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Experimental test of the system of vertical and longitudinal lithium limiters on T-11M tokamak as a prototype of plasma facing components of a steady-state fusion neutron source

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Abstract

A new functional model of the prototype of closed Li circuit for protection of the chamber wall was tested in T-11M tokamak by simultaneous use of the vertical Li limiter as an emitter of Li and a new longitudinal Li limiter as its collector. Such technological scheme can be suggested for the steady-state fusion neutron source on the tokamak basis. During plasma shots the cryogenic target of T-11M collected Li flow emitted by the vertical capillary Li limiter almost completely (up to 80%). These Li and hydrogen isotopes were captured and extracted outside the tokamak vacuum chamber without venting of the vessel which is a key requirement for the use of Li in the steady-state tokamak reactor.

Keywords: tokamak, plasma facing components, liquid lithium, limiter, divertor

(Some figures may appear in colour only in the online journal)

1. Introduction

1.1. Lithium for fusion neutron source on the tokamak basis

The creation of an industrial fusion neutron source (FNS) with steady-state (more than 80% of the operational time) production of fast neutrons with the power flux density not lower 0.2 MW m^{-2} seems to be the first step of commercial use of magnetic deuterium-tritium (DT) fusion [1].

As is shown in the analysis [1] a steady-state tokamak of energy classes between JET and ITER can be used as a FNS of a different scale. Its neutron load of $0.2\text{--}0.5 \text{ MW m}^{-2}$ could be received approximately by one half of neutral beam (NB) injection and by one half of thermonuclear output as it was in TFTR and JET.

1.1.1. P_H/S limit. In [1] it was noted that the maximum achievable neutron power, which determined the quality of the FNS based on the current tokamak, should be determined by the 'permissible' average thermal load of its first wall $p_H = P_H/S$. Here P_H is total power of plasma heating, or during steady-state operation it is the power of plasma cooling, and S is the



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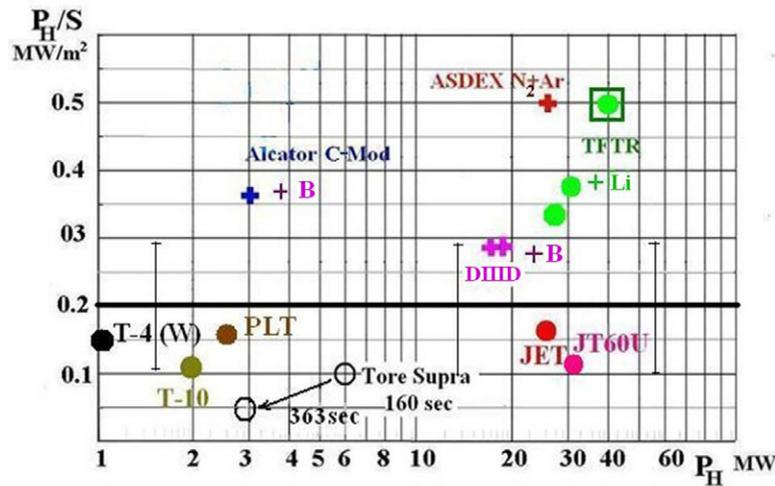


Figure 1. P_H/S – P_H diagram for several known tokamaks: TFTR [3–5], JET [6], JT-60U [7], PLT [8], T-4 [9], Asdex-U [10], Alcator C-Mod [11], DIID [12], T-10 [13], Tore Supra [14].

surface of the first wall of plasma facing the tokamak vessel. As noted in [1] during more than 50 years of experimental activity on tokamaks from early Russian TM-2 and T-3 up to JET the maximal achieved parameter P_H/S in the high-performance shots remained almost constant between 0.2 ± 0.1 MW m^{-2} , despite the fact that maximum value P_H and plasma temperature were increased over this period almost 200 times. It is interesting that in experiments with the protection of the first wall by low Z coating and with cooling plasma periphery by additional impurity injection, P_H/S parameter can increase up to 0.4 – 0.5 MW m^{-2} . This constancy of maximal ‘permissible’ values of P_H/S cannot be accidental; it seems to be evidence of the existence of the hidden phenomenological ‘permissible’ limit P_H/S for the high-performance tokamak shots. For ITER this parameter can be in the ‘permissible’ interval near 0.2 MW m^{-2} [2]. Figure 1 presents maximum values of the parameter P_H/S obtained in high-performance shots in a number of well-known tokamaks [3–13] with significantly different sizes and powers of plasma heating P_H (P_H/S – P_H diagram), with low Z coating and most successful cooling the plasma periphery by $N_2 + Ar$ (Asdex-U [10]) injection.

Although the nature of this important phenomenological limit is not completely clear, its visible sensitivity to the impurity injection in scrape-off layer (SOL) suggests that it can be caused by direct plasma-wall contact, which is known to weaken progressively by cooling of plasma periphery in particular through the impurity radiation.

1.1.2. Li as plasma facing components material. As we can see in figure 1 the highest values of ‘permissible’ P_H/S on current tokamaks were usually achieved with the protection of the first wall by the low Z materials (Li, Be, +B) and with cooling of the plasma periphery by the use of non-coronal radiation of impurities, which were injected into the divertor SOL during the discharge ($N_2 + Ar$ in Asdex-U [10]). Unfortunately, impurity injections usually accompany an increasing of $Z_{eff}(0)$, which is not allowed for FNS, where the neutron production can be achieved at one half by NBI and at one half

by fusion. It can be chosen as a primary prototype of FNS. In TFTR experiments with Li injection $Z_{eff}(0)$ was equal to 1 – 1.3 unlike $Z_{eff}(0) \approx 2$ – 2.6 without it [4].

As one can see from figure 1, injection of Li on TFTR allowed raising parameter P_H/S up to a level 0.3 – 0.4 MW m^{-2} [4] (compared to 0.2 MW m^{-2} in experiments with the pure graphite bumper-limiter). However, further increase in P_H/S up to 0.5 MW m^{-2} [5] (square in figure 1) led to the development of small disruptions and the subsequent degradation of a discharge. Exceeding the limit $P_H/S \approx 0.2 \pm 0.1$ MW m^{-2} without Li injection is usually completed in a number of tokamaks by the development of a large or small disruption.

