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On the power balance at the end plate of the plasma column in Pilot-PSI

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Introduction

The linear device Pilot-PSI is an expanding cascaded-arc plasma system in which high-density magnetized plasma beam of about 1-2 cm diameter interacts with a solid target (so-called end plate). This device is the smaller forerunner of Magnum-PSI, a high-flux linear plasma generator designed to study plasma surface interaction (PSI) at ITER relevant parameters [1]. Density, temperature and velocity components of the Pilot-PSI have been extensively studied and recently reported [2,3]. However, parameters as plasma potential, ion and electron temperature, plasma instabilities and their influence on plasma - target energy transfer have to be further studied in order to optimize thermal energy removal from plasma and the life time of the target.

In the present contribution, the experimental results obtained by electrical means are reported as a function of gas composition and discharge current in the cascaded arc source. Electrical measurements were performed by a cylindrical probe, a multi-channel analyzer (MCA) and as current-voltage characteristics of the target. Plasma potential and ion saturation current measured by cylindrical probe are used to find the radial distribution of both electric field and gradient of the plasma density. Considerations related to drift instabilities are made and the energy transferred from the plasma column to the end plate is evaluated.

Experimental set-up

The plasma source of Pilot-PSI is a cascaded arc [4], which exhausts into a vacuum vessel of 1 m length and 0.4 m diameter (~ 0.1 Pa background pressure) (Fig.1). Five coils produce an axial magnetic field up to 1.6 T. The plasma source was operated in argon, hydrogen or argon-hydrogen mixture with a gas flow rate of 1 or 2 slm (1 slm ~ 4.48×10^{20} molec/s) and a total discharge current I_d of 80 to 150 A. The target was positioned at 56 cm from the nozzle of the arc source, the gas pressure in the vessel was in the range of 3 to 5 Pa and the magnetic field strength was 0.4 T for all measurements.

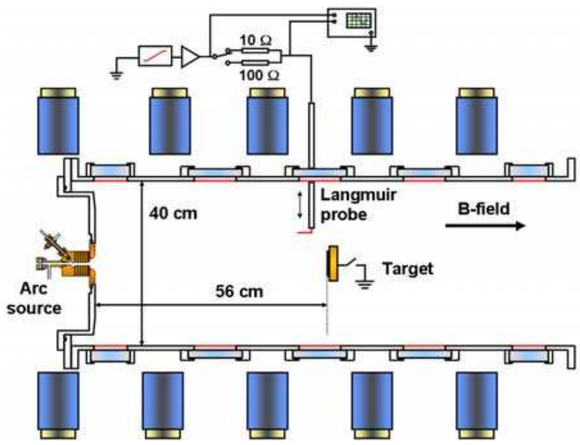

Fig.1. Electrical probe set-up on Pilot-PSI

The cylindrical probe made of tungsten wire of 9 mm length and 0.23 mm in diameter was introduced at 3.5 cm in front of the target (Fig.1). The probe was movable in the radial direction with its axis parallel to the magnetic field lines. A linear ramp voltage of ± 28 V sets the probe bias and the probe current was measured as a function of voltage across a 10 or 100 Ω resistor in the probe circuit (Fig.1).

Results and discussions

i) Current-voltage characteristics of the target and of the multi-channel analyzer (MCA)

The multi-channel analyzer (MCA) [5] was designed for the measurements of the perpendicular ion energy distribution within magnetised plasmas. It was fixed in the centre of the target, facing the plasma with a graphite multi-channel plate of 1 cm diameter. The ion current intensities of the MCA collectors have shown a non-uniform radial distribution of the plasma parameters so that, in this paper, only the current-voltage (I-V) characteristics of the MCA plate were used. Moreover, due to the interest in ion saturation current I_{si}, which is relevant for the divertor-like operating mode, the ion part region of the current-voltage characteristics was taken.

Fig.2 shows two I-V characteristics taken in Ar and in H_2, respectively, for I_d = 80 A, p = 3 Pa and 1 slm gas flow. The ion saturation current is about 0.6 A in Ar and 0.3 A in H_2. The large difference of the floating potential found in the two gases is noted: -75 V in H_2 while only -1.3 V in Ar. This result was confirmed by probe measurements. Because the area of the analyser plate is rather small and the plasma beam is not always centred on the target, the I-V characteristics were also taken for a carbon target of 3 cm in diameter. Fig.3 shows three characteristics taken in Ar at different discharge currents of 90, 120 and 150 A. It shows that an important fraction (up to 27%) of the total current intensity of the arc discharge can be drawn as ion current to the target.

