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Carbon exposed to the intense hydrogen plasma jet of Pilot-PSI

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The interaction of the magnetically confined plasma with the material wall has been identified as one of the most urgent research topics for the international fusion reactor ITER[1]. Tritium retention and erosion rates presently foreseen are critical issues for prolonged operation. ITER relies on a so-called divertor to remove helium and other impurities from the fusion plasma. The particle and energy fluxes toward the neutralizing target plates of the divertor are tremendous: typically 10^{24} ions $m^{-2}s^{-1}$ and 10 MW m^{-2} continuously[1]. The temperature of the in the divertor chamber plasma is reduced to the 0.5-7 eV range via the radiative cooling that follows the puffing of gases like neon. In this so-called detached operation, erosion by sputtering processes is efficiently reduced and chemical erosion by ions and neutrals becomes dominant.

Plasma-surface interaction under these conditions is an unexplored area. Even the fluxes in present-day large Tokamaks are too low to enter the regime relevant for ITER and beyond. Present-day linear machines are unable to produce the required high flux at low temperatures. In addition, the surface area exposed to the plasma should be large enough to capture material released from the surface in the active plasma in order to do the relevant research in a linear machine . We call this the “strongly coupled regime.” Present-day devices operate in the “weakly coupled regime” where reaction products are essentially pumped away.

We are presently designing a linear machine, Magnum-psi[2], that will use an expanding cascaded arc plasma in hydrogen as primary source to yield fluxes relevant for ITER and devices beyond. Magnum-PSI will operate in a high magnetic field (3T) and cover an area of 80 cm^2. In order to explore and develop the techniques to be applied in Magnum-PSI, we have made a pilot version of Magnum-PSI operational: Pilot-PSI. This experiment employs a magnetic field of up to 1.6 T and a cascaded arc plasma source to produce intense argon or hydrogen plasma beams.

In this contribution we present Thomson scattering results to demonstrate that Pilot-PSI offers hydrogen plasma jets with the ITER relevant plasma fluxes. These plasma conditions make Pilot-PSI a unique experiment for the field of PSI-studies. This is illustrated by the results of preliminary experiments in which carbon was exposed to this plasma jet.

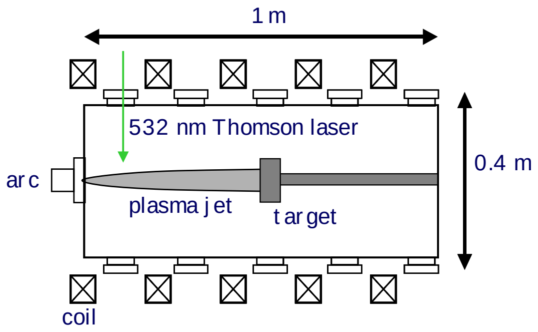

Figure 1: Schematic drawing of Pilot-psi.

The hydrogen plasma jet in Pilot-PSI (Fig. 1) is produced by a wall stabilized cascaded arc plasma source. Typical operation parameters are: 100 A discharge current, 3 slm gas flow rate, 0.1 bar inlet gas pressure. The diameter of the discharge channel was varied between 4 and 7 mm. The plasma expands into a vacuum vessel at 0.01 - 1 mbar where it is confined by a magnetic field up to 1.6 T and directed onto a carbon target at 0.5 m. Thomson scattering is performed at 40 mm downstream from the source nozzle to characterize the output of the cascaded arc. For these measurements, ~0.4 J of 532 nm laser light is passed vertically through the vessel at 10 Hz and focused in the center of the plasma jet. Stray light is minimized by long entrance and exit tubes with baffles. The scattered light is imaged on a fibre head that contains an array of 50 individual fibres and relays the image of the complete radial plasma jet profile to an in-house constructed spectrometer in Littrov configuration ($f = 1000$ mm, 1200 lines/mm grating) for spatially resolved spectral analysis.

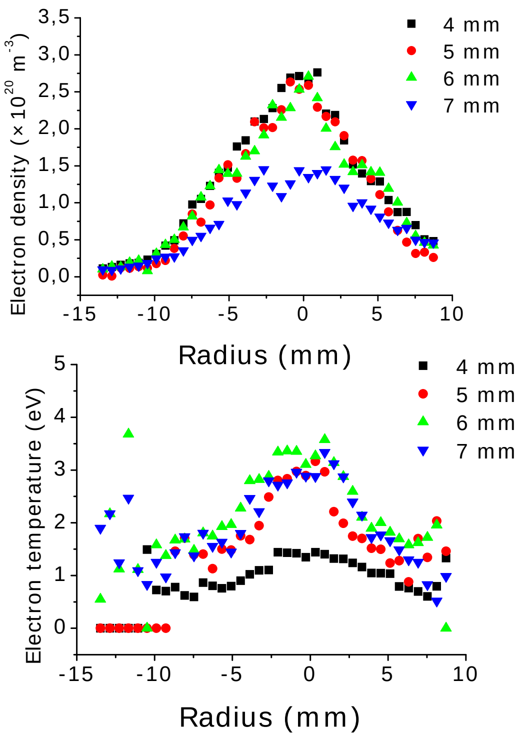

Figure 2: Electron density and temperature profiles of the Pilot-PSI hydrogen plasma jet in a 0.4 T magnetic field measured with Thomson scattering for different diameters of the discharge channel.

