Effect of Lithium Vapour Shielding on Hydrogen Plasma Parameters

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Abstract

A liquid Li vapour-box divertor is an attractive heat exhaust solution for future fusion reactors. Previous works have established the ability of vapour shielding to protect the wall, but it has not been possible to directly determine the effects of Li vapour on the plasma parameters. Experiments to investigate this were carried out in Magnum-PSI, which is able to generate a plasma with DEMO-divertor relevant conditions. 3D printed tungsten capillary porous structures filled with Li have been used as targets. A reciprocating Langmuir probe was used to determine electron temperature and density close to the target, while the power reduction to the coolant due to vapour shielding was increased from 0% to 50%. The Langmuir probe measurements directly determined an increase of density by up to 50% while electron temperature could be inferred to have dropped by up to 33% compared to the solid target reference case.

1. Introduction

Among the many challenges to make fusion energy available, one of the most demanding is the handling of the exhaust heat inside a nuclear fusion device. The current solid tungsten configuration has some critical issues, particularly the limited expected lifetime in DEMO **Error! Reference source not found.**, due to problems like erosion, that could represent a showstopper for the fusion project. A solution for this must be found, and one of the most interesting and promising concepts involves the use of a liquid metal (LM) in the divertor to face the incoming plasma power. This will protect the underlying solid tungsten matrix, reducing erosion and thermomechanical stresses. A key feature that comes with the use of a LM surface is the so called vapour shielding (VS) effect. The plasma heating leads to strong heating of the LM, that in turn will leads to the development of an evaporated vapor a cloud in front of the target shielding it from further plasma exposure. The evaporated atoms thus interact with the plasma, cooling it mainly through momentum exchange and radiation, inducing detachment. The removed amount of power will finally be spread over a wider area, reducing the load of MW/m^2 carried to the divertor's strike point **Error! Reference source not found.**.

This design forms an attractive operational mode for the fusion reactor divertor if the LMs are used in a so-called vapor box divertor **Error! Reference source not found.Error!**

Reference source not found. because it is capable of naturally inducing and controlling the detachment front while avoiding excessive LMs flow towards the core of the plasma, which would lead to a reduction in fusion power through increased core radiation or fuel dilution **Error! Reference source not found.-Error! Reference source not found.**.

The choice of the LM to be used takes an important role as well since each of them has different properties when interacting with different plasma species. Among them, two of the most promising are lithium and tin or even an alloy of both. Other candidates also exist but are less attractive; for example gallium, as it is more corrosive than Sn or Li to structural materials. A wider and well detailed list could be found in **Error! Reference source not found.**.

The LM used in this experimental campaign is lithium. This element is attractive as a choice for a vapor box divertor because it can be tolerated in relatively large quantities in the plasma core without reaching excessive dilution rates **Error! Reference source not found.**. While not typically considered a good radiator, in the low temperature area of the divertor it can be effective, particularly under the non-coronal conditions which are expected to apply in this region **Error! Reference source not found.**. Li can form chemical bond with hydrogen up to stoichiometric ratio 1:1 helping the remove of exhaust unreacted plasma atoms [ref Baldwin paper]. Because of this a vapor box divertor is considered to have a tritium flow and extraction system to quickly recover the tritium from the liquid and return it to the inner fuel cycle **Error! Reference source not found.**.

Magnum-PSI **Error! Reference source not found.** has been used to study the Li VS regime **Error! Reference source not found.** due to its ability to recreate the detached plasma conditions expected in future divertors, but until now it was not possible to directly infer the influence of VS on the plasma parameters of electron temperature (T_e) and density (n_e) due to risk of damage to the Thomson Scattering (TS) optics while Li is used. Here a reciprocating Langmuir Probe (LP) was used to investigate these parameters during Li VS to identify how the plasma is modified by the VS cloud.

