Studies of Plasma-Lithium Interactions in TJ-II.

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Abstract.

Several experiments devoted to the characterization of the interaction between a hot plasma and lithium surfaces have been carried out in TJ-II in the last year and described here. Interesting new phenomena have been evidenced. The creation of a dense plasma near a metallic Li bar directly inserted in the plasma edge is postulated based on the enhanced attenuation of Li atoms and of the survival time of the bar to the plasma nominal loads. An anomalously high SEE coefficient for lithium exposed to a cold plasma in the presence of high-energy electrons was measured. The effect of surface oxidation was ruled out as possible explanation. The concomitant decrease of the sheath potential due to this effect could explain the observed low sputtering yield of Li previously reported in TJ-II. Finally, hints of selective isotope wall retention were found during devoted experiments in H and D plasmas. A relatively low temperature peak found in the TDS spectrum of the LLI at 375 ºC and the possibility of isotope removal by simple exchange with the opposite isotope in the gas phase could relieve part of the concern about the issue of tritium retention if Li walls are implemented in a fusion reactor.

1. Introduction

The selection of plasma facing materials for future Fusion devices, aiming at steady state operation of a burning plasma, remains challenging. Solid materials are known to be prone to disintegration, dust formation and neutron-induced permanent damage, among other deleterious effects. Therefore, liquid metals, and lithium in particular, have been proposed as alternative to more conservative concepts. One of the main concerns, however, is the survival of these elements to disruptions and type I ELMs, in particular associated to the development of strong MHD forces and massive evaporation. For liquid lithium elements, it has been claimed that self-screening driven by evaporation effectively protects them against the huge heat loads present at the plasma-solid interface [1]. However, little experimental evidence of such effect has been documented to date [2,3].

On the other hand, the sputtering and power load characteristics of any material element exposed to a plasma depends strongly on the secondary emission coefficient under ion and electron irradiation [4]. Although the value of the SEE coefficient for ITER PFC’s (beryllium, tungsten and carbon) is assumed low enough not to distort the local plasma sheath created in their proximities, evidence of enhancement of such coefficient under plasma exposure has been reported at least for the carbon case [5], thus possibly leading to wrong estimates of the local power loads of paramount importance for material
survival expectations under realistic ITER scenarios. The SEE coefficients of W and lithium have been investigated in our laboratory under plasma exposure. While no significant change respect of its bibliographic value was found for W, a drastic increase of this parameter for lithium surfaces was observed [6]. Furthermore, the effect of surface oxidation on this effect was also addressed.

Finally, the exchange of isotopes on low recycling surfaces, as that of lithium, is far from trivial and no report of this kind has been found in the literature. This exchange has direct impact on the important issue of tritium retention in a fusion reactor. In this work we describe the initial experiments aimed at characterizing the H/D interchange efficiency on solid Li films and its evolution as a liquid lithium limiter (LLL) based on the capillary porous system (CPS) is inserted into the confined region of the plasma [7].

2. Experimental

In the present work, three different experiments concerning the peculiarities of lithium elements exposed to a plasma are described.

First, a solid bar of lithium with biasing and displacement capabilities has been exposed to the plasma edge in TJ-II under lithiated wall conditions [8]. Heating powers up to 0.8 MW (ECRH and NBI) were injected into the plasma, leading to unmitigated power densities at the bar tip up to 50 MW/m². Edge parameters were characterized by a supersonic He beam diagnostic and Li I, LiII and Hα emissions at the bar and its proximity were recorded. A 16-channel photomultiplier array allowed for the monitoring of the attenuation of these signals in the toroidal and radial directions, thus enabling transport studies. Biasing of the plasma-exposed bar at ±150 V was also performed.

In the second experiment, the I/V characteristics of a metal bar exposed to a He GD plasma at low pressures were recorded under the presence of a suprathermal tail in the electron energy distribution function (EEDF). Three materials were investigated: a pure stainless steel (SS) bar, a SS coated with a lithium layer and a W sample. Details about the experimental set-up and the procedure can be found in [6]. The shape of the EEDF at several pressures and plasma currents was evaluated from the data of a gridded probe and from the line ratio method based on the emission of selected He lines. Electron energies up to 200V and a ratio of hot/cold electron population up to 3.5% were deduced depending on conditions.

