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Spectroscopic measurements for deuterium retention and lithium influx studies with lithium limiter on FTU

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ABSTRACT

Spectroscopic measurements to determine deuterium and lithium fluxes were performed in recent experiments on FTU with a liquid lithium limiter (LLL) and an actively cooled limiter (CLL) using a multichannel spectrometer and using LiI–D_α filtered photodiodes. Using the S/XB method in combination with an absolute calibration, measurements of the LiI (670.8 nm) and D_β (464.8 nm) spectral lines were used to estimate the deuterium and lithium fluxes from the limiters. The estimation of the lithium fluxes has shown increased values when the CLL is closer towards the last closed magnetic surface (LCMS), according to the measurements of infrared camera. This work shows that the spectroscopic diagnostics in the visible range can be an efficient tool to determine deuterium and liquid metal fluxes in FTU in order to better investigate the interaction between the plasma and the limiter materials.

Introduction

Since 2006 extensive work has been carried out with a capillary porous system (CPS) liquid lithium limiter (LLL) 1) for its use as a conditioning technique for the lithization process [1,2] and 2) to test its capability to withstand high thermal loads from plasma interaction [1].

Particular attention has been focalized to the Li strong chemical reactivity leading to possible lithium hydride formation inside the liquid material [3], which could represent a problem for tritium retention and extraction in the future devices with a liquid divertor. The physics of Li properties to adsorb/desorb hydrogen is very complex and regulated by different mechanisms depending on: H/Li concentration inside the liquid metal, Li temperature and PH2 pressure on the Li surface. By the measurements of D influx into the plasma coming from the limiter surface and by the impinging ion flux on it, an estimation of D retention can be obtained by considering the total amount of D particles thermally desorbed [4].

Moreover the experiments with LLL on FTU have pointed out the importance of the control of the quantity of lithium and its release into the plasma [5], due to the mechanisms of the physical sputtering and of thermal evaporation.

For temperatures lower than 550 °C the physical sputtering is the dominating mechanism while for temperatures above this value, the lithium evaporation increases so much that a high quantity of lithium is released into the plasma. In order to avoid the strong evaporation and the consequent plasma disruption due to the sudden cooling of the plasma edge [5], the heat from the limiter has to be removed during the plasma exposure. To prevent the overheating of the liquid Li surface an advanced version of lithium limiter, actively cooled (CLL), has been realized and tested in FTU, for the first time during the experimental campaign at the end of 2013 [6].

In order to study the deuterium retention and the quantity of the released lithium from the limiter surface into the plasma, as previously described, the spectroscopic measurements have been proved fundamental to carry out these analyses. By the brightness of the plasma spectral lines recorded by spectrometers and interference filters in the visible range, an estimation of deuterium and lithium fluxes have been derived [7]. In particular, the deuterium Balmer series and the LiI spectral lines have been considered.

In this work the first experimental results obtained by using the spectroscopic diagnostics for the analysis of deuterium retention and for the lithium fluxes estimation will be presented. In the paper, for a more clarity, these two topics will be illustrated in two separate sections.

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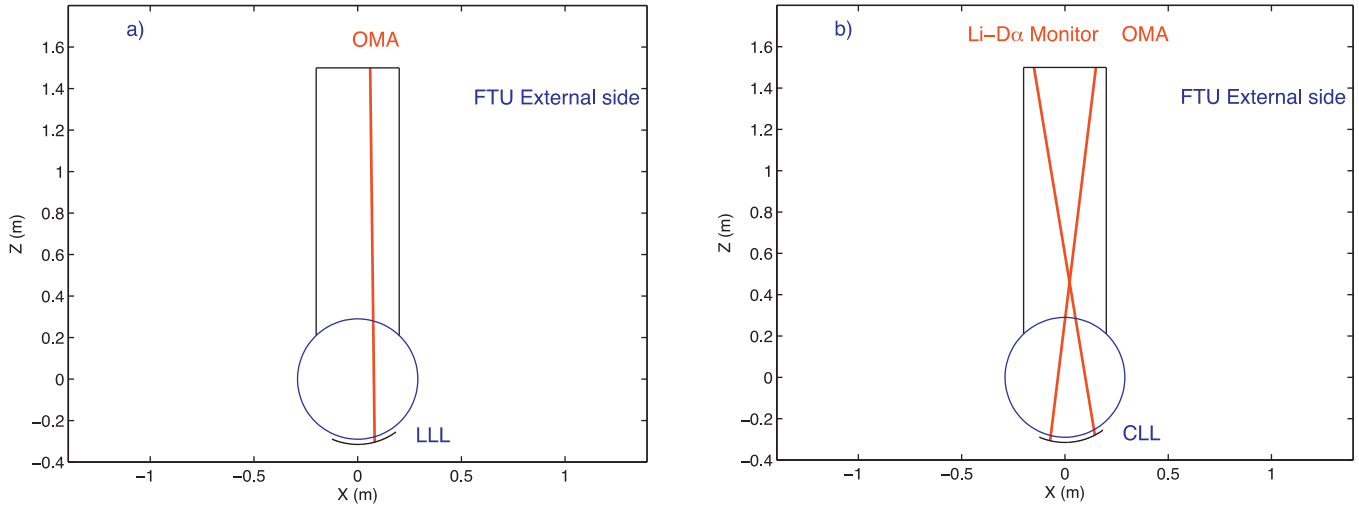