Li is widely used in tokamak practice to improve the stability of the tokamak discharge under conditions of strong plasma heating (figure 2). That is the next argument to use Li in steady-state FNS and for the further development of Li technologies, which is the main subject of this article.

The next important motive for the use of Li technology in the steady-state FNS is the potential ability of liquid Li to capture hydrogen isotopes with their subsequent return by heating up to 450 °C– 550 °C. This feature of Li significantly distinguishes it from graphite, usually used in modern tokamaks for the first wall protection from direct interaction with plasma.

Figure 3 presents, in arbitrary units, the velocities of hydrogen removal from Li and graphite samples as a function of their temperatures (TDS characteristics) after bombardment by hydrogen ions. The main difference between Li and graphite lies in the fact that the hydrogen removal from Li demands a much lower temperature than from graphite. It can be expected that at a temperature higher than 550 °C Li can be almost free from hydrogen. This effect opens a possibility of carrying out selective pumping of ‘excessive fuel’ (D and T) and achieving a closed circuit of fuel and Li in a steady-state tokamak reactor.

1.1.3. Steady-state loop of Li-circulation. A principal scheme of closed loop Li-circulation in a steady-state tokamak is shown

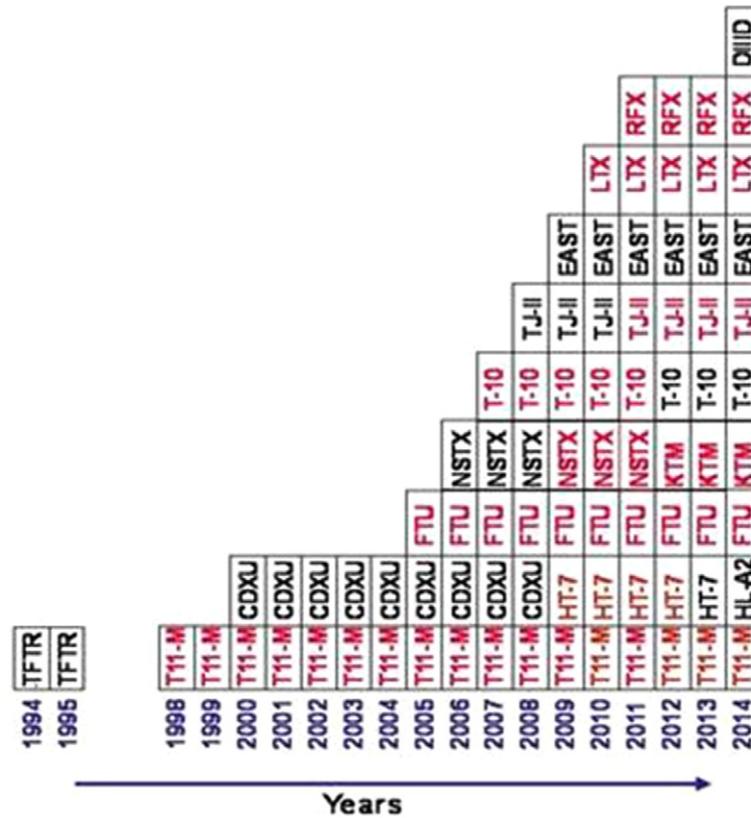


Figure 2. Lithium progress in the fusion investigations. Each rectangle represents a fusion device with Li technology, red with Li CPS, black without Li CPS.

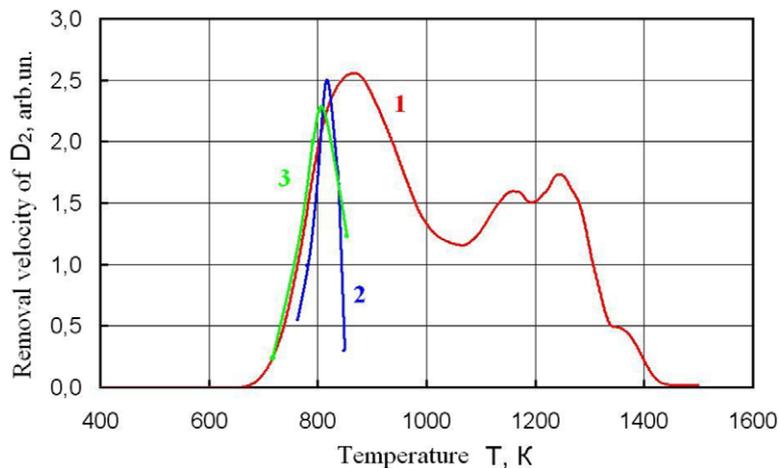


Figure 3. 1-Dynamics of hydrogen removal by heating from: C-deposit—1 [15] and Li—2 [16], 3 [17, 18].

in figure 4 [21]. The first aim of closed loop Li-circulation is the prevention of Li accumulation in the vessel during the steady-state tokamak operation or decrease of total Li amount in the vessel of the tokamak-reactor according to security demands. For this reason it was decided to inject Li atoms into the periphery of hot plasma column by a special local Li emitter and to collect the Li ions, diffused from the plasma column towards the first wall (Li wastes) by special collectors placed in the shadow (SOL) of the emitter (figure 4). In this scheme the main part of the heat flux from hot plasma into plasma facing components (PFC) will be distributed on all the surface of the vessel wall

(or its main part) by non-coronal radiation of injected Li [19], which is localized near the plasma boundary. Simultaneously some part of injected Li deposited as the Li film on the first wall can protect it from direct plasma bombardment in transient tokamak events like edge local modes (ELMs) and disruptions. Li captured by the collector can be returned back to the emitter in liquid state. As we can see from figure 3, if the temperature of the Li collector is lower than 400°C the collected Li can capture hydrogen ions from SOL (pumping of ‘excessive fuel’) and then they can be removed from the tokamak vessel together with the Li stream for future release. Note that the steady-state

