# Li experiments on T-11M and T-10 in support of steady state tokamak concept with Li closed loop circulation

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**Abstract.** The paper presents review of the last T-11M and T-10 activity in field of Li experiment in tokamaks. The main attention is spared to realization of concept of closed loop Lithium circulation as solution of plasma facing components (PFC) problem of steady state tokamak-reactor. Realization of this concept demands the decision of three main tasks: Lithium injection into the plasma, Li collection before its deposition on the vacuum vessel and Li returning to the injection zone from the collector. This emitter-collector concept assumes, that the main heat flux from a hot plasma to the PFC ( limiters, divertor plates), can be distributed on all first wall surface by non coronal Li radiation, which should decrease the local heat loads of the reactor PFC. In the last T-11M experiments were successful tested the prototype of steady state Li emitter (limiter) on the basis of capillary porous (CPS) system manufactured from tungsten felt. The experiments with Li collection by lateral sides of rail limiter with W-wings showed that significant part of Li, injected to plasma (~80%), can be collected by this way. T-10 experiments showed that Li migration around the torus from lithiation region is pretty low. The experiment with Li pellet injection in T-10 permitted to find, that probability of Li penetration into the hot plasma core from its boundary is in a factor of 5-10 lower than that of deuterium. This result can explain the effect of plasma cleaning ($Z_{eff}(0)$~1) during tokamak lithiation experiments.

## 1.Introduction

The idea of steady state tokamak use as a volumetric neutron source becomes today a high popularity. Its first reason is "the renaissance of nuclear energetic", which appeared as an answer to the challenges of XXI century. Several needs of nuclear energetic can be solved by the use of the high power independent fast neutron sources. These are: the burning of fission ashes (minor actinides Np, Am, Pu), the breeding of fission reactor fuel ($^{233}$U, $^{239}$Pu) and the independent control of fission reactor operations. The main feature of such neutron sources on tokamak basis should be the steady state (with cycle efficiency >80%) operation regimes.

It is well known, that steady state operation of current tokamaks hinders the inventory of Hydrogen isotopes (DT) and deposition of sputtered materials of tokamak plasma facing components (dust problem). The use of liquid Lithium as the material of plasma facing components (PFC) [1] can be the principal new solution of tokamak first wall problem.

This idea has opponents. The main misgivings are: 1) liquid metal splashing under the JxB forces during MHD instabilities and disruptions, 2) abnormal ion sputtering as a result of plasma-liquid Lithium interaction, 3) heat removal problem with PFC thermal stabilization for the prevention of strong Lithium evaporation and as the final problem of tritium removal from Lithium PFC, 4) steady state cooling of lithium PFC.

Almost all of these questions were solved by the community TRINITI-"Red Star"-"Kurchatov institute" Team activity during the last 12-years (1998-2010yy) [2-5].

The crucial suggestion which allowed to suppress Lithium splashing was based on the idea of compensation of ponder-motive forces in liquid metal by tension forces in capillary channels (V. Evtikhin et al [1,2]). The capillary channels from Mo, stainless steel (SS), V or W manufactured as pressed wire grids were called "capillary pore systems" (CPS). The Li CPS limiters were successfully used firstly in tokamak T-11M (1998 TRINITI) and than in FTU and T-10 experiments [2-5].

Fig.1 presents some results of vessel wall lithiation (covering of first wall by Li film) in T-10 [5 ]. The common effects of such kind operations in all tokamaks from first TFTR experiments are: the plasma cleaning (decrease of Zeff up to one), suppress of heavy impurities and light impurity decrease.