Finally, the recently installed LLL was inserted in the plasma up to 3 cm into the confined region at 200°C and then degassed under vacuum up to 500°C. The insertion was performed during H/D isotopic exchange experiments. Two campaigns of D operation in TJ-II have been carried out. In the first one, only six days of deuterium operation were produced. In the second, more than XXX shots were performed and intentional injection of the opposite isotope in a given H/D plasma was made in order to study the dynamics of the isotope exchange. Mass spectrometry and optical emission spectroscopy of the ratio Hα/Dα present in the plasma and degassed afterwards provided estimates of the relative concentrations and wall inventories for each isotope.

3. Results

3.1. Insertion of a Li bar in the plasma.

Experiments were performed at different insertions of the bar into the SOL at floating potential. Only a few experiments were carried out under bias of the Li tip. Unfortunately, no visual observation of the Li bar was possible in this campaign.
However, a highly spiky emission of neutral Li was eventually detected at maximum insertion. This was ascribed to the possible ejection of droplets from the solid, as this behaviour was not seen in the Li signal taken from the main wall, almost toroidally opposed to the location of the bar. The spikes of the Li signal were not reflected into the main plasma parameters unless a critical level was achieved. Then, a small increase of the electron density and Li signals together with a concomitant decrease of H\(\alpha\), indicating enrichment in Li of the plasmas, takes place. This behaviour was systematically recorded in low-density plasmas, on which strong contribution of runaway electrons was produced.

From the 16-channel photomultiplier array, the toroidal profile of the LiI and LiII emissions could be reconstructed. The results are shown in figure 1. As seen, two different degrees of attenuation into the plasma are seen, according to the tilting of the plasma with respect to the bar at this location. Also, a clear broadening of the Li ion emission due to plasma transport is observed. Interestingly, these profiles didn’t significantly change when a \(\pm 150\) V bias was applied to the bar. However, melting of the tip of the bar led to a broadening of both profiles (see below).

From figure 3 top and the edge plasma parameters deduced from the He beam diagnostic, located 180º away in the toroidal direction [9], the attenuation of Li atoms ejected from the bar can be calculated. For typical values of \(n_e = 1.10^{12}\) cm\(^{-3}\) and \(T_e = 40\) eV at the LCFS, a mean free path for Li atoms, at velocities corresponding to ejection by sputtering, of \(>35\) mm should be observed. The value deduced, however, is only \(7\) mm for the ECRH plasmas shown in the figure. This discrepancy points to the presence of a local plasma with higher density near the Li bar. The production of such local plasma has been reported elsewhere [2,3], and future experiments aimed at its characterization by local injection of a He beam are presently in progress.

From the edge parameters one can also estimate the local power flux hitting the bar. For an arbitrary bias potential, \(V\), the normalized heat flux to a probe is given by [4]

\[
\frac{Q(V)}{kT_e(1+e)} = \gamma(V) = -\frac{eV}{kT_e} + \frac{2.5T_i}{T_e} + 2\left[\left(1 + \frac{T_i}{T_e}\right)\left(\frac{2\pi m_e}{m_i}\right)\right]^{-1/2} \exp\left(\frac{eV}{kT_e}\right) \tag{1}
\]

In the absence of external bias, the probe stays at floating potential, which in the presence of secondary electron emission (SEE) reads:

\[
\frac{eV_f}{kT_e} = 0.5\ln\left[\left(1 + \frac{T_i}{T_e}\right)\left(\frac{2\pi m_e}{m_i}\right)\right](1 - \delta_e)^{-2} \tag{2}
\]
The SEE coefficient was recently evaluated in a separate experiment for solid lithium described below [6]. In the presence of high-energy (>100eV) electrons it can as high as 2.5, yielding a floating potential value of 1.3 Te, instead of the customary value of 3 Te. The maximum power flux to the bar deduced from eq.1 is 58 MW/m², so that ~2kJ would be deposited into the bar each shot. This is higher that the required energy to melt the 2g bar (1.5kJ). However, it was found that only after 12 repetitive shots, the tip of the Li bar was melted. For comparison, previous experiments performed on a SS bar led to a fast melting of its tip under similar edge plasma parameters. Although no direct recording of the local power radiated by the plasma near the bar was possible, an obvious explanation for the enhanced survival of the lithium bar would be the development of a local, high-density plasma with screening effects.

