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A study was made to quantify the losses during the convective hydrogen plasma transport in the linear plasma generator Pilot-PSI due to volume recombination. A transport efficiency of 35% was achieved at neutral background pressures below ~7 Pa in a magnetic field of 1.2 T. This efficiency decreased to essentially zero at higher pressures. At 1.6 T, the measured downstream plasma density was up to double the upstream density. Apparently plasma pumping and recycling at the target start to play a role under these increased confinement conditions. Feeding the plasma column at this field strength with a net current did not change the downstream density. This indicates that recycling sets the local plasma conditions.

1. Introduction

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 MWm^{-2} continuously[1]. The temperature of the plasma in the divertor chamber 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 (PSI) 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 (3 T) 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. A successful research program on the source development demonstrated the production of the required plasma flux densities near the source[3]. Transport of the hydrogen plasma to the remote target area was not considered in [3].

In this paper we focus on the transport of the high hydrogen plasma fluxes over a distance of 0.5 m (in Magnum-PSI this will be ~1 m). The key ingredient for efficient plasma transport is our strong magnetic field that confines particles and energy. The other aspect affecting transport is plasma recombination. For hydrogen plasma, volume recombination occurs via Molecular Assisted Recombination (MAR)[4]. We investigated this aspect by comparing the electron density (n_e) and electron temperature (T_e) measured with Thomson scattering near the source and at a distance of 54 cm in a scan of the ambient gas pressure. Finally, we investigated the effect of additional power input in the free plasma column from a net current to the target. This was also done on the basis of Thomson scattering.

2. Experimental setup

Pilot-PSI consists of a 1 m long, 0.4 m diameter cylindrical vacuum vessel that is placed inside five coils (Figure 1). The maximum magnetic field strength (B) is 1.6 T. The cascaded arc plasma source is centered on the magnetic field axis. Two roots blowers (6000 m^3/hr total capacity, variable pumping speed) keep the vessel pressure at 1–20 Pa during operation with hydrogen plasma (depending on inlet gas flow and pump speed). A water-cooled target is positioned at 56 cm downstream.

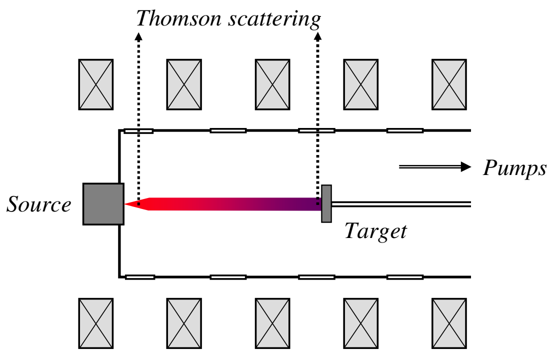

Figure 1 - The Pilot-PSI linear plasma generator. Cascaded arc source exhausts in heavily pumped vessel, where plasma is magnetized by field of up to 1.6T. Thomson scattering determines n_e and T_e.

The cascaded arc plasma source (Figure 2) consists of a stack of five 5 mm thick, water-cooled copper plates with in the centre of each a hole. Together these form a 3 cm long cylindrical discharge channel. One mm thick boron-nitride spacers electrically insulate the cascade plates from each other. The inner diameter of the channel is 7 mm. Hydrogen gas is fed under high pressure (10^3 - 10^4 Pa) into the cathode chamber at the entrance of the channel. In this chamber three 2 mm thick tungsten cathodes with sharp tips are aligned in front of the channel entrance. Each cathode is powered by a current stabilized DC power supply capable of delivering up to 100 A at up to 400 V. The grounded anode is made of tungsten-copper (75-25%) and has an inner diameter of 8.5 mm. The large pressure gradient over the channel makes the plasma accelerate to several km/s forward velocity.

During the measurements on the influence of the background pressure, the target was kept at floating potential. For the experiments on Ohmic heating the current to the target was controlled by biasing it to a positive potential. We note that at high magnetic field a bias of 0 V was enough to let a current run to the target. This is caused by (part of) the source current following the magnetic field lines into the vessel. For a description of the mechanism and its influence on the plasma production, see [3]. Thermocouples measured the temperature rise in the cooling water of the target, which was up to 3 °C in the measurements presented here. The water flow was monitored with flow meters and typically 1 l/min. The power in the cooling water was integrated over the time needed for the water to return to its original temperature to yield the total energy deposited on the target. This value was divided by the exposure time (4 seconds for the results presented here) to determine the power during plasma exposure.