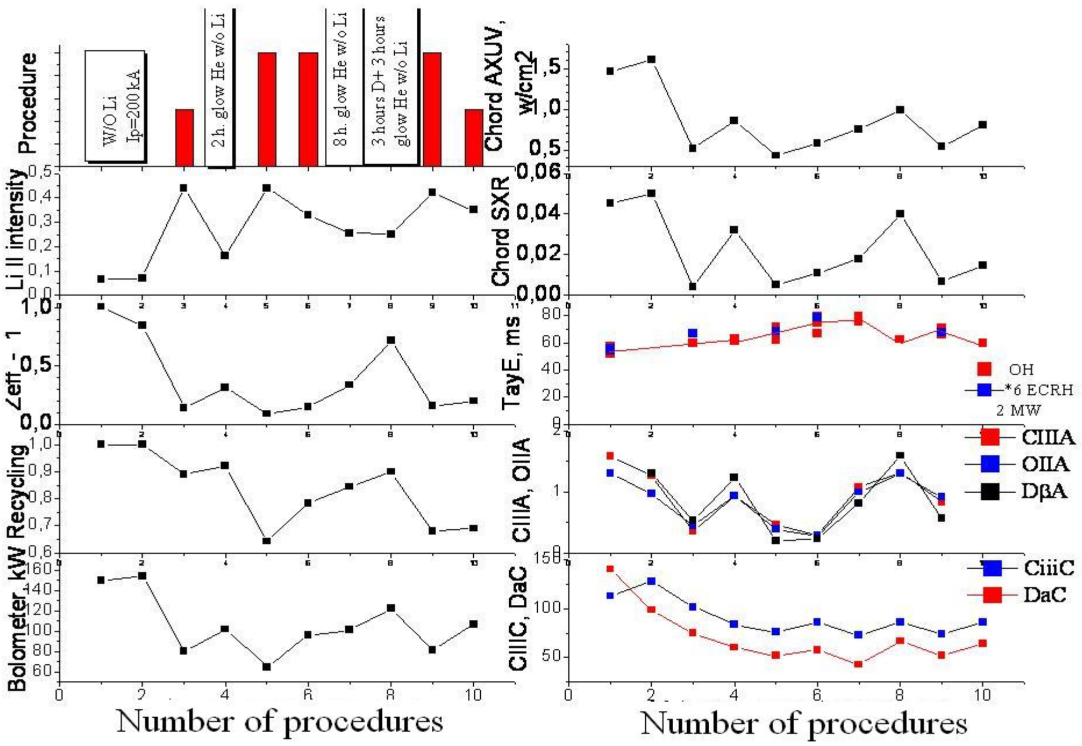


*FIG.1. Evolution of main T-10 parameters (Zeff-1,Bolometrical signal, AUXV and SX signals, Carbon spectral lines intensity) as results of different conditioning procedures: lithiation (gray-red rectangular),He GD and deuterium discharges.[5]*

The main results, which were obtained in Li-experiments with CPS PFC [2-4], are:

1. The surface tension forces in CPS may be used for suppression of liquid Li splashing.
2. The surface tension forces may ensure the PFC regeneration in steady state regime.
3. Erosion of Li PFC in tokamak SOL is close to the level of simple ion beam sputtering of liquid lithium targets;
4. The Li non-coronal radiation (radiation of non full stripped Lithium ions) can cool the tokomak boundary plasma and thus protect the PFC from the high power load during quasi steady state and disruptions regimes (<0.1ms). The main objective of this is a fast Li ions circulating between plasma and the tokamak PFC, which prevents the full stripping of Li-ions up to the coronal model limit and allows, for example, to redistribute almost 80% of total ohmic heating power ($P_{OH}$) on the T-11M vessel wall by lithium non-coronal UV radiation;
5. As a result the solid basis of CPS limiter has high resistance to disruptions;

6. The temperature of Hydrogen isotopes recovery from liquid Li after hydrogen plasma exposition is 320-500$^{o}$C. Tritium can be removed from Li PFC by its heating up to 400-500$^{o}$C;

7. Effect of “Lithium screening” (low $Z_{eff}(0)$ as result of low probability of Li penetration into plasma center) can be a basis of concept of so-called closed Li loop [3,4] in steady state tokamak operations with Li emitter and collector.

This Lithium emitter-collector concept supposes the Lithium circulation loop development close to the vessel wall and plasma periphery with the main hot (400-700$^{0}$C) limiter as a Li-emitter and the secondary limiter as a colder Li-collector. (In the main current Li-experiments the surface of tokamak chamber plays a role of Li-collector ).

This concept has four characteristic steps: Li-emission from PFC into the plasma (emitter), the boundary plasma cooling by non-coronal Li radiation, Li ions capture by the collector before their deposit on the tokamak vessel wall and Li return from the collector and the first wall into emitter or plasma column again.

The first step of Li limiter investigations was the study of properties of lithium limiter as Li-emitter. In early T-11M experiments [4] it was established that the lithium emission has a strong dependence on emitter temperature. The useful interval of Li-limiter temperatures sunk in SOL tokamak plasma can be chosen from Li-melting point (180$^{0}$C) up to the approximately 700$^{0}$C.

Spontaneous liquid metal-plasma instabilities can originate close to the limiter surface if the limiter temperature increases up to 700$^{0}$C. The next subjects of T-11M and T-10 experiments were investigation of Li migration in the tokamak vessel and its collection by different kind limiters. Summary of these investigations is the main subject of this paper.

