EXPERIMENTS WITH LITHIUM GETTERING IN T-10 TOKAMAK

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Abstract. The two experimental campaign with lithium gettering of the T-10 chamber were carried out. The experiments were aimed to prove the lithium abilities to obtain high performance discharges with lithium cover of the wall and limiters with reduced recycling of the working gas and the impurities level in ohmic and heated with the high ECR power tokamak discharges. The second goal of the T-10 experiments were to extend the operational space of discharge parameters in T-10 limiter configuration with graphite limiters in conditions of the clean plasma with low recycling and to test compatibility of the Li-gettering with the proper work of the primary vacuum windows of the T-10 ECRH system. The lithium element was manufactured on the base of the kapillar porous system. The lithium element was placed in the same port as the graphite rail and circular limiters. It was introduced to the vacuum chamber by means of the special transport vacuum system. The inner heater was able to heat it up to the 550^0 C. Typically, about one gram of Li was evaporated each time at the temperature 450 C^0 during 20 minutes. Such technique was sufficient to reduce density decay time from about 1.5 s to 0.075 s. The significant decrease of the recycling was sustained during 10 discharges. The SXR emission decreased in a factor of 10. The central radiative losses and the total radiative losses decreased in a factors of 4 and 2 respectively. This corresponds to the decrease of the high Z impurities in a factor of 4, oxygen in 7, while the main carbon impurity decrease up to 2 times and Zeff from 1.8 to 1.15. Thus the experiment showed significant decrease of the impurities and recycling. At the same time the influence of the lithium gettering on the windows transmission and stable work of the high power ECRH system were not observed.

The problem of plasma-wall interaction is now one of the main obstacle on the construction of the power tokamak-reactor. Several approaches to this problem are currently under investigation and testing on tokamaks. The lithium protection of the wall, proposed in [1] is now one of the promising solution of the problem. Several tokamaks investigate this approach using lithium either as the wall getter, or the limiter material [2-5], since the successful TFTR experiment [6]. Although all these experiments showed not only compatibility of lithium with the tokamak discharges, but even significantly improved the discharge performance, a lot of unresolved questions are still exist. So the main goal of T-10 experiments with lithium gettering is the investigation of lithium behavior and discharge characteristics in OH and high power ECR heated discharges. Apart from that these experiments had a practical goal to reduce the recycling and impurities level and provide clean plasma with density control in T-10 tokamak with the graphite limiters and typically high deuterium recycling. Experiments should also prove the compatibility of lithium with the reliable work of T-10 high power ECR system with respect to the possible damage of the gyrotrons vacuum windows. There were also questions about the techniques of the conditioning of the installation with lithium after long opening to atmosphere. Taken this into account, only the moderate Li gettering was used during the first campaign in 2006 [8]. This was done by positioning of the Li head away from the chamber in the port. As the

results were quite positive, the Li amount, evaporated during one litiization, was increased to about one gram by means of introducing the head inside the chamber.

The Li-element used for gettering was made by "Red Star" on the base of the capillary porous (10-100μm) system (CPS), which has been already successfully used in T-11M and FTU experiments in Troitsk [2] and Frascati [3]. The Li was sustained in the bottom of the Li-element and forced by capillary tension to the plasma facing surface along CPS. The Li-element was placed in the same toroidal section, where several ECRH windows, graphite rail and circular limiters were situated. The schematics of experiment is shown in the Fig.1. The Li-element was positioned in the special pump cell and transported to the plasma boundary by means of the telescopic mechanism. The electrical heater permitted to increase the Li-element temperature up to 550° C. The temperature was measured by the thermocouples and was recordered by means ADC.

The T-10 experiments were carried out in OH and ECRH discharges with the currents Jp=200 and 300 kA, toroidal magnetic field Bt=2.4 T and average density <Ne>=from 1.1 to $5.6\times10^{19}m^{-3}$. The power of central ECR heating was 2 MW.

