# Lithium as a Liquid Limiter in FTU

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**Abstract.** The experimental results of the use of a liquid lithium limiter on FTU are presented. To avoid droplet generation by JxB forces we have adopted a limiter with a capillary porous system configuration. Lithization of the vacuum vessel is performed by exposing lithium limiter to the plasma boundary for three subsequent plasma discharges after that it is extracted. Strong reduction of the recycling is observed due to the pumping capability of lithium that permits on turn operations near or beyond the Greenwald limit with very clean plasma. When the limiter is inserted into the SOL a new regime with peaked high-density profile close to the Greenwald limit has been found. Finally no damage has been observed on the limiter surface with heat loads up to 5 MW/m<sup>2</sup>.

#### 1. Introduction

The use of liquid material as plasma facing component has been considered in reactor studies to overcome the problems of heat load and erosion on the divertor and first wall [1]. Up now, only few but interesting experiments were performed on tokamaks. On T-11M a CPS liquid lithium limiter was successfully tested up to 10 MWm<sup>-2</sup> [2] and recently on CDX-U where very low recycling regimes with improved energy confinement time were obtained [3].

In this paper we present the results of an experimental program in which a liquid lithium limiter (LLL) with capillary porous system (CPS) configuration was exposed to the plasma for the first time on a medium size tokamak FTU. CPS configuration employs an innovative solution to prevent the injection of lithium into the plasma, as observed on DIII-D [1]. This solution exploits the surface tension forces in capillary channels to compensate jxB forces induced in liquid lithium. Previous tests on CPS have demonstrated that this structure is also able to sustain, in the electron beam experiments, stationary high heat flux in the range 1-25  $MW/m^2$  and short excursion up to 50  $MW/m^2$  [4-5].

The main goals of the first FTU experiments have been to test in ohmic plasma the CPS LLL like a conditioning technique to deposit a lithium film on the chamber walls ("lithization") and to investigate the important technological aspects related to the use of a liquid metal as first wall material such as: the capability to control high heat loads and to ensure the self-regeneration of plasma facing components.

FTU is a high field tokamak [6] ( $\dot{R}$ = 0.93 m, a=0.30 m,  $B_T \le 8T$ ,  $I_p \le 1.6$  MA, pulse length  $t_{pulse} \approx 1.5$ s) with a TZM (an alloy 98% of molybdenum) toroidal limiter and a Stainless Steel AISI 304 vacuum chamber. The high power density here achievable, even if only in ohmic conditions, as well as the possibility to explore a wide electron density range  $n_e=0.3-3.2 \times 10^{20}$  m<sup>-3</sup>, make these experimental programs on FTU meaningful to validate the lithium CPS concept.

In the following, a brief description of the liquid lithium limiter (LLL) will be given in section 1, while in section 2 the experimental results obtained after lithization and LLL extracted from the machine will be described and in section 3 those obtained with LLL inserted into the vacuum chamber in the shadow of the TZM toroidal limiter. Finally, in section 4 the conclusions will be drawn.

## 2. The Liquid Lithium Limiter (LLL)

In fig. 1 a photograph of the three units of LLL installed on the support used for the

introduction inside FTU and a quoted design of fully equipped lithium limiter unit are shown. The lithium limiter is made of three separated and electrically insulated modules which consist of a surface layer of wire meshes of stainless steel 304 with pore radius 15 µm and



FIG. 1. Photograph of the three units of lithium limiter installed on the support used for the LLL introduction inside FTU. The two Langmuir probes are visible in the interspace between units. 1) ceramic break, 2) stainless steel case, 3) lithium filled-capillary structure, 4) heater, 5) Li evaporating surface 6) Mo heat accumulator, 7) thermocouples

wire diameter 30 µm similar to that of T-11M lithium limiter [7]. The surface faced to the plasma is refilled through capillary forces by a liquid lithium reservoir placed on the bottom of this structure. This self-regeneration capability is a very important feature for ITER divertor plates that are expected to operate in the presence of frequent small disruptions (ELMs) that are responsible for enhanced erosion of solid plates.

The LLL is equipped with two thermocouples for each module and two Langmuir probes placed in the intermediate space between modules to characterize the scrape-off plasma near the limiter surface. Infrared detectors look at the three modules to monitor the lithium surface temperature during the shot [8] and the Li III (13.5 nm) line is used to monitor the lithium content into the plasma.