Fig. 1. a) Line of sight for OMA diagnostic in experiments performed with LLL and b) lines of sight for OMA diagnostic and Li–D_α Monitor in experiments performed with CLL.

Experimental set up and results for the deuterium retention studies

The first experiments on the topic of D retention have been performed by inserting LLL in the FTU scrape off layer, at a distance of 1.5 cm from the last closed magnetic surface and by exposing it to 6 repeated ohmic plasma discharges (temporal duration $\Delta t = 1.5$ s) at plasma current Ip = 0.35 MA, toroidal magnetic field BT = 6T and with line-averaged electron density $n_e \approx 4.0$–$6.0\ 10^{19}\ m^{-3}$, which represents a medium-high value for FTU discharges. For these studies on Deuterium retention, the light coming from LLL has been analysed using an Optical Multichannel Analyser (OMA) spectrometer.

As shown in Fig. 1a), a single line of sight collects the light from a 20 mm diameter spot on the LLL surface.

From the brightness of the D visible spectral lines the neutral flux from the LLL has been evaluated according by the relation [8]:

$\Phi\ (s^{-1}m^{-2}) = 4\pi\ I\ (ph\ s^{-1}m^{-2}sr^{-1})\ S/XB$ where I is the calibrated brightness of the spectral line and S/XB is the number of ionizations of neutral atoms for emitted photon for the specific spectral line (S being the ionization rate, X the excitation rate and B the branching ratio of the observed lines). Generally, this relation is valid for all the elements whose ionization occurs very rapidly along the line of sight before diffusing significantly into the plasma volume (the emission contribution due to the plasma core is neglecting). Moreover, the S/XB method can only be applied if the measured line intensity is mainly due to the excitation, when the recombination and molecular reactions contributions can be neglected.

For an expected range of $T_e = 6.5$–19 eV and $n_e = 4$–$12\ 10^{18}\ m^{-3}$, because the recombination contributions to the D_β line are negligible, the S/XB method can be applied and its value varies from 37 to 144 ionizations for photon [9]. The obtained flux can be overestimated due to core contributions to the light emission.

For the examined discharges, $T_e \approx 13$ eV and $n_e \approx 0.8 \times 10^{19}\ m^{-3}$, which are the values measured by Langmuir probes on LLL in similar ohmic discharges, the S/XB is equal to 96.7 with the uncertainty of the order of 50%. The uncertainty in the flux estimation is due principally to the strong dependence of S/XB on electron temperature and density at the plasma edge, near the lithium limiter where the D_β emission is localized (the uncertainty margin due to the absolute calibration of the spectroscopic diagnostic is not significant).