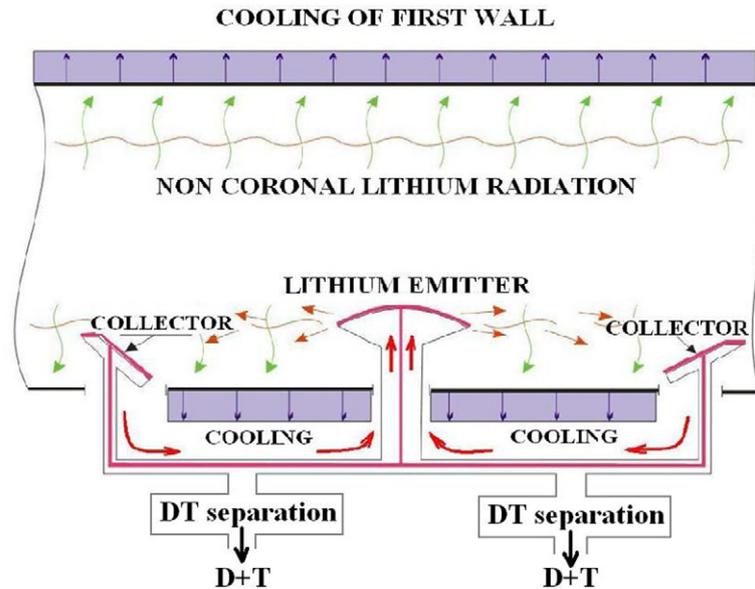


Figure 4. Lithium flow diagram in tokamak with lithium emitter-collector PFC and DT separation.

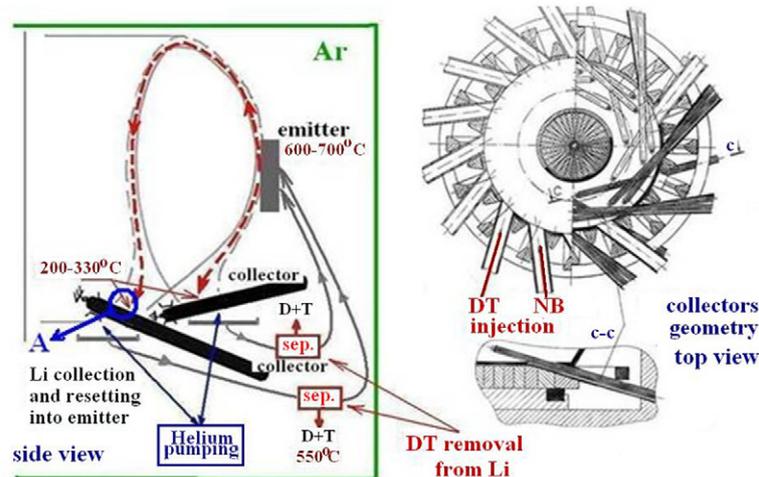


Figure 5. Left—the principal scheme of the Li circulation loop for the steady-state FNS. Arrows—traveling of Li ions in divertor SOL. A—region of most probable Li collection (from JET experience [23]). Right—the top view of the typical component arrangement of the FNS tokamak with removable type rods divertor targets [24].

operation of the FNS does not require complete removal of hydrogen isotopes from the Li stream.

In the FNS tokamak with ITER-like geometry (figure 5) a divertor should be used as the Li collector. The divertor system, the first wall of FNS tokamak and its pumping system must ensure: 1—removal of the power load of the first wall preferably through non-coronal Li radiation at the main part of the first wall surface [19], 2—continuous output of the excessive fuel (tritium and deuterium) and ash-helium from the vessel with probability of their separation, 3—the possibility of periodic replacement of main elements of PFC without long technological breaks in the operation cycle of the neutron source. We believe that all such requirements can be solved by using liquid Li as a main material of PFC interacting with plasma. Li films ($\sim 3\text{--}10\ \mu\text{m}$) can perform functions of a protector of the solid surface of the vessel wall from its direct bombardment by energetic ions of hot plasma in ordinary and transient

regimes. Such protection seems to be a method of providing a long-term resource of the FNS first wall. The real constraint will be imposed by the liquid Li splashing and erosion of the solid state PFC elements during their contact with Li. The best solid material in this capacity appears to be tungsten.

A useful technological way to avoid Li splashing of liquid PFC during tokamak transient modes was proposed by Evtihin *et al* (1996 [20]) in the form of a Li filled capillary porous system (CPS). The Li film on the surface of the capillary solid matrix (with cells $\sim 10\text{--}50\ \mu\text{m}$) made of stainless steel, Mo, or tungsten ‘felt’ protects it from hot plasma erosion, as was shown by numerous experiments (for example [21, 22]). On the other hand the capillary forces in the pores of the matrix prevent liquid Li from splashing. This idea has already been used successfully in a number of magnetic fusion plasma systems (figure 2). In the course of its further development, it can be used as a basis for the establishment of the steady-state

FNS. The main challenge is the creation of stationary loop circulation of Li near the plasma boundary and the vessel wall.

Figure 5 [21] shows schematic diagrams of one of the ways of using vertical Li emitters and collectors of Li as a set of removable CPS rods placed along the toroidal magnetic field of a tokamak (longitudinal limiters) for ITER—like FNS. The difference of emitter and collector functions is provided by varying the depth of rod insertion in the ‘hot’ zone of the plasma column. The emitter should be heated up to 500–700 °C for active Li emission and it must fill the plasma boundary (divertor SOL) with Li ions providing radiant heat transfer to the vessel wall of the reactor through Li non-coronal radiation [22]. The ‘surplus’ Li should be captured by the collector as liquid metal (200–350 °C) and can be returned to the emitter. Liquid Li will be saturated by fuel (tritium and deuterium) and it should be cleaned and separated from them during transportation by heating up to 450–550 °C. This fuel cleaned by such method can be directed in the injection system (in NBI, for example). Thus it will close the fuel circulation loop. The arrows in figure 5 (left) show traveling directions of Li ions in the divertor SOL. As it was shown in recent JET-ILW experiments [23], the most part (almost 90%) of eroded Be (material of JET-ILW first wall) was deposited very locally on tails close to the inner divertor leg. The main region of Be erosion in JET-ILW should be placed on the external side of the vessel similar to the position of the Li emitter in figure 5. We can suppose by analogy that the main part of Li flow in a magnetic configuration like figure 5 can be collected in the same place. It is marked in figure 5 by ring and letter A.

Helium not captured by hot Li could be removed from the divertor vessel by the means of ordinary vacuum pumping systems. Finally the scheme presented in figure 5 would allow:

- decreasing of local thermal loads on all PFC elements of tokamak by non-coronal radiation of Li ions with significant redistribution of heat flow out of plasma at the vessel wall, and thereby with the mitigation of the thermal load on PFC;
- implementing a closed circulating cycle of working gas (deuterium, tritium, helium) in a steady-state mode.