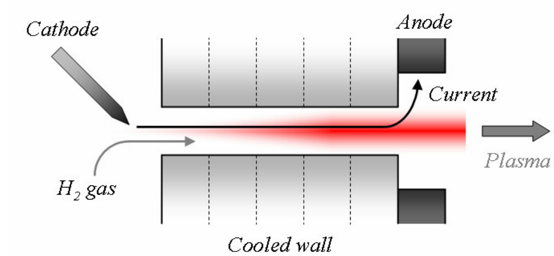

Figure 2 - Cascaded arc plasma source. Hydrogen gas at a flow rate of 0.5 - 10 slm is ionized by a discharge current of 80 - 300 A.

Thomson scattering was used to measure n_e and T_e profiles at 4 or 54 cm from the source nozzle. The measurements downstream were done either at 17 mm distance from the target or without a target present. The profiles were fitted with Gaussian functions. The maxima of these curves are reported here as n_e and T_e. The Full Width Half Maximum (FWHM) of the fit of the n_e profile was used as a measure of the beam width.

3. Results

We investigated the importance of plasma recombination via MAR as a function of the vessel background pressure. The source was operated at a gas flow rate of Φ = 1.8 slm and a discharge current of I = 150 A. The magnetic field was set to B = 1.2 T. The background gas pressure was controlled by changing the speed of the roots blowers. The plasma parameters were measured at z = 4 cm and 54 cm with Thomson scattering. The measurements at 54 cm were performed with the target at 56 cm and subsequently with the target at 100 cm.

The results on T_e are plotted as a function of the background pressure in Figure 3. It is seen that upstream T_e decreases from 3.7 eV to 3.1 eV when the pressure is increased by 13 Pa. The downstream T_e shows that the plasma is significantly cooled if the pressure is slightly higher than the base pressure of 2 Pa. At the lowest pressure, the downstream temperature is still 90% of the upstream temperature. At low pressures, there is a significant influence of the target: T_e is in this case almost 40% lower compared to the situation without target. We interpret this as increased heat losses due to a higher neutral pressure near the target.

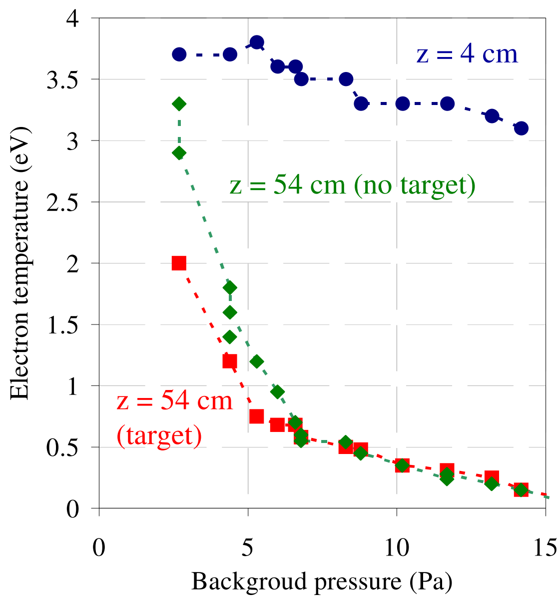

Figure 3 - Electron temperature as function of background pressure, measured at two positions: z = 4 cm (upstream) and z = 54 cm (downstream).

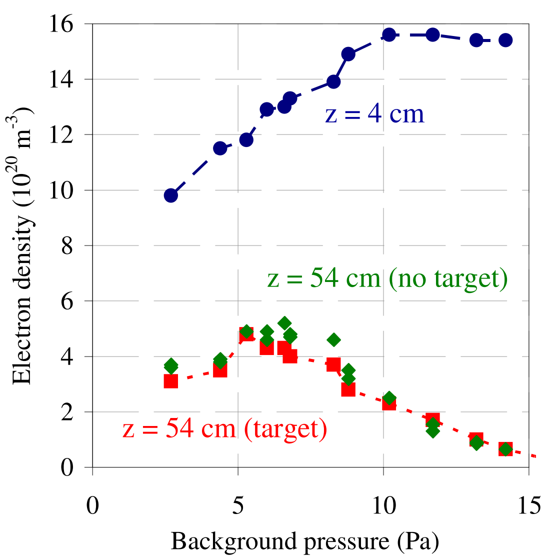

Figure 4 - Electron density as function of background pressure, measured at two positions: z = 4 cm (upstream) and z = 54 cm (downstream).