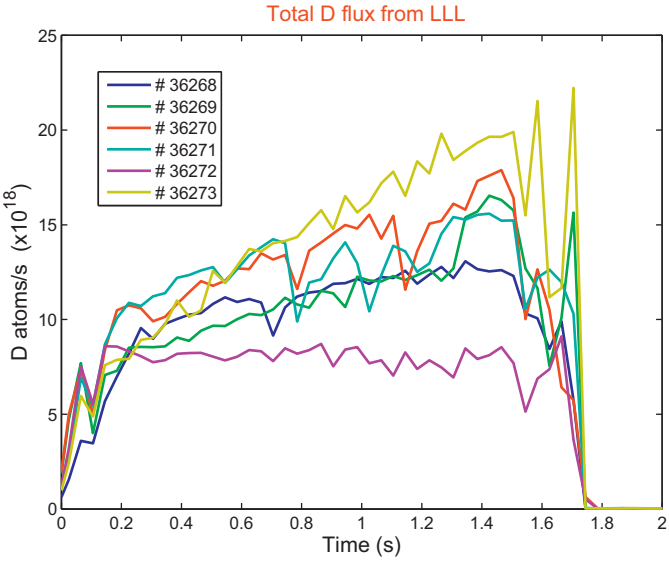

Fig. 2. Deuterium fluxes, from the whole Li surface of the LLL central unit, are shown, as evaluated by the D_β spectral line measured by OMA.

The temporal evolution of the total flux shown in Fig. 2 has been obtained considering the whole Li surface of the LLL central unit. From this experimental data an estimated total flux of $8.5\ 10^{19}$ particles is found for the total plasma duration of 7.2 s.

For some discharges the line-averaged electron densities show a rising trend due to the difficulty of the density feedback control system to reach the programmed density.

After the six repeated plasma discharges, LLL was extracted and placed in a separate vacuum volume connected to the FTU vacuum volume by means a gate valve. Thermal desorption mass spectrometry (TDS) was carried out by heating LLL (only the central unit) up to 350 °C (value below the decomposition temperature of the deuterium hydride) and by monitoring the gaseous species by means of a quadrupole mass spectrometer. The amount of recovered D2 gas from LLL, integrated on the number of performed plasma discharges, has been compared with the neutral D flux coming from LLL and the estimated incident ion flux on LLL surface.

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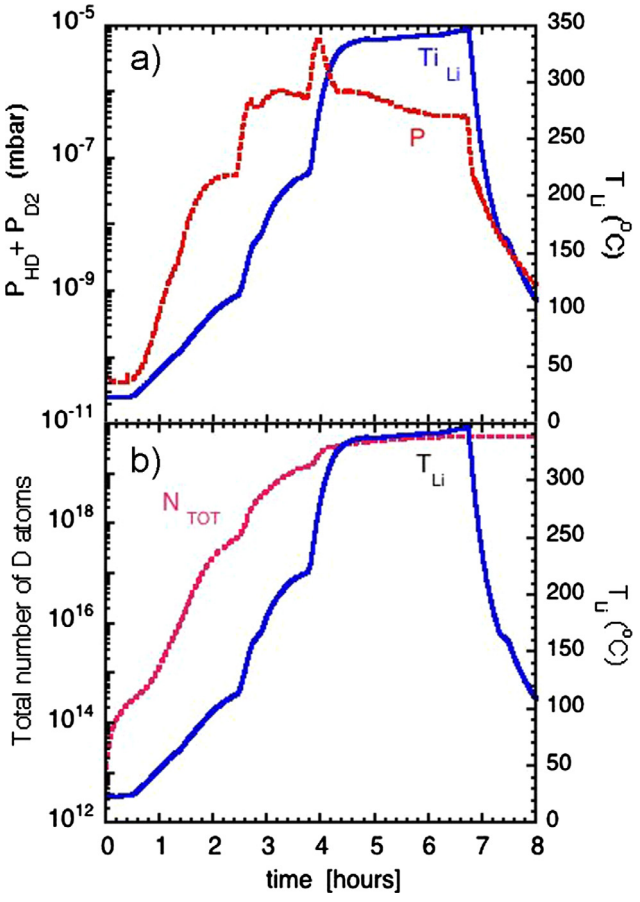

Fig. 3. a) HD+D_2 pressure and b) total desorbed D atoms as a function of time. On the right of the plots, the lithium limiter temperature, measured by thermocouples, is shown.