The Li-element was positioned in T-10 chamber before plasma experiments and was heated up to the 450° C during 20 minutes. The typical Li deposition to the chamber was about one gram. The evaporated Li amount was controlled by the time length of the temperature plato during the cooling of the element. This technique was proposed in [2] and the temperature time traces before and after experiments is presented in Fig. 2.

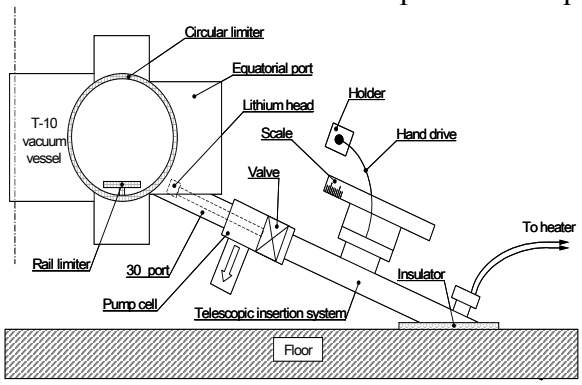

Figure 1. Schematics of T-10 Li experiment

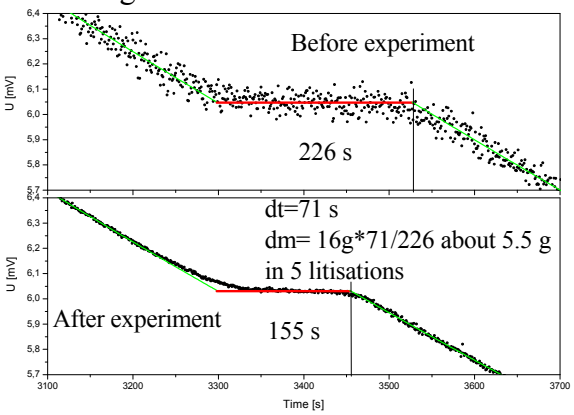

Figure 2. Estimation evaporated Li mass

Along with traditional T-10 diagnostic system, including 16 channel interferometer, 22 channels ECE temperature measurements, SXR PHA, moving radially from discharge to discharge, a number of diagnostics of special interest for Li experiments should be mentioned. These are a set of optical intrinsic impurities, lithium and deuterium lines measurements in different toroidal cross-sections. The radially resolved Zeff measurements from the visible bremsstralung. 16 chords AXUV and 14 chords pyroelectric bolometer arrays. The fast neutral particles analyser for the measurements of the central ion temperature. The Langmuir probes, equipped at the top of the rail limiter gives time variation of the edge density and temperature. The chamber condition and the chemical evolution of Li after opening to atmosphere were measured by TV inspection and the X-ray spectrum (EPMA) respectively.

The evolution of some plasma characteristics during the period of last experimental run in 2008 are shown in Fig. 3. The plasma parameters were taken in discharges with Jp=200 kA, toroidal magnetic field Bt=2.4 T and average density <Ne>=$3.5\times10^{19}m^{-3}$. As the characteristics were changed during the day, typically the 4-th-6-th discharges from the beginning were taken. Top right panel shows the preparation procedure.