2. Methods

2.1. Magnum-PSI

Experiments were carried out in Magnum-PSI **Error! Reference source not found.**, which generates a steady-state linear plasma with reactor detachment-like high n_e and low T_e. A scan in power has been made by changing the source current between130-190 A at fixed hydrogen gas flow rate and keeping the magnetic field B constant at 0.7 T.

n_e and T_e were determined from TS using a solid Molybdenum reference target. The plasma power thus obtained ranges from q_{ref}=5 to 21 MW/m², where q_{ref} is the peak heat flux calculated to arrive at the target surface from the TS data from the Bohm criterion as in **Error! Reference source not found.**. This therefore ranges from conditions where VS is not expected yet to the full VS regime **Error! Reference source not found.**. Each shot was 200 s long to reach the cooling water thermal equilibrium for calorimetry analysis.

2.2. Targets

To avoid LM motion due to $J \times B$ forces induced by the superconducting magnetic coils, lithium has been held in place in the target using 3D-printed Capillary Porous Structures (CPSs) made of tungsten as described here **Error! Reference source not found.**. Each CPS target was filled with around 1.8 g of Li, and it was ensured that at all times sufficient Li was present to avoid Li depletion which could have affected the results.

A helium plasma cleaning shot was performed before the actual experiment which removed any oxide and impurities layers on the surface of the Li-CPS

A solid Mo target with identical geometry has been used as reference under the same plasma conditions.

2.3. Diagnostics

Thomson Scattering (TS) **Error! Reference source not found.** was performed during reference shots to determine the plasma parameters to compare to the lithium cases. The TS laser beam is located 20 mm in front of the target. Due to the location of the laser port below the target holder, this was covered with a metal shield during Li exposures to prevent LM droplets falling directly onto the optics, which could lead to damage.

To overcome this limitation, a reciprocating Langmuir Probe previously used in Magnum-PSI **Error! Reference source not found.Error! Reference source not found.** has been used for the first time to assess plasma parameters in VS regime. The probe also enters the plasma at a distance of 20 mm from the target to be consistent with TS readings, and consists of up to 4 filaments of tungsten encased in an alumina rod and protruding from the latter by 0,5 mm. the alumina tube has a diameter of 4 mm while each pin is 0,5 mm in diameter.

Figure 1 contains a representation of the experimental set-up: the plasma coming from the left hits the Li-CPS on the right inducing the vaporization on lithium. In front of the target with a distance of 20 mm there is the reciprocating LP coming from the back and the optical view of the TS system from the bottom which investigate the same region of the plasma. The total power to the target is determined from the cooling water calorimetry.

The LP was used in single probe mode with voltage sweep from +15 to -60 V except for the highest source current cases where the negative voltage amplitude was limited to -45 V in order to prevent arching between probe's pin, most likely caused by the LM atoms into the plasma which create occasional short-circuit between the probe's pins.
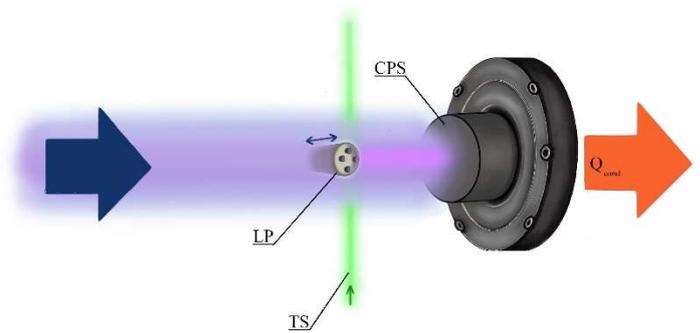

Figure 1 Langmuir probe experimental setup

The LP measurement cycle frequency was 200 Hz with a sampling rate of 5 MHz. To avoid damaging the probe, its duration in the plasma was limited to 0.2 s. Due to the plasma's Gaussian profile, collected current increases as the probe get close to the center, so its movement was deliberately chosen to extend beyond this point, which ensures that the plasma beam center was correctly identified whenever the reading returned two peaks

Calorimetry was performed on the cooling water system behind the CPS target holder.