## 2.T-11M and T-10 operations

The T-11M (R/a=0.7/0.25m, Jp=70-100kA, $B_T$=1.2T, Δt=0.2s) and T-10 (R/a=1.5/0.35m, Jp=200-300kA, $B_T$=2.5T, Δt=1s) are the classical tokamaks (Fig.2) .

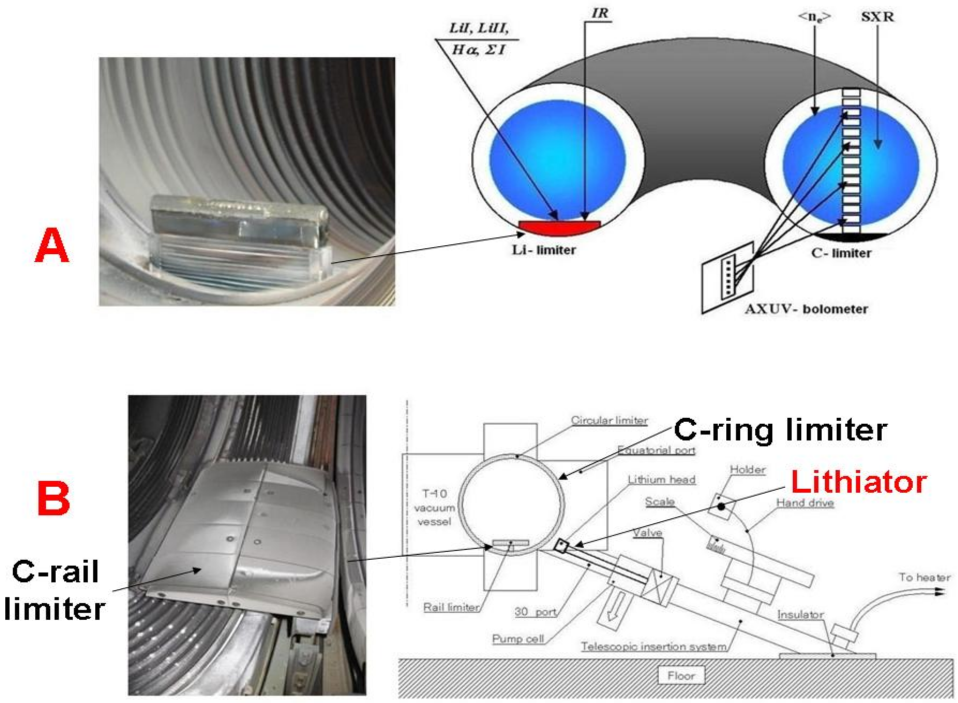


*FIG.2. Schemas of Li experiments in T-11M(A) and T-10(B).*

Two local movable rail limiters were used in the T-11M experiments (Fig.2,A): Lithium CPS (a= 0.23-0.17m), and graphite (C-limiter), [2-4]. The lithiation of the first wall was performed in T-11M by the two ways: between tokamak shots by He GD with Li limiter as anode and by Li emission from Li limiter during shot. The Lithium migration in the SOL region and its collection by limiters were studied by Li light emission from movable probe (C-limiter), which could be considered as a recombination target for the incident flux of Li ions [6] and by the postmortem analysis of the witness-samples located on a surface of Li- limiter.

T-10 has two limiters: a massive graphite rail limiter (Fig.2,B a=30cm) and a circular graphite limiter (a=33cm), positioned close to it. The lithiation of the first wall was performed in T-10 by heating of movable Li CPS evaporator during tokamak conditioning (limiters and vessel wall gettering). The Li penetration into SOL of T-10 was determined by photometric measurements of translucent $Li_2CO_3$ layer on the surface of the rail graphite limiter after experiments. Li migration around the torus was estimated during discharge by measurement of Li recombination radiation (LiII). The absolute calibration of Li flux was performed by the use of Li pellet injection.

*2.1 T-11M experiment.* Main aims of the last T-11M experiments were to test the new "W-Li" limiter with W- capillary porous structure (CPS) as prototype of steady state Li-emitter and the investigation of Li collection by lateral surfaces of "W- Li" –limiter with W-wings as the first step of Li loop development.

Fig.3 presents the scheme of the new "W- Li" –limiter with water cooling ($200^0$C) which can permit simultaneously the Lithium preheating to melting temperature ($180^0$C) and cooling during and after plasma shot. The CPS of the new limiter was made from W-felt. The lateral sides of the new limiter were coated by tungsten wings for Li collection, as it was in the previous limiter version [7].