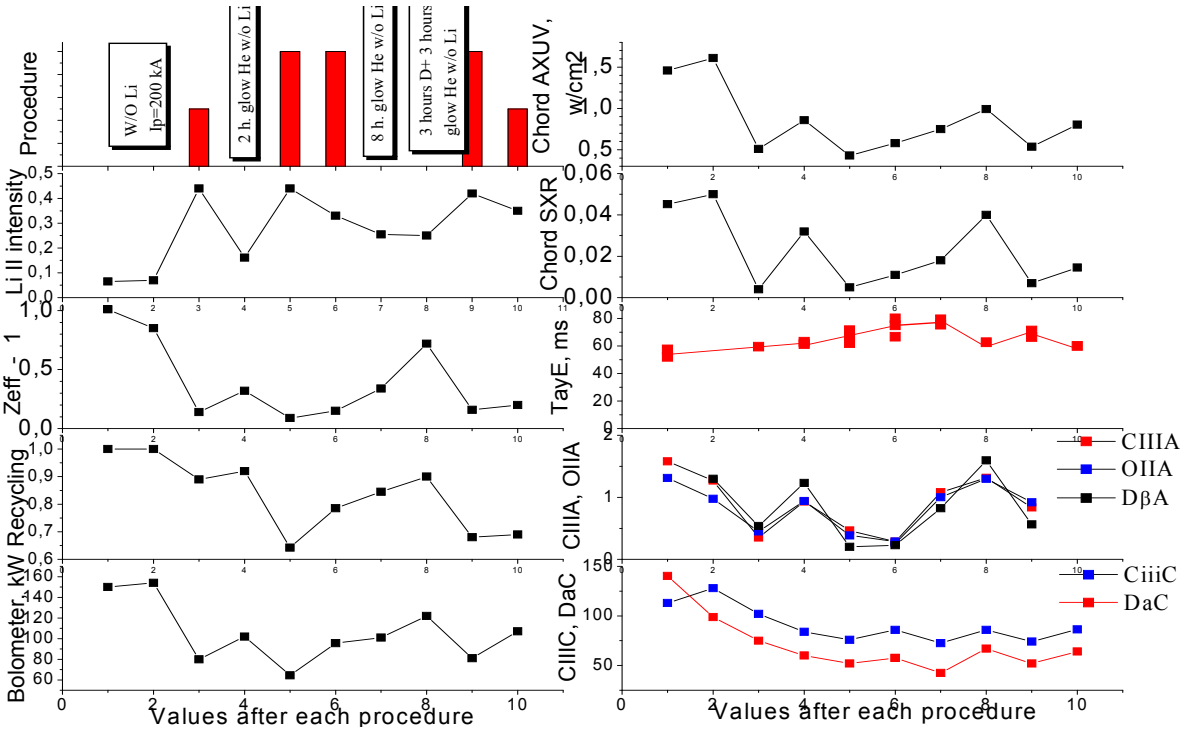

Figure 3. Evolution of some plasma characteristics during the 2008 Li campaign

Litiizations are marked as red columns. The first two points show parameters of the reference shots before litiization. The next points referred to plasma characteristics after different procedures of chamber preparation before the day run. The red columns denote the litiization. Its height is proportional to the amount of the deposited Li. It is clearly seen that, in general, litiizations greatly decrease Zeff, recycling, radiation losses, intensity of SXR, intensity of deuterium and impurities lines and increase energy confinement times in about 20%. But these values are very sensitive to the procedure of vacuum vessel preparation during the night. This fact was very clearly seen in the Li campaign in 2006, because at that time vacuum vessel was cleaned by means of several hours of deuterium Taylor discharge, without any He glow discharge. In such conditions at the beginning of each day recycling coefficient returned to the pre-lithium unity value, if no new litiization was carried out. This fact, obviously, was connected with the full saturation of lithium with deuterium during the night. The same effect can be seen in Fig. 3 at the point 8, where 3 hours of deuterium discharge was used during the night. Practically all discharge characteristics returned to the pre-lithium value with the only one exception. The deuterium and carbon lines intensity in the port "C" practically do not change. It is also clearly seen that the lines intensity in port "C" decrease very smoothly during the whole Li campaign, showing the integrated effect of the deposited lithium. Such behavior is quite natural as the port "C" is situated 180^0 toroidally from the port "A", where litiization was carried out. So the smooth decrease of the lines in port "C" may be connected with the steadily increase of the lithium due to the process of redeposition. This suggestion is supported by the smooth rise of the LiI line in port "C" during the campaign. In spite of the fact that Li migration along the torus takes place, it should be concluded that this process is very slow and do not contribute to the variation of plasma characteristics during the campaign. Such conclusion is based on the fact of strong correlation of plasma parameters with the lines behavior in limiter port "A". Thus the main factor, determining the plasma characteristics is the condition of the limiter with respect to saturation with deuterium. This process of lithium saturation with deuterium can