To avoid surface damages, the LLL is preheated at about 220 °C (melting point T=186 °C) in a separate volume and then inserted from one vertical port in the shadow of the main toroidal limiter. Its vertical position can be varied shot by shot.

### 3. Experimental Results of Lithization

Lithization of the toroidal limiter and the wall of FTU vacuum chamber is performed by three identical consecutive ohmic shots ( $I_p=0.5MA$ ,  $n_e=0.7 \times 10^{20} \text{ m}^{-3}$ ,  $B_t=6T$ ) in which the LLL is introduced in the scrape-off layer (SOL) 2.5 cm away the last closed magnetic surface (LCMS). Lithium is produced in the form of atoms and ions by physical sputtering of the liquid lithium CPS surface during the discharges and it is spread out on the chamber walls by the plasma itself. The contribution of evaporation to the production of Li atoms is instead negligible at the typical peak temperatures here obtained (350°C). Temporal evolution of VUV spectra are used to monitor the lithization process: after these three shots O, Mo and Fe lines are strongly reduced respectively by a factor 3.5, 1.8, 2.0 while Li III (13.5 nm) line emission becomes progressively the strongest line in the spectra. After these three shots LLL is extracted by the vacuum chamber and plasma phenomenology after lithization is investigated. In fig. 2 two similar ohmic discharges, one after lithization and one after boronization are compared: after lithization, the fraction of the radiated power to the ohmic power is reduced by 50% and also  $V_{loop}$  is reduced by ~ 10% due to the lower effective ion charge values ( $Z_{eff}$ ) value. The electron temperature  $T_e$  also decreases, as a consequence of the smaller input power. During almost all the experimental campaign, including about 200 plasma discharges with  $B_T = 6T$ , Ip = 0.5- 0.9 MÅ and average electron density  $n_e$  from 0.15 up to  $2.6 \times 10^{20} \text{m}^{-3}$ , the Z<sub>eff</sub> value mostly maintained below 2.0, coming from 1.5 at low density ( $\bar{n}_e = 0.5 \times 10^{20} \text{m}^{-3}$ ) to 1.0 at higher density ( $\geq 1.0 \times 10^{20} \text{m}^{-3}$ ) as shown in fig. 3.

Transport and energy balance analysis was performed for the same discharges of fig. 2 plus for an other one obtained with very clean metallic walls (e.g. oxygen-free). The analysis was made using the transport code JETTO [9] in interpretative mode as concerning



FIG. 2 Comparison between plasma parameters for two shots at  $I_p=0.5$  MA,  $B_T=6T$  after lithization and after boronization starting from the top with the average  $n_e$ ,  $T_e$ ,  $P_{rad}/P_{ohm}$ ,  $V_{loop}$ ,  $Z_{eff}$ 



FIG. 3  $Z_{eff}$  versus the total shots number during the experimental campaign. The vertical line divides the shots before and after lithization

electrons energy transport. In fig. 4 the energy confinement versus time for lithizated, boronized and metallic walls is shown. An improvement of the energy confinement time  $\tau_E$  by a factor 1.3 for lithizated and boronized discharges was found with respect to the case of the metallic one. On the other hand, the relative electron transport coefficient  $\chi_e$  decreases, but not so remarkably. These results indicate that the main responsible for the increase of the energy confinement time is the strong reduction of the ohmic power in lithizated and boronized discharges as a consequence of the lower effective ion charge, Z<sub>eff</sub>, This explanation comes from the fact that the ohmic power and the radiative losses, which mainly contribute in the calculation of  $\chi_e$ , are both depend on  $Z_{eff}$ . A lower  $Z_{eff}$  reduces these two terms so that their contribution balance each other in the calculation of  $\chi_e$ . For boronized and lithizated discharges  $\tau_{E/} \tau_{ITER97L} = 1.25$  was found; a value sensibly higher than for standard metallic FTU ohmic discharges ranging between an average value of 0.92 [10] up to 1.1 in the case of very good clean plasma. It is worth while to note that the best results for boronized discharges are observed only after a fresh boronization, as for the discharge here considered, which effects last only for a few shots. As previously reported [2,3], lithium has a very strong capability to pump D particles. The strong reduction of metallic impurities especially during the start-up phase and a strong reduction of recycling have allowed to get stable repetitive plasma operations up to the lowest electron density never reached on FTU (1.5x10<sup>19</sup>m<sup>-3</sup>). In fig 5 the plasma particles content  $(N_p)$  is plotted versus the total amount of injected particles  $(N_g)$ . The lowest value for the ratio  $N_p/N_g$  has been 7.0x10<sup>-3</sup>, a factor 4 below that obtained after a fresh boronization, as reported in ref [11] which well describes the recycling characteristics of boronized and metallic walls. The saturation effects arising with a fresh boronization after high density pulses is not observed at all and the pre-programmed density is easily obtained. This pumping effect lasts for a long time; after more than one hundred discharges after the LLL experiment, it was still necessary to inject three times more particles than before lithization.



