates the synergy of erosion and deposition processes, but quantitative interpretation of the data is extremely difficult due to the complex sequence of events (plasma, conditioning, water leak).

5. References

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