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Li applications for the plasma control in a steady-state tokamak with prospects towards Fusion Neutron Source (FNS)

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Introduction. The DT fusion neutron source (FNS) on the base of tokamak seems as the most realistic candidate for the commercial using of fusion in the next thirty years [1]. The DT FNS with neutron surface load 0.2-0.5 MW/m^2 is of interest for the programme of light water fission reactors (LWR) as a method of waste management by burning of long-lived transuranic radionuclides (minorities) and breeding of fission fuel. The main requirements to quality of such FNS are: (a) the steady-state regime of neutron production (more than 80% of the operational time), (b) the mean surface load of the fast neutron power flux should be greater than > 0.2MW/m^2 with a total neutron power > 10MW (c) [1]. That means the FNS project, based on the tokamak concept, will have a visible perspective under condition of successful improvement of the only current tokamak properties. These are: the steady–state operations with a closed DT circulation, the He removal and decrease Z_{eff} up 1-1.3. The current tokamak experience shows that the most serious obstacle to successful use of tokamak as FNS will be the hard limit of the first wall surface load p=0.1-0.2 MW/m^2 ($p=P_H/S$), which seems, as universal [1]. But, as was shown by some tokamak experiments [1,2,3] it can be mitigated by use of liquid Li, as material of plasma facing components (PFC).

However the use of the liquid Lithium PFCs in tokamak experiments meets with a number of specific problems related to the interaction of liquid metal with hot plasma. The most serious technological problem of liquid Li application in tokamaks **is** the lithium splashing under the JxB forces during MHD instabilities and disruptions that can be solved by using of the Lithium **C**apillary **P**orous **S**ystem (CPS) manufactured as a solid (W, Mo, Stainless Steal) capillary matrix, filled by the liquid Lithium [4]. The preferable matrix material for longtime operation is W. The tokamak limiters on the basis of Lithium CPS were successfully tested in the T-11M, T-10 and FTU experiments [2,3,4].

The high local heat loads on Lithium CPS can be smoothed by so-called "non-coronal Li radiation", which is the enhanced radiation of not fully stripped Li ions circulated between plasma boundary and Li PFC [4]. In the T-11M experiments, for example, the lithium non-coronal UV radiation [2] of plasma boundary redistributed almost 80% of the total ohmic heating power (P_{OH}) which should flow to the tokamak limiters on the T-11M vessel wall similar to well known heat tube technique.

This radiation cooling the plasma periphery is enhanced by a so-called "Lithium screening" effect, what means the accumulation of injected Li ions near the plasma periphery [2,4] with poor penetration in the plasma center. The effect of the plasma periphery cooling by the Li non coronal radiation was chosen as a physical basis of the closed Li loop [2] concept (so-called emitter-collector concept, Fig.1), which supposes the creation of a steady-state closed loop Li-circulation near the plasma boundary between Li emitters and collectors with aim of protection of tokamak PFC from local overheating in steady state operations and sometimes during a hot plasma outbursts (like ELMs, for example).

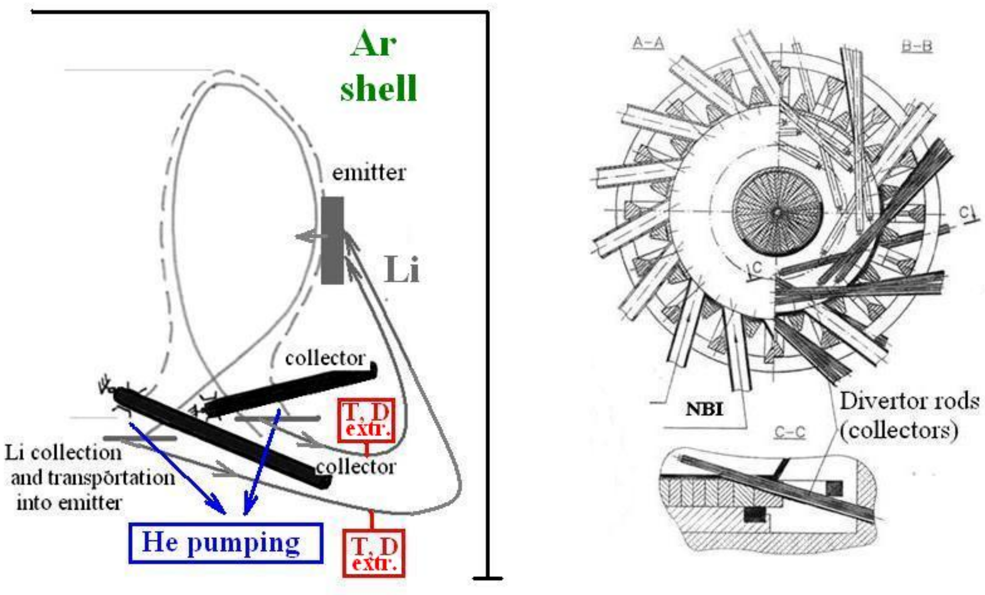

Figure1.Scheme of Li FNS with the Li loop. Left – across-section, right – top view [4].