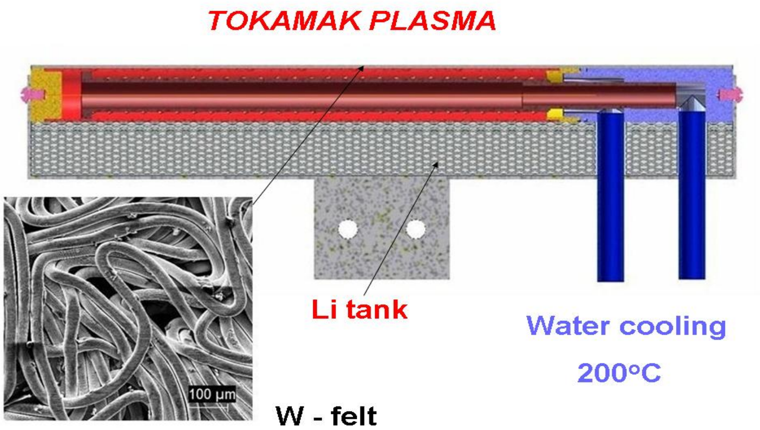


*FIG.3 Schema of steady state "W-Li" limiter of T-11M*

The new limiter was tested successfully during equal 1000 shots of T-11M with power load equal to 10 $MW/m^2$ and shots duration equal 0.2sec. About 20% shots were finished by disruptions. The main difference from SS-limiter was increase of heat conductivity of active CPS layer up to 2-3 times, than in SS case.

Fig.4 presents the common view the plasma facing surfaces of electron and ion sides of "W-Li" without any sings of plasma –limiter interactions. The total Li weight loss of "W-Li" limiter during the vessel wall lithiation procedures [3] and during plasma operations was about

0.5g. The total amount of lithium, collected by lateral surfaces of the limiter and W-wings was about 0.2g, which was, by the account, close to the total Li amount lost by limiter in process of plasma-limiter interaction during the all test campaign. The absolute measurements of surface distribution of Li deposit were performed by post mortem chemical analysis [7] of witness-samples, positioned on the limiter sides.

*FIG.4. Head of "W-Li" limiter after exposition in 1000 shots of T-11M, e-side (top) and i-side (down).*

2.2 *The chemical finding of the absolute lithium amount in the witness-samples.* Lithium has a strong chemical activity to the basic components of air - nitrogen, oxygen and water vapor. During the extraction of witness-samples from limiter lateral surfaces Lithium deposit has an inevitable contact with Nitrogen and the Oxygen of the air and forms mix **$Li_3N$:$Li_2O$=3:1** [7]. As a result the analyses of the absolute amount of the Lithium deposed on a sample, represents a serious problem. In T-11M experiments it was been resolved by the following way: the witness-samples were subjected to exposure in plasma and then were got on air during venting the tokamak vessel and seated in the boiling water.

Various chemical compounds of Lithium, which can form during the plasma exposure of witness-samples and their transportation through air, enter the following reactions with boiling water: **$2Li + 2H_2O = 2LiOH + H_2$** , **$Li_3N + 3H_2O = 3LiOH + NH_3$** , **$Li_2O + 2H_2O = 2LiOH + H_2$** , **$Li_2C_2 + 2H_2O = 2LiOH + C_2H_2$.** Alkali **LiOH** appears always as their finished product**.** **LiOH** amount in the water solution and, accordingly, the initial lithium maintenance in the witness-samples were determined by a known method of chemical titrimetric analysis. Absolute calibration of the method was carried out by the test Lithium sample.

2.3 *Lithium collection by lateral sides of Li limiter.* Fig.5 shows the distribution of collected Li deposit across o lateral side of "W-Li" limiter from the rand of its Li reservoir to the vessel wall. It is obvious, that Li distribution has minimum close to the limiter head, which had high temperature during plasma shot, increases into the limiter shadow and drops to the vessel wall with e-fold length about 2-3cm. This limiter region is as a main collector of Li losses, which should be returned in future again to the emitter head of the limiter. The measurements of Li flux distribution in shadow of limiter during discharge confirm this expectation.