The Ar (or He) hermetic shell should be established for protection of Li from chemical contact with air during possible accidents with water or during routine technological operations.

1.1.4. T-11M earlier activity. For many years T-11M experimental activity (figure 2) was focused on the development and testing of main elements (emitters, collectors) of closed loop of Li for FNS based on the tokamak. The main subjects of this activity are plasma interaction with different kinds of CPS Li limiters which are applied as emitters and collectors of Li and a long-term evolution of Li PFC under bombardment by deuterium plasma.

In particular, it was found that the main part of total Li flow from a liquid Li limiter into T-11M plasma returns to the limiter [25]. Thus, almost steady-state circulation of Li is established between the limiter and plasma. The part of Li flow that goes to the chamber wall and lateral sides of the limiter

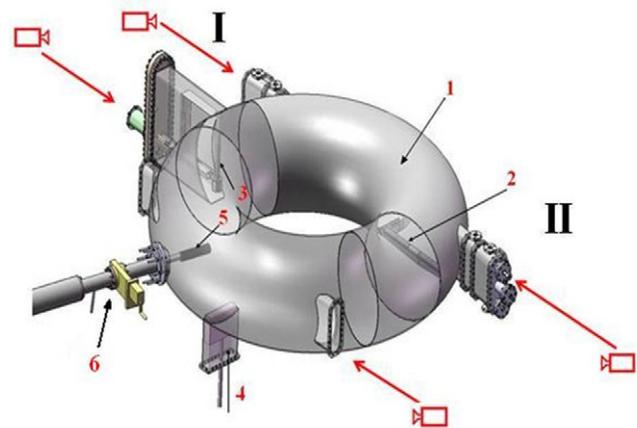


Figure 6. T-11M and limiter positions. 1—the chamber; 2—the longitudinal limiter, 3—the vertical limiter, 4—the C-limiter, 5—the cryogenic target, 6—the vacuum lock, I, II—the lines of sight of the video camera.

is equal to the total consumption of Li (primary flux) and is relatively small compared to the main circulating part (secondary flow). We can believe that the physical nature of such active reflection of Li ions from the hot liquid Li surface can be Li self-sputtering as a consequence of the increase of limiter temperature up to 500 °C and higher. It was shown [25], for example, that Li secondary flow which circulated between the rail limiter and plasma boundary of T-11M exceeds up to 4 times the primary Li flux. This effect of limiter circulation permits decreasing Li consumption up to 5 times during tokamak operations. As it was shown further in the ordinary shot, approximately 90% of primary Li flux was collected by the lateral sides of the T-11M rail limiter with approximately 10% deposited on the vessel wall. The deuterium glow discharge experiment, which was performed to test the degradation of Li emissivity of CPS Li emitter after its long-term exposition in deuterium plasma [25], showed that such degradation is insignificant. That means that CPS Li-limiter can be used successfully as Li-emitter during the steady-state tokamak operation. The simultaneous using of the vertical Li limiter T-11M as an emitter of Li and a new longitudinal Li limiter as Li collector similar to its combination presented in figure 5 was tested in the last T-11M experiments. The main attention was paid to Li collection by different Li limiters. The cryogenic target technique was used for Li collection during discharge and Li removal from the tokamak vessel wall *in situ* throughout the experiment without venting of the vessel. This paper is an overview of recent results of Li experiments on T-11M. Section 2 presents the experimental conditions and description of the main experimental results. Section 3 provides the discussion and section 4 presents the summary.

2. T-11M experiments

All experiments were performed on T-11M circular tokamak [19–22] with $R/a = 0.7/0.25$ m, plasma current $J_p = 70 \div 100$ kA, $B_T = 1.2$ T with a current duration $\Delta t = 0.15\text{--}0.2$ s, plasma density $1 \div 6 \times 10^{19}$ m⁻³ and $T_e(0) = 0.2 \div 0.5$ keV.

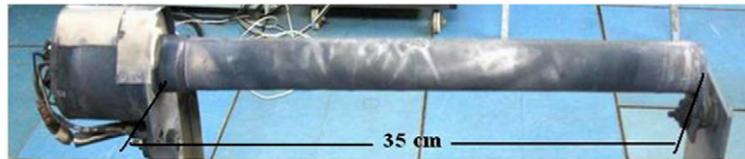


Figure 7. Vertical limiter after plasma exposition in 1000 shots.



Figure 8. Longitudinal limiter before the Li filling and plasma exposition. W—felt section is the protector of the limiter from runaway electrons.

T-11M tokamak (figure 6) has three limiters: two Li CPS limiters (2, 3) and one graphite (C-limiter) which was used as a recombination target for measurements of Li distribution in limiter SOL. Arrows show the directions of view from a color video camera Baumer HXG20C for localization of areas of plasma-wall-limiter interaction and spatial distribution of Li non-coronal radiation.

The primary lithiation of the vessel wall was carried out by heating two Li limiters of longitudinal and vertical geometry during HeGD (helium glow discharge) operations [19, 25]. Early investigations showed that during one typical shot of a regular T-11M discharge, approximately 0.25 ± 0.05 mg of Li was deposited on the cold lateral sides of limiters and about 0.02 mg was deposited as ‘lithium waste’ on the wall [25]. Relative values of neutral Li flows from limiters were registered by the emission of Li spectral lines LiI. The absolute values of ion fluxes were estimated from the analysis of Li deposition on witness samples and different kinds of limiters by using a chemical method, which was described in detail in [26]. In the process of the chemical analyses the samples were placed in boiling distilled water. All chemical compounds of Li with air components that occurred during transportation of witness samples through air should be transformed to alkaline LiOH by water. The total amount of Li deposited on the sample was found by determination of the pH value of the resulting solution by a titration method, or by using the more precise method of flame photometry (see for example [27]). The same procedure was used for determination of the total amount of Li deposited during the experiment with the cryogenic target.