3.2. Measurements of the effective SEE coefficient of Li in a plasma.

Figure 2 shows the I-V characteristics for negative biasing with respect to plasma the potential of Li, SS and W samples. In principle, the I-V characteristics at this negative bias with respect to plasma potential should be only determined by the current of ions arriving to the targets (represented with dashed lines for the Li case) unless energetic enough electrons which can overcome the voltage barrier of the plasma sheath (the difference between the plasma voltage and the bias voltage) are present. As shown in the figure, we clearly observed an anomalous current for these negative voltages. After ruling out other possibilities, the existence of suprathermal electrons in our DC glow discharges has proven the main reason for this anomalous behavior. Results from He 728/706 line emission measurements have shown effective electron temperatures of about 20 to 30 eV (depending on plasma conditions). Highest temperatures occur for the lowest pressures and largest plasma potentials. This clearly shows the existence of a suprathermal electron population, which explains the difference with respect to the bulk temperatures, obtained by the Langmuir probe (6-9eV). This kind of suprathermal population has been previously observed in DC glow discharges (Sugai). It is produced by the secondary electrons emitted from the discharge chamber walls that are accelerated to the plasma potential in the sheath and do not get thermalized by plasma collisions on their way to the anode. Even though this population is very small with respect to the thermalized (bulk) population (a few %) due to their high energies their current can be sufficiently high to generate the secondary electron emission in the targets under study to produce the observed anomalies. If the EEDF is known, the values of the SEE coefficient for each material vs. electron impact energy can be evaluated. As mentioned above, this was possible by using a gridded probe on which the collector is biased at positive voltages to avoid any possible contribution from the
escaping secondary electrons to the measured currents. The results are shown in figure 3.

While the values obtained for SS and W are in reasonable agreement with the tabulated values, making allowance for the energy range below the maximum here explored, an enhancement of a factor of 2.5 for the case of Li surfaces is deduced. According to eq 2., this value for the SEE coefficient would lead to a sheath potential of only 1.3 kTe, instead of its customary value of ~ 3 in H plasmas. Therefore a maximum value of 3.3 kTe would be expected for H ions impinging on Li surfaces for edge temperatures high enough. This fact, if confirmed by direct measurements of these potentials in TJ-II plasmas, could greatly explain the observed low sputtering yield of Li atoms reported previously [10].

One possible reason for this enhanced SEE coefficient in the case of, highly reactive, Li surfaces is the presence of an oxide layer covering it. Evidence of the fast development of such layer even under vacuum already exists. In order to check for this hypothesis, oxygen was intentionally added to the He GD to produce several degrees of oxidation sorted by their impact on the Li sputtering yield by He ions. The results are shown in figure 4. Interestingly, the evolution of the SEE coefficient mirrors that of the sputtering yield as measured through the Li emission near the sample at changing plasma ion impact energies (not shown) thus opening the possibility of a fundamental connection between both phenomena. In any case, the decrease of such coefficient upon oxidation precludes this chemical effect as main responsible for the observed enhancement.

3.3. Isotope exchange experiments on Li surfaces

In the last year, two deuterium campaigns were performed in TJ-II in order to check for a possible isotope effect on plasma confinement, similar to that widely reported in Tokamaks [11]. The first one lasted only three days (about 140 shots) while a longer one, involving a full month of operation, was performed later to guarantee a full exchange of isotopes on the walls and then, on the plasma volume. In both cases, we run
no previous, devoted lithiation in preparation of the experiments, so that the initial state of the wall was that typically found under normal H operation, after the customary He glow discharge conditioning early in the morning. The main diagnostics of the degree of isotope interchange were Hα spectroscopy, with spectral resolution high enough to deconvolute it into Hα and Dα components, and mass spectrometry. Unfortunately, the mass spectrometer could be tuned only to one selected amu value, from 2 to 4, so that no full spectrum of the release molecules, H₂, HD and D₂, could be recorded in a shot by shot basis. In figure 5, the shot by shot evolution of the HD release normalized to the particle (Hα) flux during the first, three-day operation campaign is shown. Only ECRH heated, deuterium fuelled plasmas were produced in this campaign. Two important features of the signal’s time evolution can be seen. First, there is a slow, continuous decrease of its value along the number of shots, with transient rise at the beginning of each experimental day and reaching an off-set value at long times. Second, numerous spikes, mostly at the beginning of each day of operation, can be observed. Very low-density plasmas (purge discharges) are associated to these spikes, on which strong runaway fluxes are typically produced. Therefore, we believe these bursts of HD from the walls could be due to the impact of runaway electrons on the first wall leading to the production of hot spots.