FIG. 4. The energy confinement vs time for lithizated, boronized and metallic walls



FIG. 5. Total plasma particles  $(N_p)$  vs injected particles  $(N_g)$ 

In most of the reactor scenarios, operations exceeding the Greenwald density limit are envisaged. On FTU, after lithization, discharges near or beyond this limit were easily obtained in the explored plasma current ranges ( $I_p = 0.50 - 0.9$  MA). For  $I_p = 0.5$  MA,  $B_T = 6T$ , the density limit ( $\bar{n}_e = 2.7 \times 10^{20}$  m<sup>-3</sup>) is 1.7 times higher than after a fresh boronization and a factor 1.4 higher than the corresponding Greenwald limit. In this case the electron density profile reaches a very high peaking factor  $n_{e0}/\langle n_e \rangle = 2.2$  [12]. Low particle recycling together with low radiation losses contribute to the increase of the density limit, which however does not increase with the plasma current as previously observed on FTU for plasma operations with inconel or molybdenum poloidal limiters. The mechanisms that cause these peculiarities are not yet well understood and they will be object of future investigations.

In the scrape off layer the electron temperature increases as a consequence of the strong pumping effect of lithium and the low core radiative losses that characterize these plasmas. The SOL plasma has been monitored along the poloidal circle by a set of a three reciprocating probes located at  $\theta \sim 0^\circ$  (external midplane), and  $\theta \sim -70^\circ$  (below) and  $\theta \sim 70^\circ$  (above) at  $\varphi$ =120° toroidally far from the LLL. In fig 6 and fig. 7 the SOL electron density and temperature profiles are compared for two ohmic discharges having  $n_e = 6 \times 10^{19} \text{ m}^{-3}$ ,  $I_p = 0.75$ MA and  $B_T = 6T$  as main parameters, with  $Z_{eff} = 3.9$  (Mo plus a little amount of O) for a metallic discharge and  $Z_{eff} = 2.0$  (Li plus a little amount of Mo) for a lithizated one. For the latter, the electron temperature is higher by 50 % while the electron density is very similar. Such a large temperature variation, for the same input power into the SOL ( $P_{in} = 0.5$  MW), has never been observed on FTU in any similar experimental situation where the electron temperature at the LCMS was more or less the same independently on the material faced to the plasma [11]. In the same figures, the dashed lines plus symbols are the results of the simulations obtained with the 2D multifluid edge transport code TECXY [13], which is the extended version of the 2D EPIT code [14], already used on FTU to simulate plasma transport in the SOL. As input parameters for the 2D calculations we used the experimental parameters for the specific shots as well as the results of the global code named FTU-SELF that describes self-consistently the core (0D model) and the edge plasma (two-points model) of the FTU discharges [15].

To reproduce the experimental data two important assumption were needed: a strongly reduction of the recycling coefficient (R=0.02) defined as the fraction of the particle flux impinging onto the limiter plates that is recycled as neutrals re-ionized in turn inside the SOL and a contribution of Mo to the radiative losses. The strong reduction of the recycling coefficient is related to the strong pumping effect of lithium while the Mo radiation is necessary because with only Li the temperature at the edge is much higher than the experimental value. The Mo density is consistent with the reduction experimentally observed.





FIG. 6. Electron density profile in the SOL as inferred by Langmuir probes.

FIG. 7. Electron temperature profile in the SOL as inferred by Langmuir probes.

In the metallic case the radial diffusion and the recycling coefficient are not different from those typically used to simulate FTU data (D= $0.75 \text{ m}^2/\text{s}$ , R=0.75) and the edge electron temperature is kept low by the Mo radiation in the SOL that it is a strong sink for the electron energy.

