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Carbon erosion experiments in the ITER relevant flux regime

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The FOM-Institute for Plasma Physics Rijnhuizen is building the linear plasma generator Magnum-PSI for fundamental research on Plasma Surface Interaction (PSI) in the unexplored regime of plasma conditions as expected in the divertor of ITER[1]. The heart of this device will be a high flux plasma source that is being developed at the forerunner Pilot-PSI. In this contribution we report on a breakthrough in plasma production. Thomson scattering (density and temperature) measurements are presented that demonstrate plasma fluxes ranging over two orders of magnitude around the fluxes expected for the ITER divertor ($10^{23} - 10^{25}$ $\mathrm{m^{-2}s^{-1}}$) and temperatures from 0.1 to 5 eV. Calorimetry on the cooling water of the target confirms the fluxes that are determined from the Thomson scattering data. Carbon samples were exposed to this unique Pilot-PSI hydrogen plasma jet. Via calibrated molecular spectroscopy on the CH band we determined carbon erosion yields in the flux range $1 \cdot 10^{24} - 5 \cdot 10^{24}$ $\mathrm{m^{-2}s^{-1}}$ to drop from 0.008 to 0.002 for target surface temperatures increasing from 700 K to 1550 K. Significant amounts of eroded material were observed to be redeposited within the plasma wetted area.

Pilot-PSI and Diagnostics The hydrogen plasma jet in Pilot-PSI (Fig. 1) is produced with a wall stabilized cascaded arc plasma source[2]. Typical operation parameters are: 100 A discharge current, 2 slm gas flow rate, 0.1 bar inlet gas pressure. The plasma expands into a vacuum vessel at ~ 0.03 mbar where it is confined by a magnetic field up to 1.6 T and directed onto a carbon target at 0.5 m. The carbon targets (Fine Grain Graphite, R 6650, SGL Carbon Group) were 30 mm diameter and 4 mm thickness and clamped on an actively cooled heat sink.

A schematic of the diagnostics installed at the target is also shown in Fig. 1. Thomson scattering (TS) is performed at 18 mm in front of the target. The TS system records electron density (n_e) and temperature (T_e) profiles over a chord of 30 mm covering the entire plasma jet. Typ-

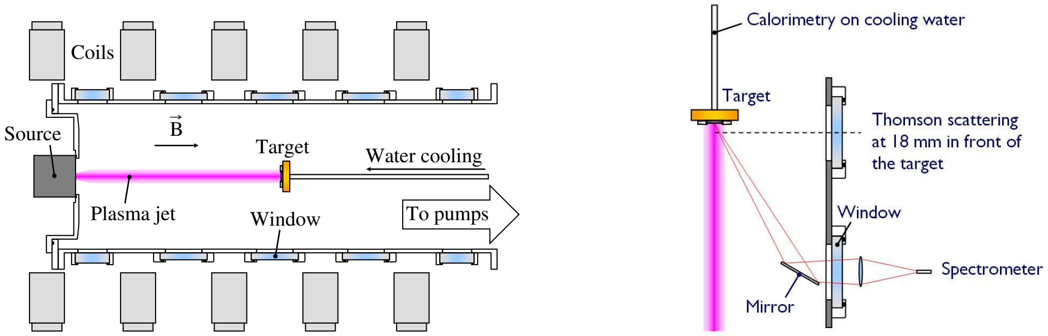

Figure 1: Schematic layout of the Pilot-PSI linear plasma generator (left) and the diagnostics installed near the target (right).

ically, the scattered light of 30 shots in 3 s are averaged. The chemical erosion is determined from emission spectroscopy on the CH $A-X$-band. These measurements were absolutely calibrated on methane injections from a 0.5 mm hole in a copper target. The power to the target was directly measured by calorimetry on the cooling water passing through the target heat sink. The temperature of the target was measured with a thermocouple in the bulk. Thermal conductivity with the measured power gives the surface temperature.