The main subject of T-11M Li program was long-term studies of plasma compatibility with different Li limiters on CPS basis (figure 2) as future variants of divertor targets or rod type limiters. It should be noted that the divertor targets of rod type and tokamak limiters of rail type on Li CPS basis have one important advantage: their long ‘cold’ ends ($T < 400$ °C) should operate during tokamak discharge as collectors of Li which can be returned in the ‘hot emission spot’ ($T > 400$ °C) by capillary forces along the rod [19]. As a result the Li convection near the Li CPS should increase [28]. Recently vertical ($l = 0.35$ m) and longitudinal ($l = 0.55$ m) Li CPS limiters have been tested in tokamak T-11M as versions of future Li emitters and collectors [21]. The main aims of these

investigations were: study of mutual influence of both limiters, determining e-fold length for neutral Li in plasma periphery and measurements of e-fold length Li ion penetration in limiter SOL. The cryogenic target was used for estimation of the efficiency of Li collection by an adsorbing target placed in the shadow of the vertical Li emitter during tokamak discharge.

2.1. Limiter compatibility

The experimental studies of the vertical CPS Li limiter [25] as an emitter of Li and longitudinal CPS limiter (figures 6(2), (3)) as a collector/emitter of Li were successfully performed in order to test the scheme like figure 5 on tokamak T-11M. Figures 7 and 8 show the views of the vertical Li limiter after its test in 1000 ordinary T-11M shots and the longitudinal limiter before tokamak operation. The tungsten section (figure 8) was used as a local protector of the longitudinal limiter from its bombardment by runaway electrons.

Figure 9 shows the longitudinal limiter in the geometry of T-11M vessel and a limiter view after plasma exposition. The expanded length of the plasma-limiter contact is clearly visible.

‘Cold ends’ of the limiter show Li deposit collected during plasma exposition. (Last limiter expositions were performed in ‘cold regime’ with limiter temperature lower than the melting temperature of Li 180 °C.)

Figure 10 shows the view of the longitudinal limiter during plasma discharge in visible light by a Baumer HXG20C video camera from direction II with time exposure $4 \mu\text{s}$. The light emission of neutral Li and Li^+ can be divided into visible light by color of emission LiI in general rose–orange (670.7 nm, 610.3 nm) and green LiII (548.47 nm). LiI emission (670.7 nm)—rose light is localized near the limiter surface from the ‘ion side’ of the limiter (‘ion side’ is facing towards the direction of current I_p , ‘electron side’ is opposite it). The green emission corresponds with the Li^+ ions strong line LiII (548.47 nm). This non-coronal Li emission is localized near the ‘separatrix’ and SOL region. In figure 10 the ‘ion side’ of the longitudinal limiter is positioned at the left surface of the limiter. In this case the vertical limiter operated as a main Li emitter and was placed well left. Different sections of the longitudinal limiter are noted in figure 10 II by numbers 1, 2 and 3. In the process of the plasma experiment one part of the Li

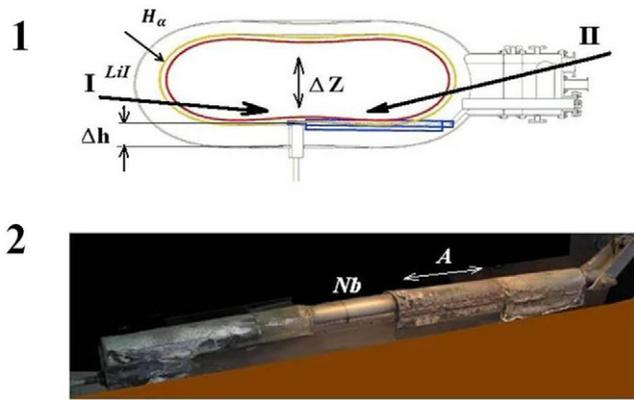


Figure 9. The longitudinal limiter in the chamber of T-11M. 1—the drawing of the longitudinal limiter in geometry of T-11M, I and II are sight views of the limiter in visible light, H_α and LiI emission. 2 is views of the longitudinal limiter after plasma exposition in approximately 1000 shots. A—W is felt section with Li and signs of plasma interaction. Nb is section of the heat accumulator without Li CPS. It does not demonstrate any signs of interaction with plasma.

CPS section (2) was removed up to the Nb surface of the heat accumulator [21] of the limiter. Assuming the full reflection of Li flow from the Nb surface (figure 10 II) the comparison of LiI emission from the Li CPS and the Nb section provides a qualitative estimation about collection ability of CPS surface for Li ions from plasma. Accordingly number 1 indicates W-CPS section with Li content, number 2 is the clean Nb section and number 3 is the Li section with CPS based on stainless steel. The vertical line A marks the ‘hot spot’ of the longitudinal limiter which is an area of its most active heat interaction with the plasma column (from post mortem analysis).

The observation of LiI emission from the surface of both longitudinal and vertical limiters during plasma shots with the use of a spectral filter shows that the penetration depth of neutral Li atoms into the plasma column from the emitter is equal to 1.5–2 cm. This depth can be accepted as a lower value of the cooling depth of the plasma edge during its interaction with the Li limiter which is a very important parameter for calculations of the plasma–lithium interaction in FNS.

At a simultaneous operation of the vertical and longitudinal limiters their interaction will strictly depend on their relative position. Figure 11 shows the relative positions of both limiters and plasma column. LiI V marks LiI intensity from the vertical limiter as an indicator of Li emission and LiI II marks the same from the longitudinal limiter (figure 9).

Figure 12 shows the behavior of the main parameters of T-11M discharges in cases of different positions of both limiters relative to the plasma column. In the case of #34234 (case III figure 11) the vertical limiter is placed into the common limiter SOL 1.5 cm from the edge of the plasma column (case I figure 11) and the longitudinal limiter operated as a main Li emitter. On the contrary the vertical limiter in the case of #34242 (case II figure 11) is shifted into the plasma column at 1 cm and performs almost completely the role of the main Li emitter. The behavior of plasma density is an indicator of plasma conditions in both cases. Figure 12 shows that the discharge performances in both cases remain

roughly identical. Thus both limiters are almost identical in the role of the Li emitter.

Measurements of the penetration depth of Li in plasma SOL (figure 13) by the Li recombination [26] on the vertical movable C-limiter (figure 6(4)) showed that the e-fold length of Li in the SOL is minimal (1.5 cm) in case I (figure 11) where both limiters work simultaneously and grows to about 2.9 cm with the activity of only one longitudinal limiter. This is a clear indication that a further increase in the number of collectors, as is suggested by the scheme in figure 5, will reduce Li penetration in SOL, and its ‘waste’ on the wall.