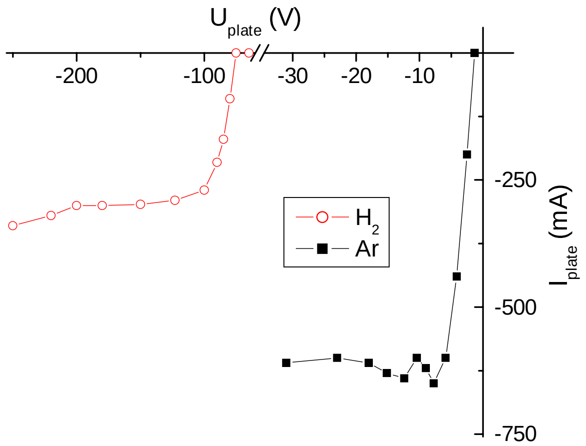

Fig.2. Ion part of the MCA plate I-V characteristics in Ar and in H_2 (I_d = 80 A, p = 3 Pa, 1 slm gas flow)

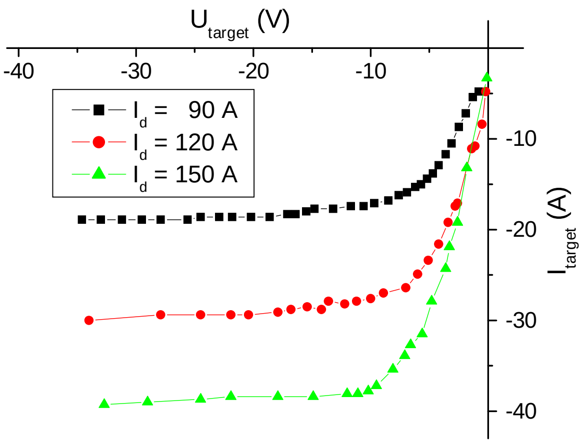

Fig.3. Ion part of the target I-V characteristics in Ar for different discharge currents (p = 3 Pa, 1 slm gas flow)

In order to operate in a divertor-like mode, the target of the Pilot-PSI was kept floating with respect to the plasma. In this case, the electron current and the ion current are equal at the target surface, $I_e = I_i = I_{si}$ and the total current drawn by the target is zero. The power density transferred from the plasma to the target can be estimated as $P = P_e + P_i + \beta P_R$, where $P_{e,i}$ is the power density transferred by electrons, respectively ions, P_R is the power density due to electron-ion recombination at the target surface and β is the fraction of P_R captured by the target. The power density transferred by electrons or ions can be calculated as $P_s = n_s v_s \varepsilon_s$, where $n_s v_s = I_s /eA$, ε_s is the mean energy of *s*-type particle ($s = e, i$) at the target surface and A is the target area collecting the plasma current. The power density due to electron-ion recombination at the target surface is $P_R = n_e v_e E_{iz}$, with E_{iz} the ionisation energy of the gas. Thus, the total power density becomes $P = I_{si}(\varepsilon_e + \varepsilon_i + \beta E_{iz})/eA$.

When the discharge current is 150 A in Ar (E_{iz} = 15.76 eV), the ion saturation current is about 40 A (Fig.3). The target area is ~ 7 cm^2. Estimating that the mean energy of the ions at the target surface is of the order of the electron temperature (Bohm's criteria) (T_e ~ 1 eV [2]), the mean energy of the electrons is of the same order of magnitude and supposing a fraction $\beta \approx 0.5$ (from geometrical considerations), we obtain $P \approx 0.6$ MW/m^2.

ii) Probe measurements

Typical I-V characteristics of the cylindrical probe taken in Ar at different radial positions (with r = 0 on the vessel axis) are presented in Fig.4. At present there is no satisfactory model of the probe characteristic obtained in such experimental conditions, but ion saturation current I_{si}, floating potential V_f and plasma potential V_p might be obtained from these characteristics at least as relative values. These parameters can be used to estimate at least two rotational drift velocities of the plasma beam: the electric drift velocity ($v_E = E_r/B$) and the diamagnetic drift velocity ($v_n = kT/eB*\nabla_r n/n$).