Fig. 6 (I) [6] shows the small radial ($Z_C$) distribution of the lithium flux along the torus in the shadow of T-11M Li-limiter during middle part of plasma shot. It was obtained from recombination probe dates. It is obvious, that Li flux radial distribution has two exponential views – with e-fold length about λ=2.2cm and 0.7cm. It was supposed, that the second exponent with λ=0.7cm was a secondary effect, connected with Li flux intersection by semi ring ICRH antenna, positioned on the low magnetic field side with $Z_c$= 22cm. The delay plasma column up to 1cm outward (+1cm) confirmed (Fig.5 (I) dashed line) this supposing.

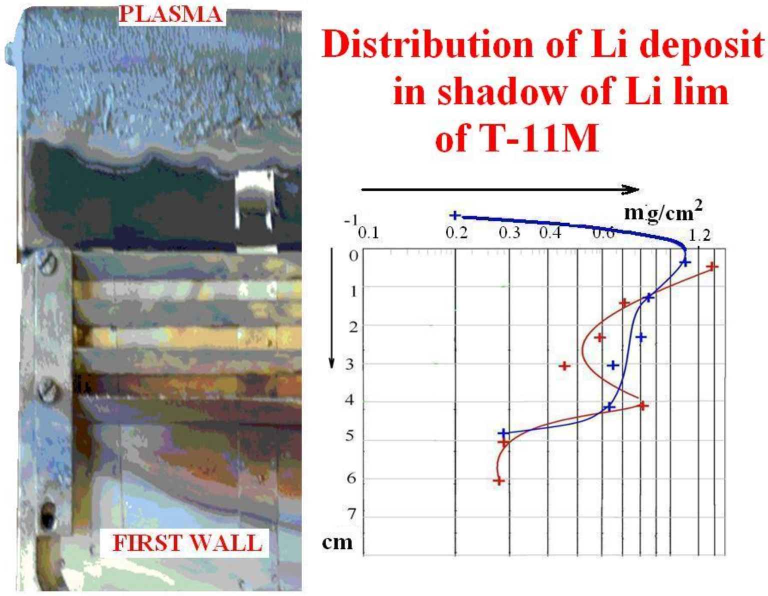


*FIG.5. View to e-side of "W-Li" limiter after exposition (left) and distribution of Li deposit (right) in shadow of limiter (middle of limiter). The vertical strip is the witness – sample.*

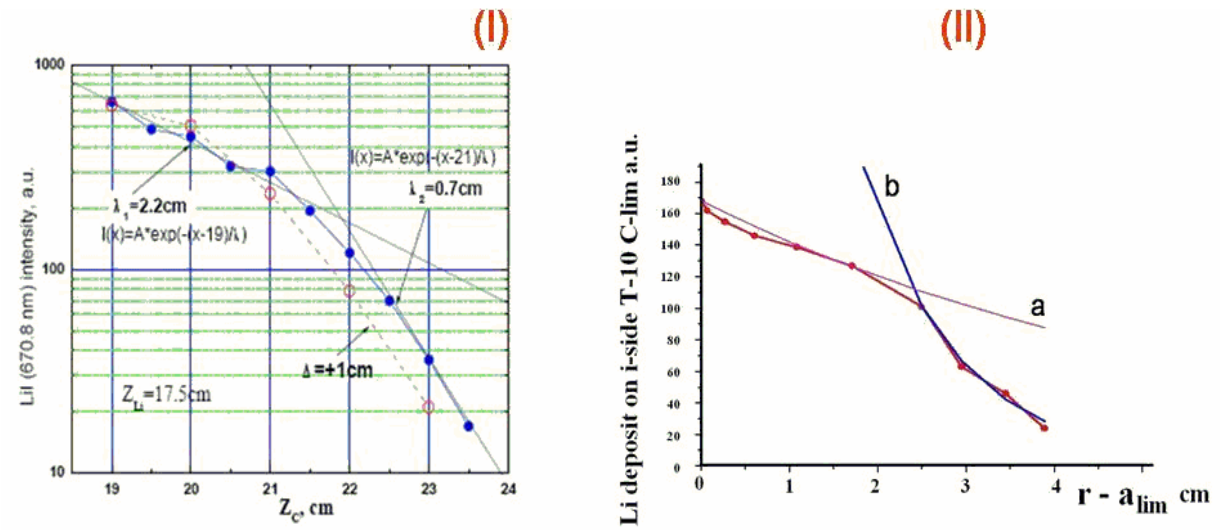


*FIG.6.(I) - The small radial ($Z_C$) distribution of the lithium flux along the torus in the shadow of T-11M Li-limiter (middle of discharge). (II)- the small radial distribution of the lithium deposit on C-rail limiter of T-10.*

The numerical model of the Lithium transport in SOL [6] showed that the measured Li distribution can be explained by abnormal diffusion with coefficient approximately 0.5 Bohm.