Plasma conditions near the target Fig. 2 shows an overview of the plasma conditions that can be created near the target of Pilot-PSI. Plotted are combinations of n_e and T_e as were measured with TS at 18 mm in front of the target. The shaded areas indicate the range of flux density that corresponds to the a given combination of n_e and T_e assuming acceleration of the ions to their acoustic velocity and a density drop of 0.7 over the pre-sheath. The experimental parameters that were varied in order to set the plasma conditions in a reproducible manner were the magnetic field strength B, the discharge current and the potential of the target. It is noted that the entire $10^{23}-10^{25}$ $\mathrm{m^{-2}s^{-1}}$ flux range is accessible with a floating target (i.e. without a net current to the target).

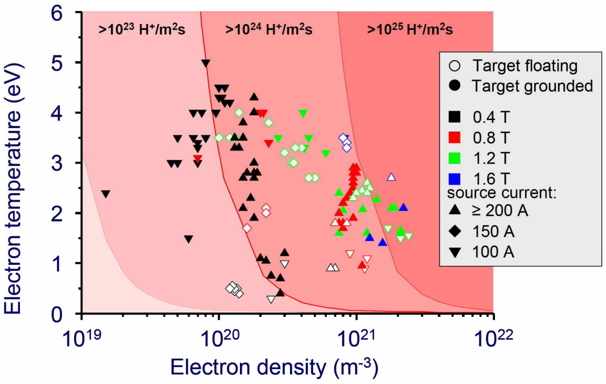

Figure 2: Combinations of n_e and T_e measured near the target of Pilot-PSI with TS.

Plasma and power fluxes Sheath theory [3] predicts an acceleration of the ions to their acoustic velocity, which is connected to a drop in density over the pre-sheath with a factor of 0.7. However, this assumes sufficient power supply via e.g. conduction to the sheath region. In our case, T_e is too low for efficient conduction and all power has to be delivered convectively. In order to check if the flux to the target is still determined by the plasma conditions measured at 18 mm distance, we measured the power deposited in the cooling water of the target. Assuming 20 eV per ion to be delivered to the target (the sum of the ionization energy and $5/2kT$ for both the ions and electrons) yields the total ion flux to the target. Assuming a radial profile as measured for n_e with TS gives the flux density. Fig. 3 shows the results for a 1 eV plasma at different densities. The bottom panel is a plot of the measured power to the target versus the peak n_e measured by TS. The upper panel compares the flux density determined from these power measurements with the flux density calculated from the TS data. This confirms that also in our situation the ion flux may be calculated as $0.7 \cdot c_s(T_e) \cdot n_e$ [3] (with $c_s(T_e)$ the ion acoustic speed at T_e).

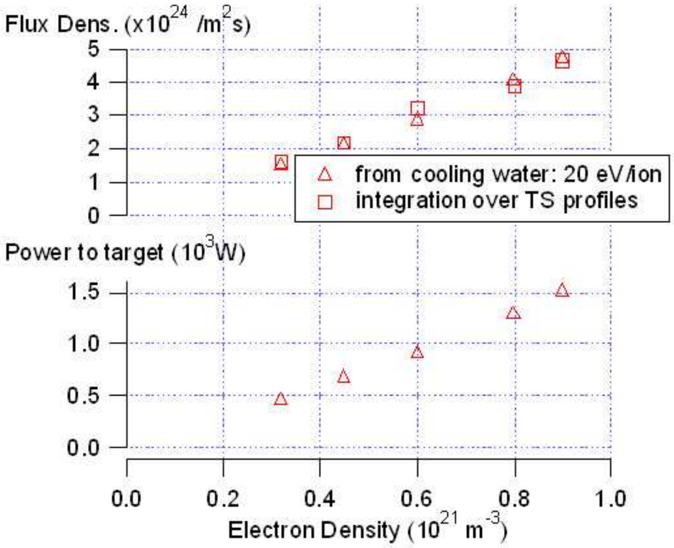

Figure 3: Comparison of TS measurements and target calorimetry.