#### 4. Discharges with LLL

As the interaction between plasma and LLL increases (i.e. LLL position is more close to the LCMS) strong modifications in the SOL are observed that, in some cases, affect heavily also the plasma core properties. Two features are very interesting: a new plasma regime characterized by a strong electron density peaking and an increase of the radiation losses in the



wall x 10 8000 P<sub>rad</sub> 6000 4000 2000 TZM 0 0.325 e-side 0.3 TZM -2 i-side 0.275 core

FIG.8. Plasma viewed by an FTU visible CCD camera. At the bottom is clearly visible a bright ring separated by a darker zone from the main toroidal limiter. LLL is located on the far bottom right, where the glow is most intense.

FIG. 9. 3D plot of the radiated power inside the SOL calculated by TECXY. A clear bump develops between the liquid lithium and the main limiter extending also in the core plasma

SOL close to the LLL due to enhancement of lithium production by sputtering and evaporation. In fig. 8 the plasma image recorded by a visible CCD camera is shown. The six superimposed array of tiles of the toroidal limiter are recognized at the picture centre. The LLL is at the right bottom where the light is more intense, but it is also clearly visible a bright ring corresponding to the same LLL poloidal position, separated by a darker zone from the toroidal limiter. The out of coronal equilibrium lithium radiation losses, close to the LLL, determine a local cooling of electron temperature. The condition of constant plasma pressure along the magnetic field lines implies on turn an increase of the plasma density, and a consequent shortening of the e-folding decay length.

A self-regulating mechanism between Li production and Li radiation losses is operating and this situation can be maintained stable. The following results are referred to a medium density shot ( $n_e = 1.0 \times 10^{20} \text{m}^{-3}$ ) with  $I_p = 0.5 \text{MA}$ , magnetic field  $B_T = 6T$  and  $Z_{eff} = 1.2$  with LLL placed at about 2 cm behind the LCMS. The analysis of the experimental data in the SOL shows that the profiles of plasma density were much steeper for the Langmuir probes magnetically connected with the LLL than for the other ones. In addition the measured values of  $n_e$  on the two Langmuir probes, which equip the LLL, stay in a ratio which well agrees with that deduced from the reconstructed magnetic topology. These experimental situation is well reproduced by TEXCY code. In fig. 9 a 3D plot of the radiative power in the SOL is given. The localized annular bright corona in the vessel bottom, well separated from the limiter, is formed at the LLL poloidal location and correspond just the lump of P<sub>rad</sub> shown in the simulation close to the e-side of the main limiter. Consistency with TECXY simulation is also found for the Langmuir probe measurements. The contribution of D recycling is negligible. Finally this situation is similar to the TEXTOR MARFE [16] but, in our case, the local decrease of the electron temperature is not due to deuterium recycling at the bumper limiter but to the lithium production.

In fig. 10 the time evolution of electron density for two high-density identically preprogrammed discharges is shown together with the  $D_{\alpha}$  emission and the density peaking factor. Dotted lines in the upper frame mark the time slices for the non-inverted density profiles as obtained by the scanning of CO<sub>2</sub> laser interferometer and shown in fig 11. In #28510 the LLL is 1.4 cm behind the LCMS while in shot 28508 is outside the vacuum vessel.



FIG. 10. Comparison of time traces of line dnsity,  $D_{\alpha}$  light intensity and density peaking factor (respectively upper middle and bottom frame) for two high-density dischsrges identically pre-programmed. Dotted lines in the upper frame mark the time slices for the profile shown in fig. 11



FIG. 11. Time evolution of the non-inverted density profiles for #28510 that shows a higher particle confinement than #28508. The rectangular box puts into evidence the change in the radial slope.

With LLL inside the vacuum vessel (#28510)  $n_e$  grows up to  $2x10^{20}m^{-3}$  (~ $n_{GW}$ ), twice the preprogrammed value (#28508) and stay almost constant about 0.4 s, despite no gas is fuelled into the vessel. At the start of the high density phase in #28510 the  $D_{\alpha}$  light drops and remain low, indicating a strongly reduced D particle recycling, whereas in #28508 the  $D_{\alpha}$  signal is saturated. The density peaking rises from  $f_{pk}\sim1.5$  in #28508 up to  $f_{pk}>2$  in #28510. This is a quite high value for  $n_e$  so close to  $n_{GW}$  and contrasts with the common observation of flatter density profile as  $n_e$  grows. A new regime lasting for about 0.5 is established; then its termination is probably due to a SOL modification; the production of lithium and radiative losses in the SOL are not sufficient to sustain this regime as consequence of a reduced LLL plasma interaction. This is inferred by the time evolution of the Li III 13.5 nm line emission, which falls to negligible level. The back transition in turn is marked by a quick simultaneous increase of plasma density on the LLL fixed probes, of the LLL surface temperature and of the  $D_{\alpha}$  light, followed in a short time by a strong Li III light.