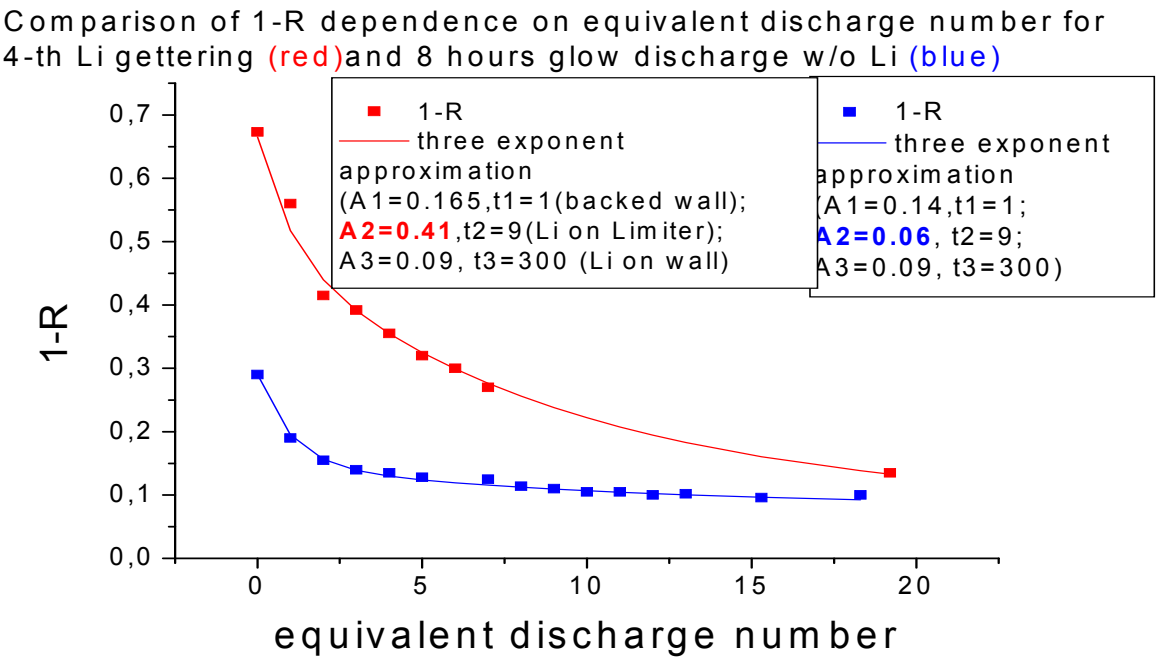

Figure 4. Comparison of 1-R dependence on equivalent discharge number for 4-th Li gettering (red) and 8 hours glow discharge w/o Li (blue)

be investigated by decrease of recycling during the working days with different procedures of the vessel cleaning. Such information is presented in Fig. 4. It presents the comparison of 1-R dependence on equivalent discharge number for 4-th Li gettering (red) (number 6 in Fig. 3) and 8 hours glow discharge w/o Li (blue) (number 7 in Fig. 3). Equivalent discharge number was determined by the integral deuterium influx. For example the ECRH discharges have higher "weight" during ECRH proportional to the ratio of ECRH to OH power. It is clearly seen that recycling value without litiization significantly increases, but varies in time more smoothly. The time variation may be described rather nice by the sum of three exponents, shown as lines. The first exponent is very fast and has e-fold time one discharge. Such rapid rise of recycling occurred in T-10 at the first discharges of the day irrespectively of lithium. The very rapid decay suggests very low capacity and is consistent with absorption of monolayer on the whole area of chamber, which was clean after the long backing. The second exponent has the e-fold time of 8 discharges. This value is consistent with the volume saturation of the lithium, covering the limiter with 1 μ lithium layer, suggesting the Li/D ratio equal to one. Such deep Li penetration may be connected with the high porosity of the lithium layer on the graphite substrate. The third exponent has e-fold time about 300 discharges. Such long saturation time is natural for the lithium, deposited to the ¼ of the chamber surface. It easily explained by the fact that 90% of lithium deposited to the wall and the deuterium flux to the ¼ chamber is in a factor of 4 lower then to the limiter. Thus this time should be equal 8*10*4=320. So one can conclude from the data of Fig.3 and 4 that the time behavior of recycling implies the volume Li absorption, even at the layer thickness 1 μ and slow Li redeposition due to the low spattering. The analysis of the weighting factors of the three exponents shows the constancy of the factors for the fast decay and for the wall pumping. But the coefficient of the limiter exponent is lower in a factor of 7 after 8 hours of the glow discharge. Taking into account that the duration of the glow discharge was enough long to remove deuterium (which was monitored by the change of the