Chemical erosion and target temperature The surface temperature of the target is set by the power that is delivered by the plasma in combination with the heat resistance between the target and heat sink. For the measurements presented in Fig. 3 we determined a surface temperature that increased from 700 K at the lowest flux to 1550 K at the highest flux. At the maximum flux density, it takes ∼ 20 s to obtain a steady state temperature. Fig. 4 shows the measured chemical erosion yields. It shows a strongly reduced chemical erosion at the highest target temperature, in total by a factor of 4. There is also a flux dependence hidden in this data series for which we have not attempted to correct the data for. On the basis of [4] we estimate that an increase of

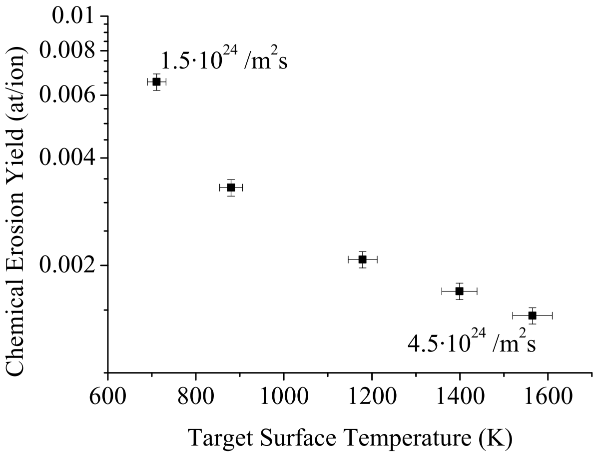

Figure 4: Erosion yield versus target surface temperature.

the flux density from $1.5 \cdot 10^{24}$ $\mathrm{m}^{-2}\mathrm{s}^{-1}$ to $4.5 \cdot 10^{24}$ $\mathrm{m}^{-2}\mathrm{s}^{-1}$ could decrease the erosion yield by a factor of up to 2. More important is that the maximum yield is at the lowest temperature. Generally, the temperature for maximum yield is assumed to be at $\sim$ 850 K[4]. Our measurements show the maximum at $\sim$ 700 K, which is in line with ion beam experiments[5]. These demonstrated an energy dependence in the position of the maximum. Our results confirm for the first time that the maximum shifts to lower temperatures for $\sim$ 1 eV plasma temperatures.

Redeposition of eroded material All previous measurements were performed at the same target. After $\sim$ 12 exposures we measured *ex situ* the surface profile with a profilometer. This demonstrated that significant amounts of the eroded material are redeposited around the eroded crater, as can be seen in Fig. 5. This deposition zone is within the plasma wetted area, which is $\sim$ 1 cm diameter. The volume of redeposited material is roughly 50% of the crater volume. As this target was exposed to a wide range of flux densities it is not possible to quantify the redeposition yet.

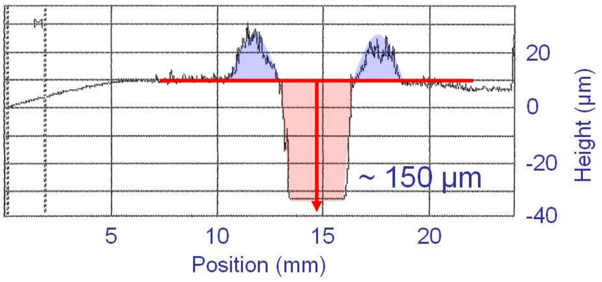

Figure 5: Surface profile of an exposed carbon target.

Conclusions Material targets can be exposed to plasma fluxes that are expected in the ITER divertor in the linear plasma generator Pilot-PSI. The fluxes that are measured to the target can be predicted on the basis of n_e and T_e with general sheath theory. Carbon targets were exposed to unique flux and power densities: $4.5 \cdot 10^{24}$ $\mathrm{m}^{-2}\mathrm{s}^{-1}$ and 15 $\mathrm{MW/m}^2$. In these experiments, the chemical erosion yield was measured to drop from 0.008 to 0.002. This was due to a combination of a flux density effect and an surface temperature increase from 700 K to 1550 K. A significant amount of eroded material was found to be redeposited in the plasma wetted area.

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