Figure 2 shows the results of a series of measurements in which we investigated the effect of the discharge channel on the source output. The discharge current was kept constant to 100 A, the gas flow at 3 slm, and the magnetic field was 0.4 T. The density profiles in the upper panel indicate that the plasma flux is not influenced by increasing the channel from 4 to 6 mm (where we assume that the forward plasma velocity is not significantly changed). However, the discharge voltage was observed to decrease from 150 V to 130 V. This means an efficiency improvement of the source by increasing the channel diameter of $\sim$ 15%. A further increase to 7 mm leads to a density decrease of nearly a factor of 2, a clear decline in efficiency. We interpret this to be the consequence of the discharge current and/or gas flow to be too low to obtain efficient operation in such wide channel diameters.

The temperature profiles in the bottom panel of Figure 2 indicate a different operation regime for the 4 mm channel at temperatures up to 1.4 eV opposed to the more than 3 eV temperatures for the wider channels. The exact mechanism behind this is presently not fully understood. We expect that it is the result of a complex interplay between current pathways, expansion details and magnetic field.

In preparation for detailed PSI studies of the hydrogen plasma and carbon surface system, we have performed preliminary experiments by exposing carbon targets to the Pilot-PSI plasma jet. The results are presented in Figure 3. In the top panel, a photograph of the exposed target (carbon R6650, SGL Carbon Group) is shown. The erosion patterns that are seen were the result of 120 s exposure. The depth of the erosion profile was measured to be 75 μm. This corresponds to a maximum erosion of $6.9 \cdot 10^{24}$ atoms/m^{-2}. We relate this to the maximum ion flux that we calculate from the product of the electron density, acoustic velocity and exposure time: $4.2 \cdot 10^{26}$ ions/m^2. This gives an erosion yield of 1.6%. It is noted here that this yield may be not a pure chemical erosion yield. The target temperature was not measured yet and might have increased significantly during exposure. This means that

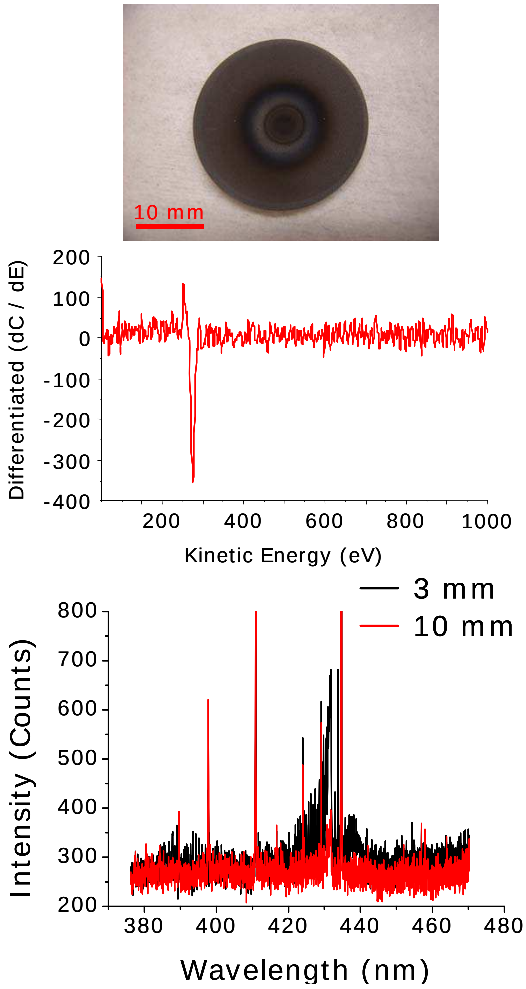

Figure 3: Carbon exposed to the 10^{20} m^{-3} 3 eV hydrogen plasma jet. The upper panel shows a picture of the target and shows the significant erosion after 120 s. The middle panel shows that Auger spectroscopy measures no impurities in the exposed target. The CH emission band in the bottom spectrum demonstrates that the target subjected to chemical erosion.

part of the erosion might have been the result of ablation. However, that chemical erosion was occurring is supported by the emission spectra shown in the bottom panel of Figure 3. Plasma light collected parallel to the target at a distance of 3 mm shows the CH band that indicates chemical erosion. At larger distances such as 10 mm, this light is not detected. Finally, we do not expect that significant erosion (sputtering) happened from heavy impurities as copper or tungsten from the source components. The Auger spectrum in the middle panel of Figure 3 shows no traces of such impurities.

For detailed insight into complicated plasma-wall interactions, it is required to determine concentration profiles of the hydrocarbons in the plasma close to the target. We envisage to use Cavity Ring-down Spectroscopy (CRDS) for this. The CRDS technique has recently been installed at Pilot-PSI and was successfully applied to investigate atomic hydrogen transport via light absorption at the Balmer alpha wavelength. Figure 4 shows that the natural fine splitting is easily resolved by scanning the laser wavelength over the absorption line.

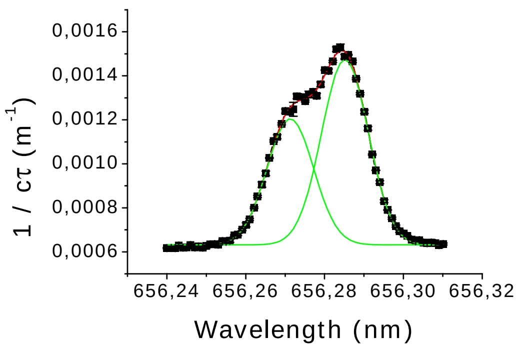

Figure 4: CRD was tested on the Hα transition. This provides sufficient resolution to resolve the natural splitting of the atomic line.

References

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