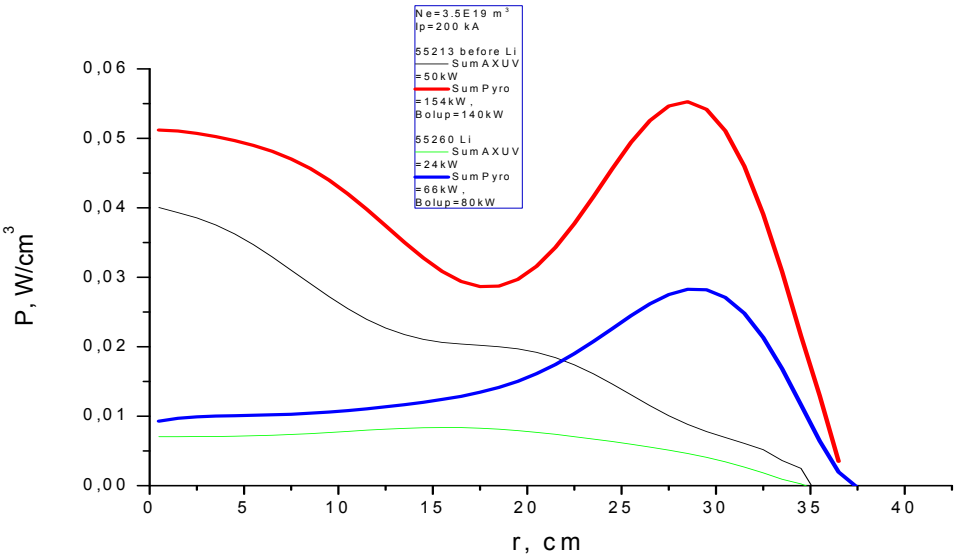

Figure 5. Radial losses before and after Li, measured with bolometers and AXUV

discharge color from white to green), one should suggest that He remove deuterium only from the surface, but not from the lithium volume. Thus He glow discharge has low efficiency to recover all deposited lithium.

The radial distribution of the radiation losses were measured with a set of 16 chords of the semiconductor detectors AXUV and 14 chords of the pyroelectric bolometers. The pyroelectric bolometers measure the total losses, including the neutrals of the charge exchange, while AXUV detectors only radiation losses with the energy higher 10-20 eV. Thus the AXUV detectors have low efficiency at the edge, but should have equal sensitivity with bolometers in the center. The abelized radial profiles of the both detectors before and after litiization are shown in Fig. 5.