A quantitative assessment of the amount of released deuterium has been derived from the total evacuated D flux, taking the HD and D2 partial pressure time traces and the effective pumping speed at the quadrupole position, as given by the formula:

NTOT (D atoms/hour) $= \Sigma \Delta t$ [(PHD+PD2 × 2) (mbar) * Sp(l/s) * 3600 s * 7.25×10^{21}/T(K)] where Sp (l/s) = 100 l/s is the effective pumping speed at the quadrupole position and T (K) is the ambient temperature at the quadrupole level. Here 7.25×10^{21} is the conversion factor from (mbar x liters) units to number of atoms. From the integral of the pressure curves, a total amount of $\approx 6 \times 10^{19}$ D atoms has been found (see Fig. 3).

The ion flux to the LLL has been estimated from the number of particles escaping from the last closed magnetic surface (LCMS) $\Gamma = \overline{n_e} V/\tau$ and taking in account the presence of the toroidal and poloidal limiters inside the scrape off layer (SOL). For $n_e = 5.510^{19}$ m^{-3}, plasma volume of 1.6 m^3 and a particle confinement time of $\tau = 3\ 10^{-2}$ s, $\Gamma_{in} = 3 \times 10^{21}$ part s^{-1} [4]. With a particle e-folding length of 0.02 m and the LLL located about 2 cm from LCMS an ion flux of 40% (0.33 Γ_{in}) (the remaining 60% being distributed on the toroidal and poloidal limiters, based on their extention in the poloidal cross-section), a total flux of 4 10^{20} part. s^{-1} is expected to hit the LLL [4].

Due the fact that the retained D comes almost completely from one of the three LLL units (only one heated), the ion flux to be compared to the retained deuterium is 1/3 of 4 10^{20} and considering a flat top duration of 1.2 s the total amount of particles impinging on one of the three LLL elements during six discharge is 9.6 10^{20} particles. From the particle balance equation, the sum of deuterium escaping from LLL (8.5 10^{19}), given by the spectroscopic measurements, with the deuterium released during the TDS (6 10^{19}), is significantly lower than the expected value, being only a 15% of the estimated fluence (9.6 10^{20}). In order to clarify this discrepancy, considering the complexity of the lithium hydride behavior, thermal desorption up to temperatures promoting decomposition of lithium deuterides (500 °C) should be carried out. The problem of lithium hydride formation and release is a crucial point that has been investigated on other devices, such as T-11M [10] and on laboratories [11] and plasma facilities [3].

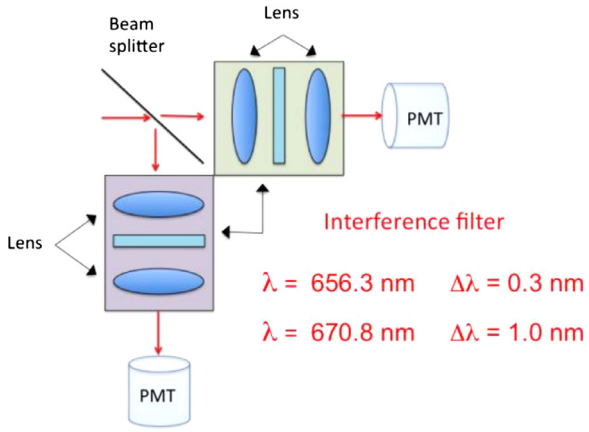

Fig. 4. The scheme of Li–D_α Monitor. The light on the beam splitter (red lines) is focalized on the two photomultipliers through the two optical systems including two interference filters as indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Experimental set up and results for the lithium influx studies

The analysis of Li influx into the plasma has been only carried out for experiments performed with the CLL.

The lithium limiter surface is monitored by an infrared camera [6] and by two optical systems connected, through optical fibers, with a visible spectrometer OMA and a Li–D_α Monitor that uses photomultipliers as detectors [7]. The lines of sight of these two optical systems are shown in Fig. 1b).

As shown in Fig. 4, in the Li–D_α Monitor the collected light, through a beam splitter, is focused on two sets of photomultipliers after having selected the wanted wavelength by interference filters with FWHM (Full Width Half Maximum) of 1 and 0.3 nm for wavelengths, respectively, of 670.8 nm (LiI) and 656.3 nm (D_α). The lens situated in front of the interference filter permits to work with parallel incident rays on it while the lens at the rear focuses the exit beam on the detector.

The lithium limiter is inserted from one vertical port at the bottom side of the machine and its radial position can be varied shot by shot from 4 cm outside the last closed magnetic surface (LCMS) up to 2 cm inside the LCMS with the TZM toroidal limiter acting as main limiter.