*2.1 T-10 experiment.* Fig. 6 (II) shows the small radial distribution of the lithium deposit on C-rail limiter, positioned close evaporator, by photometric measurements of translucent $Li_2CO_3$ layer on the limiter surface (second lithiation campaign). It is clear visible again the two exponential views – with the e-fold length λ about 6cm and 1 cm. The second exponent with λ=1cm is result of Li flux intersection (collection or reflection) by circular graphite limiter. This coincidence with T-11M permits to suggest an idea of two CPS limiters – rail and circular in its shadow for collection of Li rest, migrated to the vessel wall.

One of the important characteristic features of the Li behavior in T-10 is the very slow migration of Li deposit along the tokamak chamber. There were four T-10 campaigns with 14 Li gettering procedures. The estimated total amount of Li introduced into the chamber was about 20g. But neither spectroscopy, no chamber inspection after venting detected any Li traces at the chamber side, opposite to Li gettering port. This phenomenon definitely connected with the high efficiency of the Li screening by the limiters.

This was proved qualitatively by the comparison of Li behavior during the first T-10 lithiation campaign, where Li covered mainly the wall vessel and the second campaign, where the rail and circular limiters were also covered by Li. The increase of the Li spectral lines around the torus in factor of 3-4 was observed in the second campaign with respect to the first one. It means that Li, deposited to the vessel wall had low probability to enter the plasma, obviously, due to limiters screening.

The comparative analysis of the Li distribution over the surface of the rail limiter after the first and the second campaign was carried out in order to prove the hypothesis of the Li screening by limiters. As Li converts to the final white dust of $Li_2(CO_3)$ after two weeks of exposure to atmosphere, so its distribution was estimated by the degree of local "whiteness". It was found that after the first gettering, when the primary Li source was vessel wall, Li was deposited only at the rail limiter edges. After the second gettering, when the primary Li sources were both limiters and wall, Li was deposited mainly at the center of rail limiter in contrast to the first gettering. That can be the additional evidence of low probability of Li penetration during discharge from vessel wall to the plasma.

The absolute Li outflux from plasma was estimated by means of the injection of Li pellets by pneumatic gun. The increase of the plasma density and the decay rate was controlled by eight channel interferometer. Assuming that all plasma density increase and its decay were consequences of Li injection, it was possible to calculate the Li outflux from the plasma. As the experiments showed that in stationary conditions Li influx was significant only near the limiter (where evaporation was made), so the brightness of the Li lines away from the limiter should be determined only by recombination of Li outflux. Thus the increase of LiII intensity after pellet injection can give information about the stationary Li outflux. The intensity of the LiII line increased approximately in two times. So the Li outflux from the pellet was equal to the steady state one. The data for lithium outflux was calculated from the decay rate of the total number of particles from the measured density profile. The decay rate was estimated at 45 ms after injection, when the plasma parameters perturbation was relaxed. The value of integral Li ions outflux was $2\times10^{20}$ ions/s. This value was approximately 10% of the integral deuterium influx. Assuming the equal penetration probability of Li and D to the core one can estimate $Z_{eff}$ about 1.6. As the experimental value of $Z_{eff}(0)$ = 1.1-1.2 [1], the penetration probability of Li in a factor of 3-6 lower than that of deuterium. It should be noted that the real Li penetration probability must be much lower (supposed 5-10), as the influxes of carbon and iron decreased only in a factor of three [5] and still must be the main contributors to $Z_{eff}$. The more accurate measurements of Li penetration probability will be obtained in future T-10 experiments with CHERS diagnostic.

## 3. Conclusions

1.During the last Li experiments on T-11M and T-10 in support of steady state tokamak concept with Li closed loop circulation the new steady state "W-Li" limiter was successfully tested in 1000 shots of T-11M. Clear visible advantage of new limiter is up to 2-3 times higher heat conductivity of active layer, than in SS case and high resistance to runaway and disruptions

2.The T-11M experiments with Li collection by lateral sides of rail limiter with W-wings showed that significant part (~80%) of Li, injected to the plasma and diffused than out can be collected by this way.

3.T-10 experiments showed that migration of Li deposit around the torus from lithiation (gettering) region was pretty low. Li films was absent in opposite vacuum port of T-10.

4.As was showed by use Li pellet experiment in T-10 the probability of Li penetration into hot plasma core is in a factor of 5-10 lower than that of deuterium.

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