Shot #34242 (figure 12) corresponds to position II of figure 11 when the vertical limiter operated as a main Li emitter and the longitudinal limiter operated as the collector of Li, which simulates the steady-state FNS scheme in figure 5.

The cryogenic target located in the shadow (SOL) of the vertical limiter was used in the T-11M experiment as an additional limiter-collector. The experiment was performed with a primary aim to estimate the quantity of Li which circulates in the shadow of limiters during plasma shots.

2.2. Investigations of lithium collection by the cryogenic target in T-11M experiments

The position and the scheme of liquid N_2 cooled Li collector in the shadow of vertical Li limiter of T-11M are shown in figure 6(5) and in figure 14. Figure 14 presents photos of the head of the cryogenic Li target before (A) and after (B) collection experiments. Cooling of the target by liquid N_2 was applied for more effective Li capturing.

Figure 15 II presents the distribution of captured Li in the middle part of the target head along the small radius r in SOL for ‘ion’ (A) and ‘electron’ (B) sides of the target. Li deposition on the target surface demonstrates typical features of Li deposition on the cold lateral sides of Li limiters: strong asymmetry between ‘ion’ and ‘electron’ sides of the limiters and a typical two-hump form of Li distribution along r [21]. The second maximum is most likely to be a consequence of return flux of Li from the vessel wall into the SOL of the limiter. The same distribution of Li deposition can be expected in the case of the longitudinal limiter.

During T-11M experiments the cooled target collected about 60 mg of Li (see figure 15 III) in 200 regular shots. That is approximately equal to the total assumed losses of Li (0.25 ± 0.05 mg per shot) on the coldest parts of the limiters and the wall in previous T-11M experiments [19]. The total amount of Li collected in the shadow of the vertical limiter increased proportionally to time up to 30 s of integral plasma exposition (0.15 s \times 200). It is noteworthy that all Li collected by the cryogenic target can be removed (figure 6(6)) outside the tokamak vacuum vessel through the vacuum lock and could be regenerated later without disturbing the tokamak operation cycle. If we take into account the accuracy of our measurements, we can say that a rather high (up to $70 \pm 10\%$) extraction of total Li flows directed during the plasma shot from the edge of the hot (10^6 K) plasma boundary to the vessel wall was achieved on T-11M.

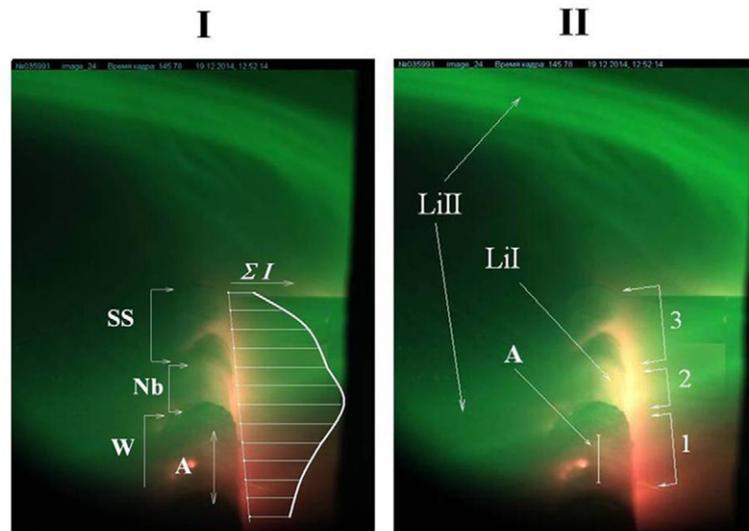


Figure 10. View of the longitudinal limiter during plasma discharge in visible light from direction II (figure 9) in ordinary T-11M plasma shot. I— ΣI -distribution of the red light (LiI) intensity along limiter, II—view of limiter and Li emission around it. A—W-felt area with the maximal heat contact of limiter with plasma.

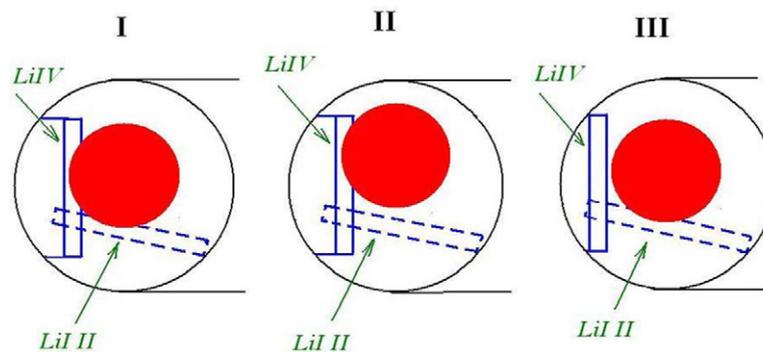


Figure 11. Relative positions of the vertical limiter, projection of longitudinal limiter and plasma column.

3. Discussion

The extraction of erosion products of PFC from the vessel of a steady-state tokamak without interrupting its operating cycle should be the first demand to PFC-divertor system of FNS. The most crucial element of such a system is the collector of erosion products. As we can see from the experiments with the cryogenic target in T-11, M Li flows in the shadow (SOL) of the main limiter are distributed well locally and can be effectively collected. This behavior of Li deposition is like the behavior of eroded Be in JET-ILW [23]. It is obvious that the same property will have a magnetic configuration, presented in figure 5. It is possible to use the surface of liquid Li with CPS for collection of Li ions in a steady-state regime, as was proposed in figure 5. A similar kind of limiter configuration corresponds to case II which was presented in figure 11. One can see that the emission of neutral Li from the vertical emitter (LiIV) is maximal and Li emission from the longitudinal limiter (LiII) is minimal in these cases. The low intensity of LiII can mean that in this case the longitudinal limiter works mainly as a collector of Li ions, therefore the reverse flow of neutral Li from its surface into the plasma is low. A simple

reduction of the Li ion flux from the plasma to the surface in the new position of the longitudinal limiter could be another explanation.