The electron densities that correspond to the results in Figure 3 are shown in Figure 4. Striking is the more than 50% increase in upstream n_e at the higher background pressures. We assume that the forward velocity does not change due to a change in pressure and since the beam width was roughly constant (see Figure 5), the electron density is a measure of the production. We explain the increased production as a result of a higher neutral pressure in the anode region where power is still dissipated in the plasma column [3], which leads to extra ionization. The downstream results show that at low pressures the transport efficiency over 50 cm is about 35%. Above a pressure of 7 Pa (below T_e = 1 eV) the transport efficiency quickly decreases. The rise in density between 2 and 7 Pa follows the rise in production. The density starts to drop where the temperature is lower than ~1 eV. The power deposited on the target was 1.7 kW at 2 Pa, 0.5 kW at 7 Pa and 0 at higher pressures. This shows that target detachment occurs at 7 Pa. The results furthermore show a marginally higher density downstream if the target is at large distance. However, the difference is of the order of the error (10%) and thus holds little statistical significance. Based on these results, we conclude that we require a pressure below ~3 Pa in order to have successful plasma transport over 0.5 m. We note that the pump system for Magnum-PSI has been designed for an exposure chamber pressure of 1–2 Pa.

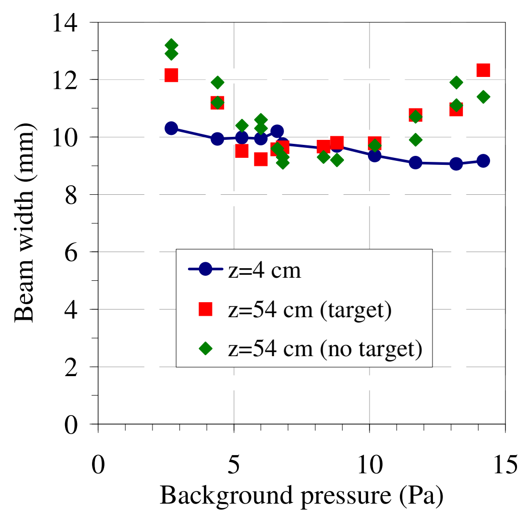

Figure 5 - Beam width (FWHM) as function of background pressure.

In Figure 5 we have plotted the width of the plasma jet as a function of the background pressure. At low pressures, the beam becomes up to 30% wider during its transport. There is no significant influence from the position of the target. With increasing background pressure, the beam width is reduced. This is in line with the earlier observation that recombination losses become high at temperatures below 1 eV. This is the case at the edge of the jet. In other words, the edges are subjected to a higher recombination rate and thus the jet becomes smaller. This does not fit the observation that the beam widens again at very high pressures. However, we note that at these pressures the electron density is very low (Figure 4) and therefore the beam width is no longer well defined.

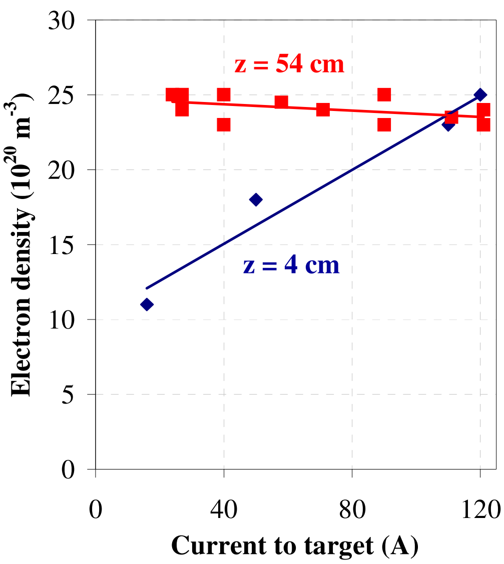

Figure 6 - Electron density as function of the current through the plasma beam at B = 1.6 T.

Figure 6 shows the effect of feeding the plasma column with a net current. For these measurements, the source was operated at a gas flow of Φ = 1.8 slm and a discharge current of I = 200 A. The magnetic field was 1.6 T. The production measured at z = 4 cm showed a strong increase with current to target of more than a factor of 2. This is possibly caused by a continuation of discharge current and thus an effective extension of the arc, which leads to more plasma production. Striking is that downstream the electron density is more than double the upstream density if no current is drawn and that it is independent of the net target current. This implies additional ionization between the source and the target. The high density, 2.5 eV hydrogen beam effectively ionizes neutral gas particles that enter the beam. This results in a "pumping" effect of the beam. The fact that the plasma flux to the target does not increase with the target current seems to indicate that the extra production is limited by the overall gas recirculation and recycling in the vessel and at the target. The measured electron density of $2.5 \cdot 10^{21}$ m^{-3} is to our knowledge the highest published hydrogen plasma density near the target of a linear plasma generator.

4. References

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