The experiments, described in this work, have been performed by inserting CLL in the FTU scrape off layer (SOL), at different distance from LCMS, in ohmic plasma discharges at plasma current $I_p = 0.5$ MA, toroidal magnetic field $B_T = 6$ T and with a preprogrammed electron density of $n_e = 4.0 \times 10^{19}$ m^{-3}.

On FTU, measurements of temperature and density in the SOL are performed with arrays of reciprocating Langmuir probes and the CLL has been equipped with local Langmuir probes. However, for the examined discharges no Langmuir probes were available and the experimental data from similar discharges have been considered to characterize the SOL. The temperature and density in the SOL are estimated by the relation $f(\delta) = f_{LCMS}\ exp(-\delta/\lambda)$, where

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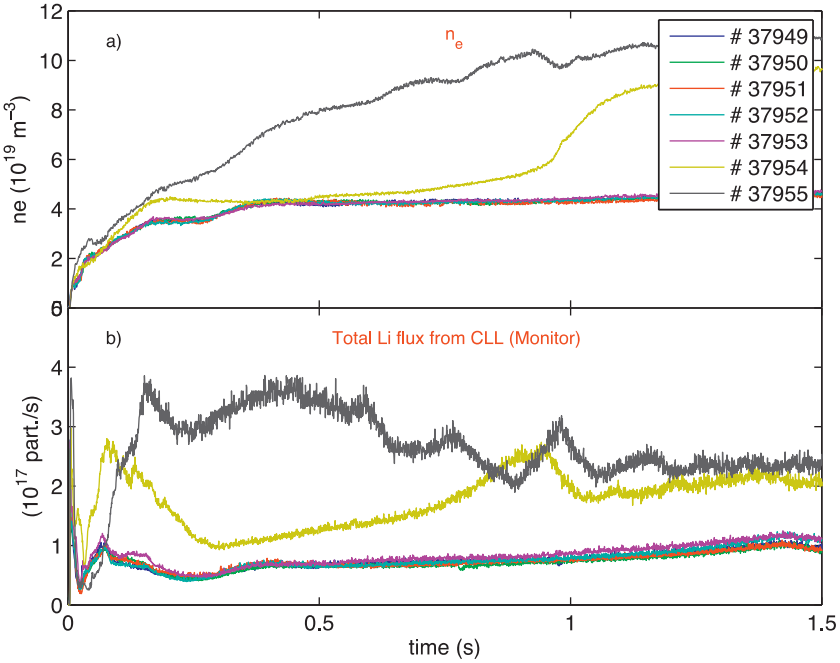

Fig. 5. a) Line-averaged electron density, measured along a central chord, b) total Li flux from CLL versus time, evaluated by the brightness of LiI 670.8 nm spectral line detected by the Li–D_α Monitor.

$f(\delta)$ is the value at the δ distance from LCMS and λ is the decay length for electron temperature or density.

In Fig. 5(a) for the examined discharges, it is shown the time evolution of the line- averaged electron density, measured along a chord crossing the plasma centre.

Three different types of discharges can be distinguished depending on the distance, δ, from LCMS:

(i) For $\delta = 3.4$ cm, discharges #37,949–37,953 are characterized by a flat density with an average central value of 0.4×10^{20} m^{-3}. The decay length is 5 cm for temperature and 2 cm for density, whose values, at LMCS, are respectively 18 eV and 0.7×10^{19} m^{-3}.

(ii) For $\delta = 2.9$ cm, discharge #37,954 shows an average central value of 0.4×10^{20} m^{-3} until t = 1.0 s. The decay lengths are the same of previous discharges.

(iii) For $\delta = 2.4$ cm, discharge #37,955 shows a rising density. In order to estimate the decay lengths, by the set of similar discharges, a single averaged value for the density has been taken in account. For an averaged value of 0.8×10^{20} m^{-3} the decay length is 3 cm for temperature and 2.5 cm for density, whose values, at LMCS, are respectively 22 eV and 1.0×10^{19} m^{-3}.