One can see that both diagnostics showed significant decrease of the losses in OH discharge. The integral losses decreased in a factor of two in agreement with the integral bolometer, showed in Fig. 3. The pyroelectric bolometers clearly showed that before Li there were two distinct maxima: in plasma center, caused by high Z metallic impurities and at plasma edge, caused by carbon radiation. As the bolometers positioned toroidally 90^0 away from the limiter, the input of the charge exchange neutrals was small. This conclusion is also supported by the fact that reductions of the edge losses were equal for the bolometers (sensitive to neutrals) and AXUV detectors (not sensitive for neutrals). Figure 5 clearly show the reduction of the high Z impurities in a factor of 4, while carbon losses were decreased less, then in a factor of two. This is consistent with the fact that Li cover mainly the some part of the limiter, while the ¾ of the wall was not covered. So, assuming that the impurities influxes from the limiter and the wall are equal, one can expect the impurity decrease in a factor of two. The higher reduction of the metallic impurities can be explained by the decreased sputtering due to the measured lower edge temperature. At the same time carbon influx is less sensitive to the temperature, while the efficiency of carbon radiation should be enhanced due to the decrease of the edge temperature. The lower decrease at the edge also may be due to the rising input of the lithium, but this needs absolute lithium density measurements, supposed in future.

The comparison of the plasma characteristics before Li and after in a reference discharge of 200 kA and density 3.5×10^{19} m^{-3} showed the reduction of the electron temperature in 20% in OH discharges. The central ion temperature was not changed. The comparison of the density profiles showed that with Li they are slightly broader. The edge

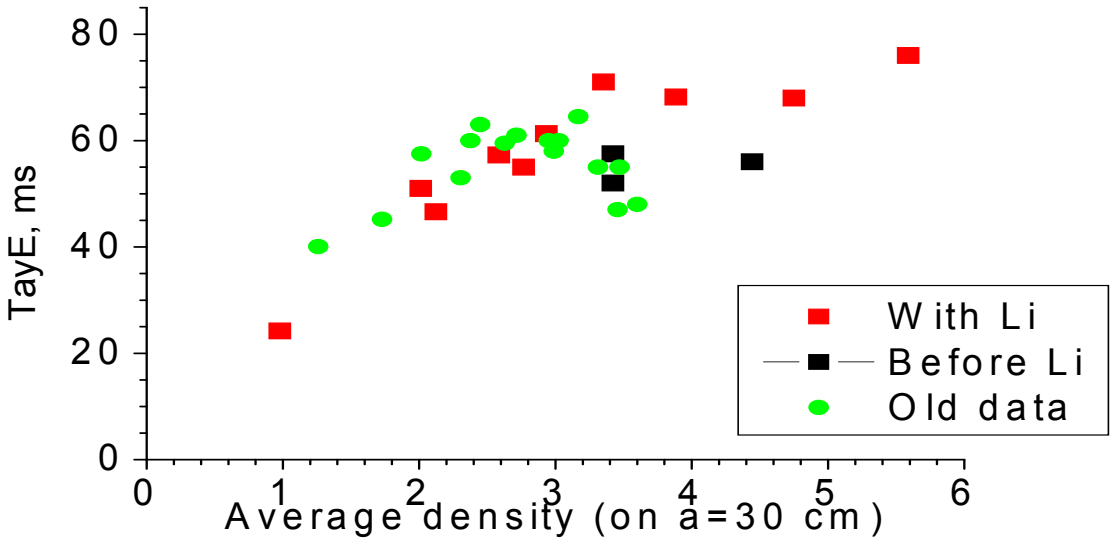

Figure 6. The energy confinement dependence in 200 kA OH discharges on density.

density increase was about 20%. In spite of the decrease of the electron temperature, the energy confinement increased from about 60 to 70 ms. due to the reduction of the heating power as the loop voltage decreased from 1.3 to 1.1 volt. This increase is shown in Fig. 3. The comparison of the ECRH discharges was more difficult due to the different density behavior in time. Typically average density decrease was significantly higher with Li at the beginning of ECRH, but the feedback system return it to the programmed value, while without Li it stays lower. As the confinement depends on density, the comparison was difficult. The energy confinement dependence in OH discharges on density is shown in Fig.6.