3. Results

3.1. Langmuir Probe

A comparison between TS and LP was first carried out on the reference sample. Results confirmed the reliability of the LP in obtaining n_e data, whereas for T_e the values were much higher for the LP than for TS (Figure 2).
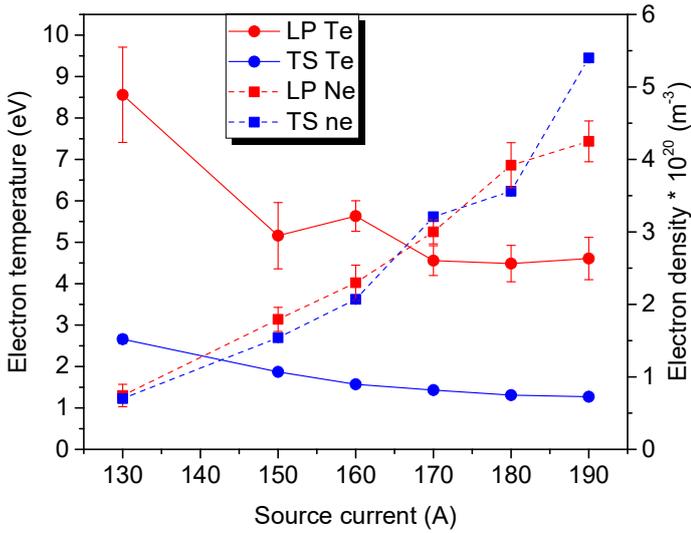
Figure 2 Plasma parameters on reference target acquired with TS and LP both. Solid lines for T_e, dash lines for n_e.

This effect has been attributed to fluctuations in density and potential on the timescale of the I-V sweep of the LP **Error! Reference source not found.**. Therefore only n_e data was considered reliable for the measurements during VS. These are shown in Figure 3. As expected, plasma density increases due to interactions between the neutral lithium cloud and the plasma **Error! Reference source not found.**.
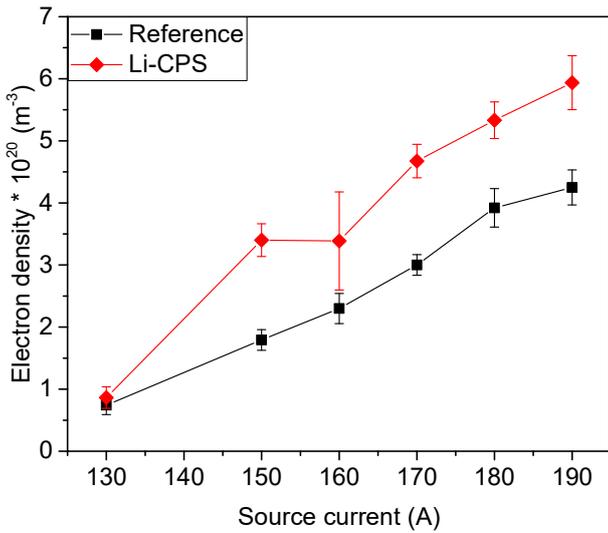

Figure 3 Electron density LP acquired on reference and Li-CPS

3.2. Calorimetry and T_e

To bypass the lack of T_e LP data, calorimetry has been used to have an estimation of the power delivered to the target cooling system. Since TS and LP investigate the plasma in the same position, the reference plasma power and cooling water ΔT were used together with the Li-CPS cooling water ΔT to calculate the amount of dissipated power due the lithium presence, as shown in **Figure 4**. It was therefore possible to estimate the removed plasma power flux to the target after the interaction with the lithium cloud as

$$\Delta Q = Q_{cond}^{ref} - Q_{cond}^{Li} = Q_{evap}^{Li} + Q_{cool}^{Li} \quad (1)$$

Where Q_{cond}^{ref} and Q_{cond}^{Li} are the power flux delivered to the cooling water assuming identical plasma widths in both cases, and Q_{evap}^{Li} and Q_{cool}^{Li} the contributions from Latent heat of evaporation plus the cooling processes such as radiation, charge exchange and recombination in the plasma respectively.
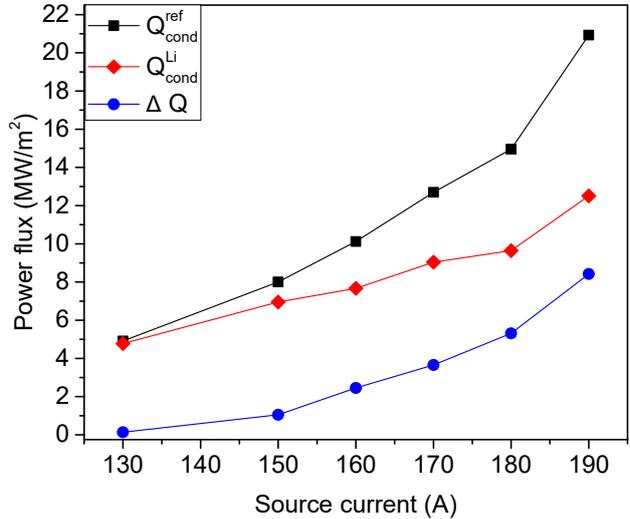