The sudden variation of the radial density gradient  $dn_e/dr$  that occurs at the onset of the enhanced regime, close to the edge at r/a~0.7 as evidenced by the rectangular box put in fig. 11, suggests that some sort of density barrier is established. Particle transport analysis confirms that the largest improvements in the particle transport occur at r/a~0.7 where simultaneously the inward pinch velocity increases (in absolute value) and the outwards diffusion coefficient decreases [17]. This regime develops only at relative high density  $n_e > 0.5 n_{GW}$ , and with the LLL present inside the vessel so that the strong interaction with plasma exalts the Li pumping effects. The associated very low recycling is consistent with the analogous need to obtain in divertor plasmas a good quality H-mode, where an edge barrier is built. However, no significant improvement of the energy confinement time,  $\tau_E$ , has been observed.

One of the important point of LLL experiments is the capability of CPS to sustain high thermal load. In fig. 12 the temporal evolution of the LLL surface temperature of the three limiter units have been plotted together with the temperature evolution as found from the calculations of ANSYS code[18] for the unit # 2 assuming a constant input thermal load of 2.0 MW/m<sup>2</sup>. Surface temperature deviation from ANSYS calculation after 1s is related to a dissipative heat process not considered in the code as the Li radiation in front of the limiter surface. This phenomenology is similar to that experimentally observed in electron beam experiments where the formation of a Li radiative layer in front of CPS prevents surface damage. Calculations of TECXY code support this view; the total power to the LLL is estimated =11 kW, which gives a power flux at LLL of the order of 2.1MW/m<sup>2</sup> on CPS surface well in agreement with ANSYS code. The total D<sup>+</sup> flux on the three Li limiter units is equal to  $\Gamma_{D_+} = \Sigma_n (S_n q)/7T_e$  with  $T_e=10$  eV (from Langmuir probes on LLL) and  $S_n$  equal to the effective area of the interaction surface ( $S_1=18cm^2$ ,  $S_2=16cm^2$ ,  $S_3=18cm^2$ ). Taking into account the evaporation rate and the D<sup>+</sup> fluxes we conclude that Li flux is mainly produced by sputtering process (5.0x10<sup>20</sup> atoms) while evaporation contributes only for a small amount (about 6.9x10<sup>18</sup> atoms).

The CPS is not able to act as main limiter for all the discharge duration so that to increase the thermal flux, the plasma has been shifted for about 0.5 s towards the liquid lithium. Despite to the fact that thermal loads up to 5 MW/m<sup>2</sup> where obtained, the temperature increase on the Li surface didn't exceed 250 °C.

No anomalous phenomena like "lithium bloom" [19] occur during plasma discharges and no surface damage have been observed on the LLL after operations, also in the case of plasma disruption. Nevertheless sometimes large spikes in the Li III intensity line have been observed probably due to unipolar arcs or small droplets as consequence of JxB forces. In other cases surface temperature peaks correlated to plasma instabilities have been observed.



FIG.12. Experimental temperature evolution for the three LLL units vs time. The temperature calculated by ANSYS code is also plotted for unit 2

After lithium experiments many droplets were found inside the vacuum chamber during the visual inspection. These droplets were only in two directions relative to the LLL surface: radially towards the high field magnetic side and perpendicularly towards the upper port. Instead they were completely absent in the toroidal direction. We believe that most of vertical droplets are generated as a consequence of plasma disruptions while those in the radial direction should be due to mechanical vibrations. Both these hypothesis are still under investigation.

#### 5. Conclusions

The first experimental campaign to test a liquid plasma facing component has been successfully done on FTU. Both physical and technological results are extremely positive. Lithization of the first wall is a powerful method to get very clean discharges comparable or even better than boronization. Recycling is strongly reduced by the Li pumping capability and consequently also MARFE edge instabilities are reduced to a great extent. These effects deeply modify the edge conditions allowing the access to new interesting regimes. These are characterized by lower particle outward transport and remarkably peaked density profiles close to the Greenwald limit, without any central particle fuelling tool. The LLL has been also tested as plasma facing component for thermal loads exceeding 5 MW/m<sup>2</sup> without any surface damage or phenomena as "lithium bloom".

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