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A Quantitative Study of the Carbon Impurity Production Mechanisms from an Inertial Limiter in Tora Supra as Determined by Visible Spectroscopy

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1. Introduction. In a steady-state tokamak, impurity production and transport from plasma facing components will have to be controlled. Recent results from several divertor tokamaks (JT-60U [1], JET [2] and ASDEX-UG [3]) suggest the importance of chemical sputtering as an impurity production mechanism. However, since impurity production is minimized in high recycling divertor configurations, the quantitative characterization of impurity generation is more difficult than in the high heat flux environment of a limiter configuration. Such an experiment was carried out on Tore Supra to examine the absolute carbon flux from the inertially-cooled outboard limiter. Previous Tore Supra experimental and modelling results (BBQ) ([4] and [5]) have shown that chemical sputtering and radiation enhanced sublimation (RES) play a significant role in the total carbon erosion for certain regions of this limiter. Recently, CD molecular spectra, a signature of chemical sputtering, have also been observed. This work describes the observed temperature dependence of the methane and carbon flux.

2. Experimental setup and plasma conditions. The principal diagnostic was a visible spectrometer with an Optical Multichannel Analyzer (OMA) detector. Light emitted by low ionization states near the limiter surface was guided by a mirror to a series of lenses followed by fiber optic cables, each cable imaging a different 2 cm² region of the limiter. Absolute intensity calibrations of the entire system, performed in the torus before and after an experimental campaign, have shown that the mirror and sapphire window transmission were severely degraded by plasma exposure, thus invalidating the absolute calibrations. However, the relative change in the calibration as a function of wavelengths was understood. To take advantage of this knowledge, it was concluded that a self-consistent absolute calibration could be approximated if the calibration factor was known at one wavelength. It was decided to obtain the calibration factor at 4300 Å by assuming a reasonable methane yield value from published data.

$$\text{Methane Yield} = \Gamma_{\text{particle}}^{\text{CD}} / \Gamma_{\text{particle}}^{\text{D}^+} = 4\pi * S / XB(T_e) * \text{brightness}(\text{CD}) / n \sqrt{kT_e / m_i}$$

The methane yield is a function of three parameters: the electron temperature (T_e) and density (n_e) measured by the Langmuir probes and the brightness of the CD spectrum. From a value of 0.02 molecules per incident ion (ion flux of $6 * 10^{18} \text{ D}^+ \text{ cm}^{-2} \text{ s}^{-1}$, $T_e = 20 \text{ eV}$, $\langle n_e \rangle = 5 * 10^{18} \text{ m}^{-3}$, SX/B for CD₄ from CD(4310Å) of 110 dissociation processes per photon [6]) a brightness (and thus a calibration factor) was determined.

The reciprocating Langmuir probe referred to above was located 60° toroidally and 90° poloidally away from the limiter. T_e and n_e just inside the last closed flux surface (LCFS) were

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measured by Thomson scattering. The surface temperature of the limiter was determined from black body radiation measured in the visible. The error bars for these measurements are $\pm 20\%$. Z_{eff} was determined from continuum bremsstrahlung measurements in the visible.

Two plasma conditions were studied; both were deuterium, ohmic plasmas. The first condition will be referred to as Series A for which the toroidal magnetic field was 3.8 T, the minor radius 0.72 m, the major radius 2.40 m, the toroidal plasma current 1.54 MA, the safety factor 3.0 and the volume averaged electron density $3.9 \times 10^{19} \text{ m}^{-3}$. For Series B these parameters were 3.80 T, 0.76 m, 2.36 m, 1.69 MA, 3.1 and $3.5 \times 10^{19} \text{ m}^{-3}$, respectively. Identical shots were repeated for each series to allow data for different wavelengths to be taken for the same optical view. Leading edge (located 1.5 cm radially away from the LCFS) data was taken for Series A parameters and data from near the tangency point (a few mm from the LCFS) was taken for Series B. The limiter was made from a large block of Carbon Lorraine graphite (5890 PT).

3. Experimental Results and Discussion. During earlier experiments an image of the C II emission from the entire limiter was measured with an interference filtered, CCD camera and the visible endoscope. From the 3D Monte-Carlo modelling (BBQ) of this data, it was determined that chemical sputtering was a significant source of carbon for the leading edge as well as possibly at the tangency point of the limiter [4]. Hence a search for direct evidence of chemical sputtering by-products (C_2 and CD molecular bands) was undertaken.

CD molecular bands were observed on both the leading edge (Fig. 1) and tangency point of the limiter for the plasma parameters of Series A and B. However, C_2 molecular bands were not identified in either location. In Fig. 2a and 2b the brightness of the CD molecular band, integrated over a $15 \text{ \AA}$ region starting at the $\sim 4310 \text{ \AA}$ band head, is shown as a function of time for the leading edge region (Series A) and the tangency point region (Series B), respectively.