A part of CPS with Li protection of the longitudinal limiter was removed away from the main area of the energy contact with plasma and thereby replaced by pure Nb (heat accumulator of figure 9(2)). The pure Nb surface with no signs of Li deposition (figure 9(2)) proves that in general it served as a reflector for the incident flow of Li ions. Being ‘reflected’ from Nb, the flow of Li ions from the plasma to the limiter returned to the plasma in the form of neutral atoms. Accordingly their LiI intensity should be proportional to the flow of Li ions on Nb. Thereby the LiI intensity near the treated area is an indicator of local Li ion flux from the plasma to the limiter.

As we can see from figure 10 I and II non-coronal (green) radiation of Li ions (LiII, $\lambda = 549$ nm) is localized near the walls of the discharge vessel, while the neutral Li glow (red, LiI, $\lambda = 671$ nm) is localized on the limiter near its ‘ion’ side. As it was stated earlier, the greatest deposition of Li is located on the ‘ion’ side. As we can see from figure 10 maximal brightness of red and orange emission is observed in the area of the Nb section. The fact that the limiter CPS sections with Li shine

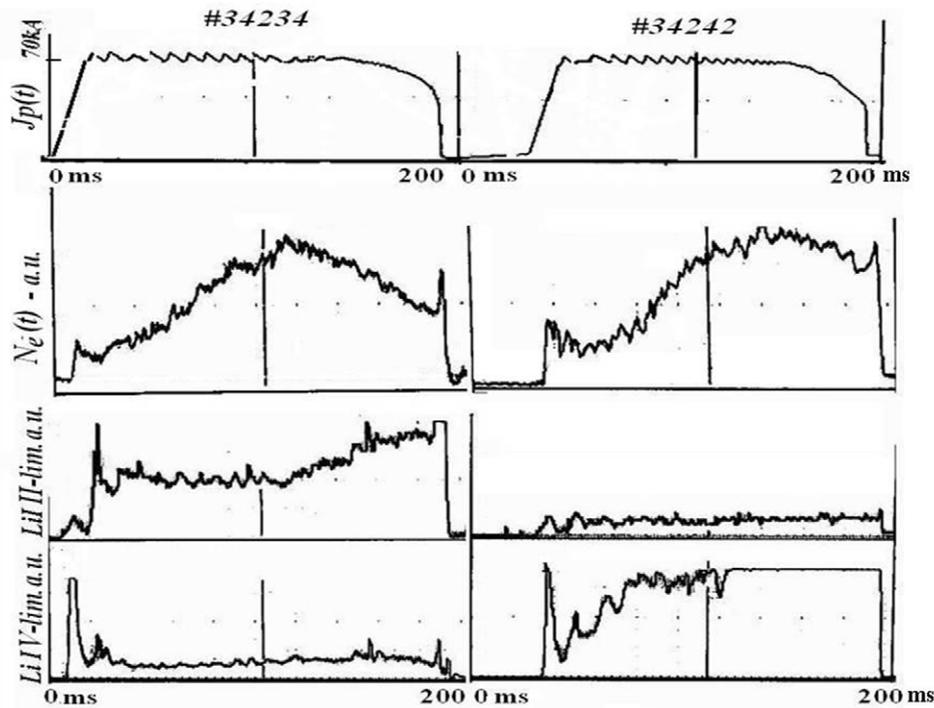


Figure 12. Two T-11M shots with different relative positions of both limiters. #34234—III type and #34242—II type in figure 11.

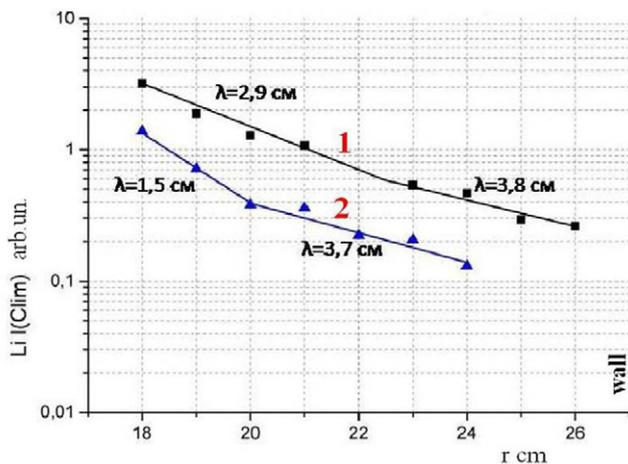


Figure 13. Lithium penetration in SOL ($r = 18\text{--}27$ cm), 1—with one longitudinal limiter, 2—with both limiters.

much lower means that the incident Li flow is reflected from them much weaker than that falling to the niobium target. In this case, CPS sections with liquid Li operated preferably as a collector of the flow of Li ions. Thus the longitudinal limiter, which was placed in the discharge vessel of the T-11M in the shadow of the vertical Li-emitter, demonstrated clearly prominent collector properties of the liquid Li surface in relation to the flow of Li ions.

What is the temperature range in which liquid Li can act as a collector of ion fluxes of Li and hydrogen? In the case of Li flow this temperature is in the range from 200 °C to 450 °C while the self-sputtering coefficient of Li exceeds 1. To determine this range for hydrogen an additional experiment with the exposure surface of the longitudinal Li limiter, pre-heated

to the temperature of 200 °C and 400 °C in the steady-state hydrogen glow discharge (HGD) duration 1 h in 10^{-1} Pa of H_2 and voltage 200V was performed on T-11M. After each exposure the longitudinal limiter was heated up to 500 °C at constant speed pumping of the vessel. During this heating the rate of hydrogen removal from the Li surface was determined by hydrogen pressure in the vessel (thermal desorption spectroscopy (TDS) characteristics). Pa H_2 dynamics in the process of heating is shown in figure 16. Case 1 corresponds to the HGD exposition of pre-heated limiter at 200 °C and case 2 corresponds to the HGD exposition at 400 °C. Curves 3 and 4 show temporal behavior of limiter temperature during H_2 removal in both cases.

One can see that peak 1 corresponds to the hydrogen removed from the Li collector into the vacuum vessel under heating from 200 °C up to 400 °C. That means the preferable temperature of the Li collector in figure 5 should be 200–330°C and operation temperature of the Li-H separation sections can be in the range of 500 ± 50 °C.

4. Conclusions

In T-11M a new functional model of the prototype of closed Li circuit was tested for the protection of the vessel wall by simultaneous use of a vertical CPS Li limiter T-11M as an emitter of Li and a longitudinal Li limiter as a collector of Li ions.