A more quantitative analysis of the H/D ratio in the plasma is obtained through the deconvolution of the Hα signal. Again, interesting features were found in the shot by shot evolution of the Dα/Hα ratio. While this ratio at the beginning of the discharge was higher than 5, after 160 ms of plasma it became almost one, thus indicating a fast enrichment of the wall in the lightest, H isotope. On the second day, the initial ratio was lower, but its evolution with discharge time was the same. Finally, in the third day, a basically constant ratio of ~ 3.5 was kept over the full discharge duration. Therefore we should conclude that the H reservoir on the previously deposited Li film plays an important role in the dynamic inventory, being transported to the surface overnight, as well as during the plasma shots, even with the wall close to room temperature.

In the second campaign, a total longer exposure of the Li films to deuterium plasmas was achieved. The injection of hydrogen was eventually used for the study of the dynamic exchange of isotopes into the film. Although a full description of these experiments will be given in a separated publication [12] several important facts are here outlined. First, a deeper analysis of the Hα emission showed two different ratios for the Dα/Hα signals, depending on energy. While ratios of the order of 2:3 were deduced for low, few eV energies, a much higher value, up to 6, was seen at energies corresponding to the CX neutrals at the plasma core. This result can be understood if one considers the typical low recycling properties of our Li films [13]. While an almost pure D plasma should prevail in the center, with little contribution from recycled

Fig 5. Shot by shot evolution of the yield of released HD per Ha photon in D fuelled ECRH plasmas. Vertical lines indicate the change of day.
neutral, strong isotope mixing takes place on the walls, leading to formation of HD molecules at the plasma periphery. Another interesting observation is the fact that by simply puffing one of the isotopes into the vacuum vessel, with no plasma, strong release of HD was detected, its value corresponding to half that obtained in the presence of plasma with the same puffing settings. This obviously eases the release of the unwanted isotope from the wall, as it would be the case of tritium in a fusion reactor.

Finally, it was also observed that if hydrogen plasmas are created in a D-rich wall, a relatively high recycling, \( R \), of H is seen, even when low values of \( R \) would be measured in the absence of the opposite isotope. This behavior led to the unsuccessful attempts to create NBI heated deuterium plasmas with H neutral beams. No clear conclusion about the reverse situation, deuterium recycling on H-loaded walls, could be obtained to date.

During the last week of deuterium plasma operation, the Liquid Lithium Limiter was inserted into the plasmas. It was kept at 200 ºC and eventually withdrawn in order to perform TDS studies by ramping up the temperature up to 500 ºC. Insertion of the limiter up to 3 cm inside the confined plasma was possible without any obvious detriment in plasma parameters, including density control by external puffing. However, no significant change in recycling characteristics was detected upon deep insertion either. Figure 6 shows the TDS spectrum of released species from the LLL after exposure to a mixture of H and D plasmas, once corrected for the background of gas released from the TJ-II walls during the ramping up of the temperature. As seen, a dominant contribution of H\(_2\) molecules, followed by HD and D\(_2\), exists. Also, all the species are released at the same temperature, 375 ºC. This temperature is significantly lower than that seen in T-11 [1] but higher that that reported by Baldwin et al [14]. It is also worth noting that a very low background of water under any of its possible isotope forms was detected, as expected from the fact that the limiter was thoroughly degassed previous to its insertion into the plasma. Most interesting is the particle balance performed from the calibration of the mass spectrometer used for the TDS recordings. While a total of 2.2x10\(^{21}\) and 1.6x10\(^{21}\) atoms of H and D, respectively, were injected during the day, only 10\(^{19}\) and 2.1x 10\(^{18}\) H and D atoms were recovered in the TDS. Since at least an 85% of the injected fuel is seen to be retained in the wall in our ECRH plasmas, only a 0.6% and a 0.15% of the H and D respectively is accumulated into the LLL at 200ºC. This is an indication of the low limiter efficiency already reported in TJ-II [15]. More interesting is the fact that, while only a 30% more of H was injected during the day into the plasma, the amount recovered by TDS is a factor of 4 higher than that of D. This is in direct contradiction with the above reported high recycling behavior of H plasmas created on a D-loaded wall, and more work is required to assess this important point of relevance for a possible selective isotope retention behavior of Li surfaces.


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