The energy confinement with Li is shown by red squares. The values for the reference discharges are shown by black squares and they are in good agreement with the previous data, shown by green squares. One can see that at low densities the old and Li values are close, but with increase of the density the difference appears. The confinement values with lithium are higher than the reference and old data. As the confinement without Li degraded with density the values with Li appeared to be higher more then 50%. At the same time the lithium gettering significantly increases the maximal attainable density from 4.5×10^{19} m^{-3} in the reference run before Li to 5.6×10^{19} m^{-3} (the Greenwald value 7.0×10^{19} m^{-3}). It is should be noted that degradation of the confinement with density rise in old data transferred to slow increase in Li case. The detailed analysis of these phenomena will be done in a future experiments, but it should be noted that in Li case the density was sustained in significant part by the strong gas influx by the valve, while without Li main source was recycling. As in T-10 the plasma is feeded by deuterium in on location, it may significantly decrease the maximal attainable density. In fact, even at lower densities periodical switch on and off the gas influx due to non-proper work of the feedback system, holding the density in average at constant value, caused the synchronous appearance and disappearance of the MARHY and strong variation of the edge temperature. The plasma gas feed spreading over the torus may increase the critical density and improve the confinement.

A special attention in the 2008 campaign was devoted for the disruption characterization with and without lithium. As it was mentioned in JET experiments with beryllium walls [8], the disruptions characteristics changed greatly at critical density. It is consistent with the present day understanding that the time of the current quench should greatly depend on the

rate of plasma cooling by radiation of the impurities and plasma resistance due to impurities, entering plasma after thermal quench. Thus the substitution of Fe and C with Li should increase the current quench time, or, even eliminate it. Unfortunately, from one hand, in present T-10 experiment ¾ of the wall was not covered, which makes experiment more uncertain and, from other hand, such comparison needs a large statistic and well defined conditions, because the characteristics of each disruption may be rather individual. So the detailed investigations will be done in future experiments. Nevertheless, some preliminary comparison was done. The disruption without Li occurred earlier at lower density. In both cases the time sequence includes several pre-disruptions and the final disruption with the current quench. The first pre-disruption without Li caused significant current drop, while in Li case the drop didn't appeare. The jumps of the radiation losses, measured with AXUV in pre-disruptions were much lower with Li. The time of the current quench was less with lithium in particular shot, but this phenomena should be investigated with more statistics in future experiments.

Spectroscopic measurements of lithium lines LiI, LiII and LiIII point out the high screening of Li ionization influx by SOL. The estimated relative ratio of the ionization flux from Li0 to Li+1, from Li+1 to Li+2 and from Li+2 to Li+3 were estimated as 1, 0.01 and 0.0001 respectively. So high screening efficiency may be connected with the low ionization potential of neutral Li and, possibly, with some special transport process. Very important additional information was obtained by the analysis of the TV inspection of the chamber after the experiments. The distinct shadows of the deposited Li were observed on the surface of the rail limiter, shown on the left photo of Fig. 7. These shadows aroused due to the screening of the rail limiter by circular one along the magnetic field lines. This fact unambiguously proved that the evaporated on the limiter Li was spattered by plasma and redeposited back along the magnetic field lines. These three observations: the slow Li migration along the torus (no Li in port D and C with TV inspection); deposited Li shadow on the rail limiter and strong decrease ionization fluxes from LiI to LiIII confirm dramatic screening effect of the limiters. This feature may be very important for the future reactor Li perspective, because it may radiate significant power near separatrix and SOL regions. The lithium radial distribution will be the topic of the future experiments with the CHERS diagnostic.

The chemical transformations were observed after the vacuum chamber opening to atmosphere. The dark blue color of the lithium element and the port walls was observed after 10 minutes. The X-ray spectrum (EPMA) (Fig.7 right top panel), showed the dominant