Figure 4 Plasma Power flux removed by the cooling water. The difference in power between the case without lithium and the case with it is shown in blue circles showing the increase with plasma power.

From the measured n_e and calorimetric data it is possible to find the expected range of T_e from the two extreme cases. In the first case we assume lithium re-deposition rate $R = 0$, and that therefore all Li escapes the plasma beam. We also assume that $\Delta Q = Q_{evap}^{Li}$ so that power

lost in from the plasma beam is negligible and therefore $q = q_{ref}$. In the second case we assume $R = 1$, i.e. that the lithium is all either ionized or driven by friction force back to the target. In such a case we assume $\Delta Q = Q_{cool}^{Li}$ and that therefore $q = q_{ref}\left(Q_{cond}^{Li}/Q_{cond}^{ref}\right)$ and that the increased density arises also from the ionization of Li, which therefore modifies the average mass of the plasma ions.

In both cases we assume that pressure is conserved between the TS and LP measurement region and the sheath entrance. By doing so is possible to get two curves that delimit the region where the real value lies. The two curves and the reference case measured by TS are shown in Figure 5. R was not measured in this experiment but previous results have estimated it to be around 0.9 in similar experiments **Error! Reference source not found.-Error! Reference source not found.**, thus suggesting a value closer to the second case.
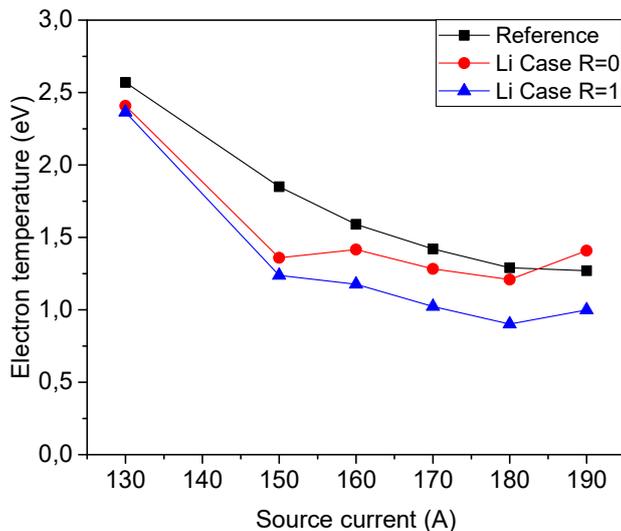

Figure 5 *Plasma T_e. Black curve shows shot on reference target, red on Li-CPS assuming R=0, blue on Li-CPS assuming R=1*

4. Discussion and conclusion

By combining the data from the LP, the TS reference data and the calorimetry, it is possible to better estimate the plasma parameters and gain better insight into the VS process. When comparing the reference measurements to the VS measurements, an increase in n_e by up to 50% and a decrease in T_e by up to 33% is indicated. An increase of n_e and a decrease in T_e is consistent with observations using Sn for VS in **Error! Reference source not found.**. This cooling is indicative of a combination of collisions slowing the plasma down and radiative processes, while recombination can also start to play an important role, all of which could strongly reduce the power to the strikepoint locations in a VS divertor of a fusion reactor **Error! Reference source not found.**. This information gives further insight into how a vapor box divertor can be designed and can be expected to perform. Furthermore, the difficulties in the use a LM inside of Magnum-PSI and the maintenance that must be done after, stress once again the importance of a vapour box divertor design to prevent lithium escaping toward the plasma core in a nuclear fusion facility, where this kind of problem become even more severe.

5. Acknowledgements

6. Data Replication

The data that support the findings of this study are available at http://doi.org/10.5281/zenodo.4897758

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