The limiter surface temperature, for the same region as the CD measurements, is also shown as a function of time. This surface temperature was determined from the black body radiation (measured at $\sim 6550 \text{ \AA}$ for Fig. 2a and $\sim 5140 \text{ \AA}$ for Fig. 2b). Since the black body radiation is too weak to determine the temperature below $\sim 1200^\circ\text{C}$, the pre-shot temperature (measured by thermocouple gauges within the limiter) was related to the temperature determined from the black body radiation by the semi-infinite, one dimensional surface temperature scaling law, which states that the surface temperature varies as the square root of time. From experiments in which IR camera data is compared to this scaling law, it was determined that the surface temperature is somewhat over-estimated by this scaling law at the beginning of the shot; this over-estimation was corrected for. The temperatures measured from the black body radiation are consistent with IR camera measurements for similar plasmas.

The plasma was moved onto the limiter at $t=1.6\text{s}$. From this time on, the plasma shape remained constant but the plasma current and density continued increasing until $t=3.5\text{s}$, thus complicating the calculation for the maximum data points in Fig. 2a (maximum point $T_e = 20 \text{ eV}$, remaining points $T_e = 30 \text{ eV}$) and Fig. 2b (60 eV and 80 eV, respectively)

It is shown in Fig. 2a and 2b that the production of methane was significantly reduced for temperature above 1100°C and negligible for temperatures above 1300°C . Respective temperature ranges of $\sim 350^\circ\text{C}$ to $\sim 700^\circ\text{C}$ and 470°C and 770°C corresponded to the maximum methane flux for the two regions of the limiter. This is consistent with laboratory measurements [6], in which a surface temperature of around 550°C corresponded to the maximum methane yield on both the leading edge and tangency point.

In Fig. 3a and 3b the molecular flux (SX/B of 110 diss./photon for highest point and 120 diss./photon for the remaining points [7]) and the C^+ particle flux ($T_e = 30 \text{ eV}$, SX/B = 60

ioniz./photon [8]) were calculated from Fig 2a and 2b. A 300% decrease in the methane influx corresponds to a 10% decrease in the influx of single ionized carbon. This indicates that methane has a slight or negligible influence in the C^+ flux. Near the end of the shot the C^+ signal increases significantly, this is attributed to RES since the only parameter simultaneously changing with the C^+ signal is the surface temperature. Variation in the C^+ signal from chemical sputtering and RES did not correspond to variation in Z_{eff} . Traditionally, carbon is the only significant impurity in these plasmas. This lack of impact on the core impurity content is attributed to a low core penetration efficiency for both of these sputtering mechanisms.

4. Impurity transport calculations. The data have been modeled with the impurity code BBQ. The code incorporates a 3D Monte-Carlo description of both neutral and charged impurity transport in Tore Supra geometry. Impurity generation processes related to physical and chemical sputtering are included. Given the limiter temperature distribution and the incident D^+ flux parameters, BBQ calculates the evolution of both physical (C) and chemical (CD_4) sputter products. The code calculates spatial distributions of CII and CIII brightness. The physical sputter products are emitted with a Thompson energy distribution, with energies as high as 5-10 eV; the chemical products are emitted at the wall temperature (0.1 eV) as CD_4 , which then experiences a break-up chain.

The measurements focus on the vicinity of the limiter. It is of importance to know what effect these processes have on core impurity accumulation. BBQ comparison allows us to see what the sensitivities are. Result shows (1) high penetration efficiency for physical, low for chemical, so physical dominates the core accumulation (2) a very strong dependence on basic surface data, with important (but somewhat less) dependence on uncertainties in SOL perpendicular transport.

5. Conclusion. A quantitative study of the role of temperature dependent sputtering mechanisms on the outboard limiter in Tore Supra was performed. The methane flux proved to be significantly reduced above surface temperatures of 1100°C and negligible above 1300°C. The peak in the methane yield as a function of surface temperature is consistent with lab results. It was determined that chemical sputtering (early in the shot) had a small, to negligible, impact on the C^+ flux; while RES (late in the shot) had a strong impact on the C^+ flux. However, from the Z_{eff} measurements, it was concluded that neither process contributed to the core carbon content.

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8. Figures.

Fig. (1) Sample CD molecular band spectra

Fig. (2a) CD brightness and surface temperature vs. time measured from the leading edge

Fig (2b) CD brightness and surface temperature vs. time measured from the central tangency point.

Fig. (3a) C^+ and CD_4 flux vs. time measured from the leading edge .

Fig. (3b) C^+ and CD_4 flux vs. time measured from the central tangency point.

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