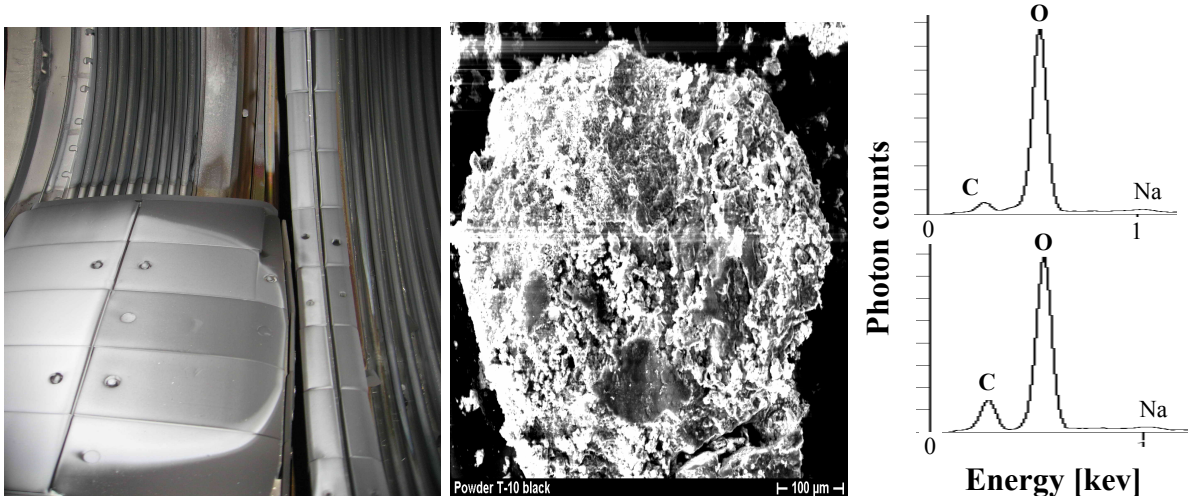

Figure 7. Left photo: the Li shadow on the rail limiter; middle photo: the grain of white Li powder; right panels: SXR spectra for the dark blue (top) and white (bottom) Li stage.

oxygen line. Carbon was 10 times less and nitrogen was absent. One may conclude that at this stage lithium oxide is formed. After two weeks the color became white. The example of the white grain of the Li cover is shown in the middle of Fig. 7. The highly porous structure can be seen. The X-ray spectrum, showed also in this case the dominant oxygen line, but the carbon concentration increased and reached 1/3 of the oxygen one (Figure. 7 right bottom). The nitrogen was not observed again. As the ratio of 1/3 is characteristic for $Li_2(CO_3)$ we can suppose its formation as the final substance (the lithium can't be detected due to wavelength limitation of the used EPMA system).

The inspection of the T-10 chamber with the TV camera after the campaign 2008 revealed the white cover of the walls and limiter in the port "A", where evaporation was occurred. Such cover was not seen in ports "D" and "C", 90^0 and 180^0 away toroidally respectively. These observations support low rate of Li migration along the chamber.

The special attention was paid to the process of chamber conditioning after long exposure of the Li coated chamber to atmosphere. The time for conditioning of the chamber was not longer then before lithium. Thus it is possible to conclude that the presence of Li in $Li_2(CO_3)$ form did not cause additional difficulties with the chamber conditioning.

The T-10 Li-experiment didn't show any problems for ECRH system (the full power 2 MW). The degradation of the spectroscopy quartz windows transmission was not observed.

It is possible to conclude that the T-10 experiments support the results of previous experiments with respect to decrease of recycling and plasma purification. T-10 experiments reveal the volume absorption of the films up to 1 μ and low rate of lithium migration along the chamber. The plasma characteristics strongly depended on limiter condition with respect to saturation with deuterium. The He glow discharge appeared to have low efficiency to recover the lithium in its volume. Lithium gettering was more efficient in decrease of the high Z materials, then carbon. Lithium application leads to some decrease of the electron temperature and slight spreading of the density. In spite of the decrease of the temperature the energy confinement time was increased, especially at the highest densities, due to the decrease of the loop voltage. Lithium increased the maximal density, but the high gas influx needs gas spreading over the vessel. There were no any problems with the chamber conditioning, reliable work of high power gyrotrons and transmission of the spectroscopic windows.

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