The electric drift velocity v_E was estimated using the radial electric field E_r derived from the radial distribution of the measured plasma potential. Assuming that the ion saturation current of the probe is proportional with the plasma density, one can write $\nabla_r n/n = \nabla_r I_{si}/I_{si}$ and the diamagnetic drift velocity v_n can also be evaluated. The radial profiles of both calculated v_E and v_n are plotted in Fig.5, for Ar and H_2 respectively, with I_d = 80 A, p = 4.8 Pa and 2 slm gas flow. Comparing the radial profile of the calculated v_E (Fig.5(a)) with the plasma jet rotation velocity profiles measured by optical methods [3] in hydrogen, learns that the magnitude, the radial position of the maximum velocity and the profile width are similar. The diamagnetic drift velocity has the same order of magnitude as v_E in argon, while it is one order of magnitude lower for hydrogen plasma.

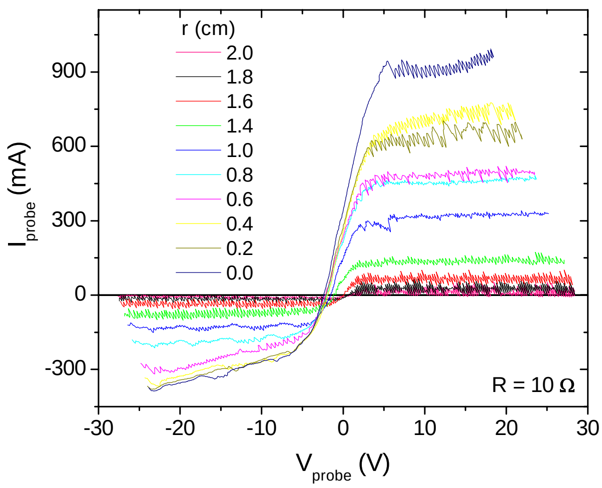

Fig.4. Current-voltage characteristics of the probe in Ar for different radial positions (I_d = 80 A, p = 4.8 Pa, 2 slm gas flow)

The fluctuations of the current intensity measured either on the probe (Fig.4) or on the target can be associated with possible instabilities of the drift motion previously described.

This is proved by the fact that the fundamental frequencies in the power spectrum of the current fluctuations (~ 6.5 MHz for H_2 and ~ 80 kHz for Ar) are comparable to the plasma rotational frequency of the electric drift, $\omega = v_E/R$, with R the radial position of the v_E maximum (Fig.5(a)).

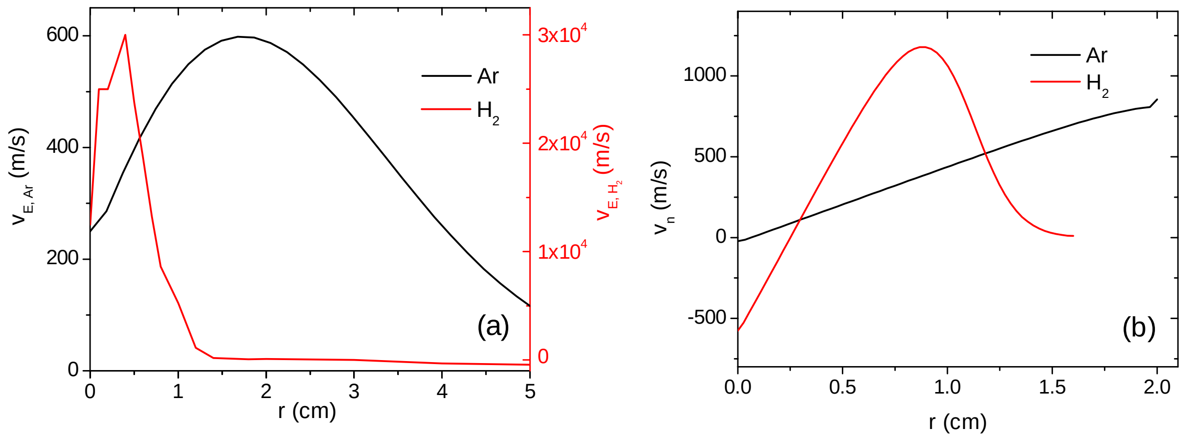

Fig.5. Radial distribution of the electric drift velocity (a) and the diamagnetic drift velocity (b) calculated for Ar and H_2 (I_d = 80 A, p = 4.8 Pa, 2 slm gas flow)

Conclusions

Electrical measurements in Pilot-PSI allow the estimation of the power density transferred from the plasma to the target. The obtained power values (~ 1 MW/m^2) confirm that Magnum-PSI will be able to operate at ITER relevant parameters for plasma surface interaction at the divertor. Probe measurements show that plasma parameters are significantly different for Ar and H_2. The presence of the radial electric field determines the appearance of a drift instability, which may enhance radial particle losses and consequently diminish the energy transferred from the plasma to the target.

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