The total fluxes, evaluated by the brightness experimental data and considering a CLL interaction surface of 50 cm^2, are reported in Fig. 5(b). The values of *S/XB*, necessary to evaluate the flux from the LiI spectral line, for these three different types of discharges, are summarized in Table 1. Because these values have been calculated with the constant electron temperature and density values estimated near the CLL during the stationary phase of the plasma, in which significant thermal load occurs, the Li flux evaluation is valid only during this phase. In order to extend the flux evaluation in conditions of variable plasma parameters, as the current ramp up phase, different values of *S/XB* would be considered.

In addition, as described in previous section about the deuterium flux, a small deviation in the measurements of electron temperature and density leads to a significant uncertainty in the lithium flux estimation. For a reasonable expected interval given by $T_e = 5$–19 eV and $n_e = 0.5$–8.0 10^{18} m^{-3}, the *S/XB* value ranges from 0.118 to 0.339 providing an uncertainty in the flux estimation is of the order of 50%, see Table 1.

Table 1
Values of S/XB for the LiI 670.8 nm spectral line [9], at different values of Te and ne in the plasma SOL, at distance δ from LCMS, estimated by the relation $f(\delta) = f_{LCMS}$ exp(-δ/λ).

δ (cm)	T_e (eV)	n_e (10^{18} m^{-3})	S/XB @ 670.8 nm
3.4	9	1.3	0.159
2.9	10	1.6	0.168
2.4	10	3.8	0.216

For the first type of discharges, the small and flat total flux indicates that at the distance of $\delta = 3.4$ cm the interaction between CLL and plasma is negligible. For the second type of discharges, restricting the analysis before the sharp density rise occurring at t = 1.0 s, the increased total flux, respect to the previous type of discharges, indicates that a significant interaction has taken place. From the IR images the rise of the CLL temperature is observed according with the continuous increase of the total Li flux. The D_α signals of the Li–D_α Monitor show the same trend but with a rise starting at 0.6 s. Further investigation is under way to understand the relation between Li flux and density after t > 1.0 s.

For the third type of discharges, with $\delta = 2.5$ cm, an accurate analysis of the temporal evolution would require measurements of plasma temperature and density close to the CLL region. It is evident that the intensity of the interaction between plasma and limiter depends on the distance of the limiter from LCMS, as observed by the spectroscopic signals.

No sharp rises of lithium flux were observed in any of the examined discharges. This indicates that the strong release of lithium into the plasma by evaporation, which was observed with the LLL [5], is avoided with the CLL. This suggests that the evaporation is negligible according to the IR images which show temperatures

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of about 430 °C in the hottest spots of CLL surface. For this condition most of the lithium is produced by physical sputtering, as expected.

Conclusion

In FTU, an effort has been made to explore the quantity of lithium in the plasma and the deuterium retention in the lithium limiter, which are considered important issues in experiments with liquid metals.

An efficient tool for evaluating lithium and deuterium fluxes is given by the spectroscopic diagnostics in the visible range, such as Li–D_α Monitor and OMA.

Spectroscopic measurements have been used to evaluate the deuterium fluxes coming from the lithium limiter surface in experiments with LLL performed to study the retention proprieties of the liquid lithium on FTU. The analysis has carried out by exposing the limiter to the plasma for six repeated ohmic discharges and then submitting the limiter to the thermal desorption up to 350 °C. A value of 8.5×10^{19}atoms, for the neutral D flux leaving the liquid lithium surface during the discharges, has been obtained. In addition the retained D inventory has been estimated to be 6×10^{19} D atoms corresponding to about 6% of the total incident ions fluence ($\approx 9.6 \times 10^{20}$ atoms). The obtained results suggest that not all the deuterium atoms have been removed from the lithium limiter and that the thermal desorption up to lithium temperature promoting decomposition of lithium deuterides (≈ 500 °C) should be carried out.

Spectroscopic measurements have been used also to evaluate the lithium fluxes coming from the lithium limiter surface in experiments with CLL.

The Li flux signals can been used as a monitor to optimize the CLL radial position inside the vacuum chamber of FTU machine in order to improve the plasma performances without reaching an uncontrolled release of lithium by evaporation.

For FTU discharges in ohmic regimes at $I_p = 0.5$ MA, $B_T = 6$ T and $n_e = 4.0 \times 10^{19}$ m^{-3}, with the CLL inserted in the vacuum chamber at 2.9 cm from LCMS, the preliminary analysis has given a Li total flux of the order of 1.5×10^{17} part./s.

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