It was shown:

1. The e-fold length of neutral Li penetration in plasma periphery near the active part ('hot spot') of the Li CPS longitudinal limiter is equal to 1–2 cm. This depth of penetration can be accepted as a lower valuation of cooling

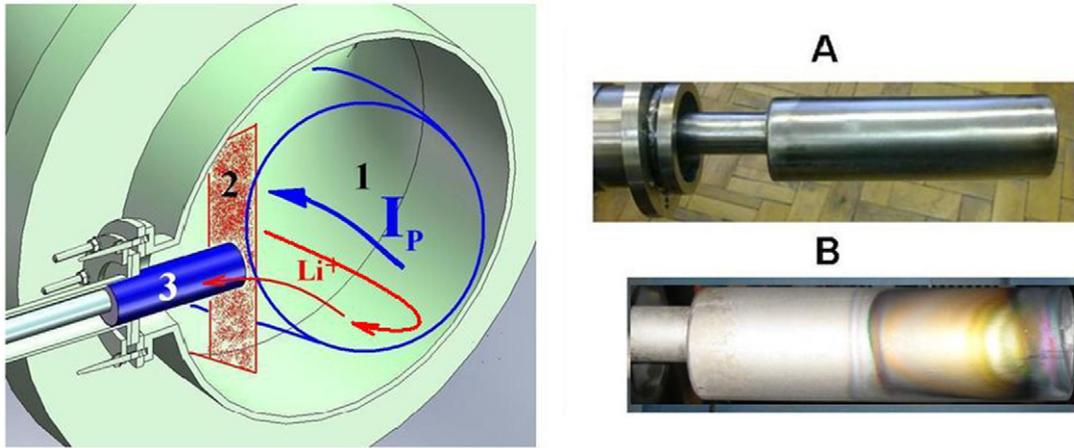


Figure 14. The cryogenic target in T-11M, 1—plasma, 2—the vertical limiter, 3—the target, A—view of head of target before lithium collection, and B—after collection experiment with clear visible Li_3N film on its surface.

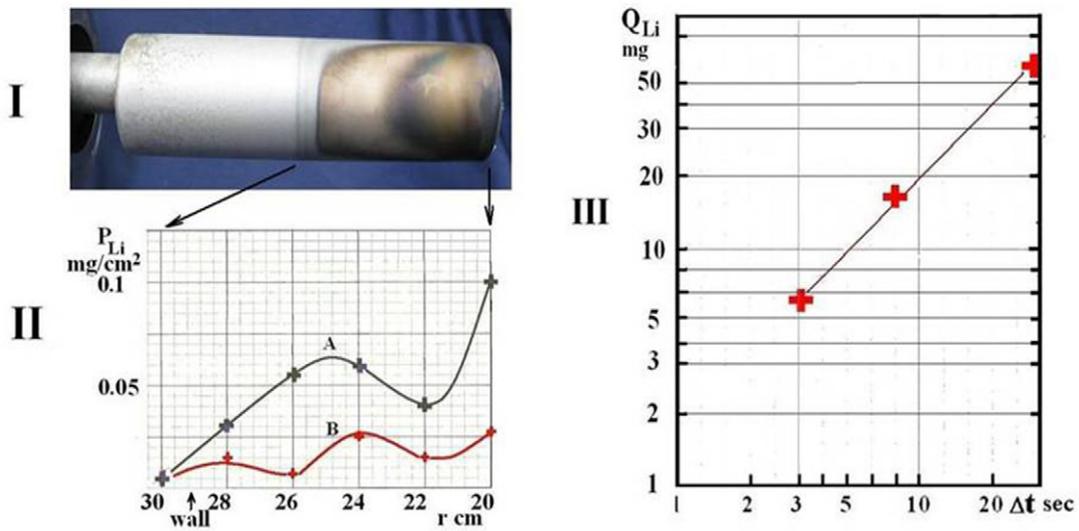


Figure 15. I and II—lithium distribution on the target surface, A—on the ‘ion’ side, B—on the ‘electron’ side, III—the evolution of the total amount of collected lithium, as a function of integral plasma exposition.

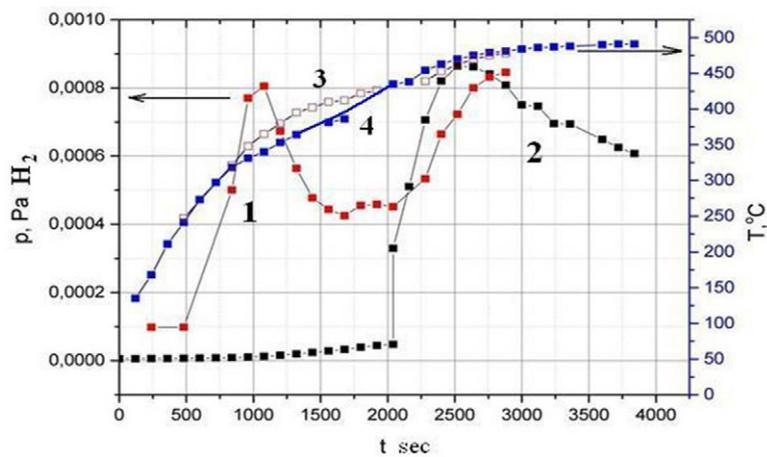


Figure 16. Pa H_2 dynamic in the process of heating of longitudinal limiter after exposition in hydrogen plasma under 200 °C (1) and 400 °C (2). 3 and 4— $T(t)$ dynamics in both cases.

- depth of plasma edge during its interaction with the Li limiter.
2. The e-fold length of Li ion penetration in limiter SOL is equal to 1.5–2.3 cm depending on the relative position of both Li limiters.
 3. Up to $70 \pm 10\%$ Li emitted by the vertical capillary Li limiter during plasma operations was collected in T-11M by a movable cryogenic target placed in limiter SOL and removed outside the tokamak vacuum vessel without interrupting tokamak operation.
 4. The longitudinal Li limiter which was placed in the shadow of the vertical Li limiter/emitter has demonstrated the collection ability of the flow of Li ions in SOL of the emitter.
 5. The preferable temperature of the Li collector in a steady state FNS should be 200–330°C and the operation temperature of Li-H separation sections should be in the range of 500 ± 50 °C.

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