Fig.1 shows some version of steady-state ITER-like FNS with a closed Li loop. Such loop maintains the removable Li CPS rail emitter, touched in divertor SOL and extended lithium divertor plate consisted from numerous removable Li-CPS rods placed tangential to the axis of toroidal magnetic field. Such Li-CPS rods should play a role of Li ions collector (T~250-350^{0}C) with simultaneous capturing of D^+ and T^+. After DT extraction (by heating the liquid lithium stream up to 500-550^{o}C) the purified Li will be transported back to the emitter by pump. He atoms, which can't be captured by hot (> 100^{o}C) lithium surface can be pumped directly from the divertor volume. All lithium FNS should be surrounded by Ar or He hermetic shell to prevent Li contact with air gases during accidents.

As we can see from Fig.1, two main elements are crucial in the Li loop scheme – the lithium emitter and the collector. The first one was subject of previous investigations on T-11M, FTU and T-10 [2,3,4]. The main subject of the last investigation in T-11M was the lithium collection process, in particular the lithium collection in shadow of Li emitter by the cold target. The main scheme of T-11M (R/a=0.7/0.27m, J_p<120kA, Δt=0.15-0.2s [2]) experiment with vertical CPS limiter used as Li-emitter and the longitudinal CPS limiter, which can be used as Li-collector or emitter, is presented in Fig.2.

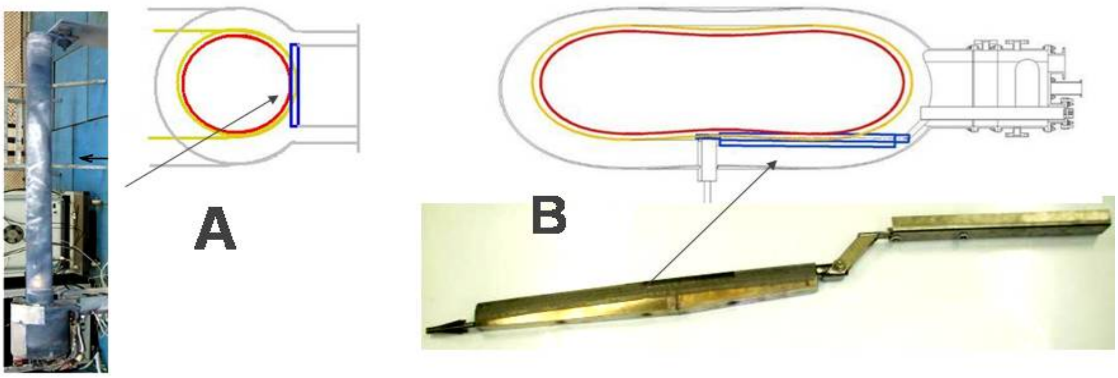

Figure.2 Left - vertical limiter after ~ 1000 plasma shots and A – T-11M across-section with it. Right – longitudinal limiter and B- longitudinal T-11M section.

Lithium collection by the cooled target. The massive cooled target (L=20cm, d=6cm) as the equivalent of future CPS collector (Fig.3) was used for the investigations of Li migration from the vertical Li-limiter (emitter) to collector in T-11M experiments. This target cooled by the liquid nitrogen was placed in shadow (SOL) of the vertical Li-emitter of T-11M (Fig.3). During the plasma shots such target acted as a cryogenic pump towards the lithium atoms and ions. Simultaneously the Li-deposit played the role of the getter towards the hydrogen isotopes (in future tritium) bombarding the target. After exposition in the series of regular plasma shots such cooled target with collected lithium and hydrogen isotopes can be removed from the tokamak chamber without its venting through the vacuum lock with followed measurement of the lithium deposition and retained hydrogen isotopes. The left side of the Fig.3 presents the scheme of the cryogenic target (collector) in shadow of the vertical lithium limiter of T-11M. The right side of the Fig3 presents the view (I) of head of cooled lithium collector ("ions side"-be facing away from direction of current I_p, 1) after 50 plasma shots, which were equivalently to 7.5 seconds (50 shots x0.15s) of steady state T-11M operations. The brown color of the deposit is a consequence of Li_3N formation after the contact of Li with air. The right side (II) presents the distribution of the lithium deposition in the middle part of target head along the small radius r for “ions” (A) and “electrons” (B) sides of the target. The lithium deposition on the surface of the cryogenic target demonstrates the typical features of the lithium deposition on cold lateral sides of lithium limiters: strong asymmetry between “ions” and “electrons” sides of limiters, which can be indicator of tokamak plasma rotation in the ion side, and typically two-wave form of lithium distribution along r. This clear visible second maximum is most likely the result of lithium flow back from chamber wall to the hot plasma column during the plasma shot.

As was established by measurements of Li deposit, the total amount of lithium collected by cryogenic target was close to the total weight losses of vertical Li limiter (up to 80%) during regular plasma shots. The total weight of the deposition increased well proportional to time up to 30 seconds of integral plasma exposition (0.15s x 200shots). That seems as important argument pro reality of used scheme of lithium circulation in a steady state FNS.

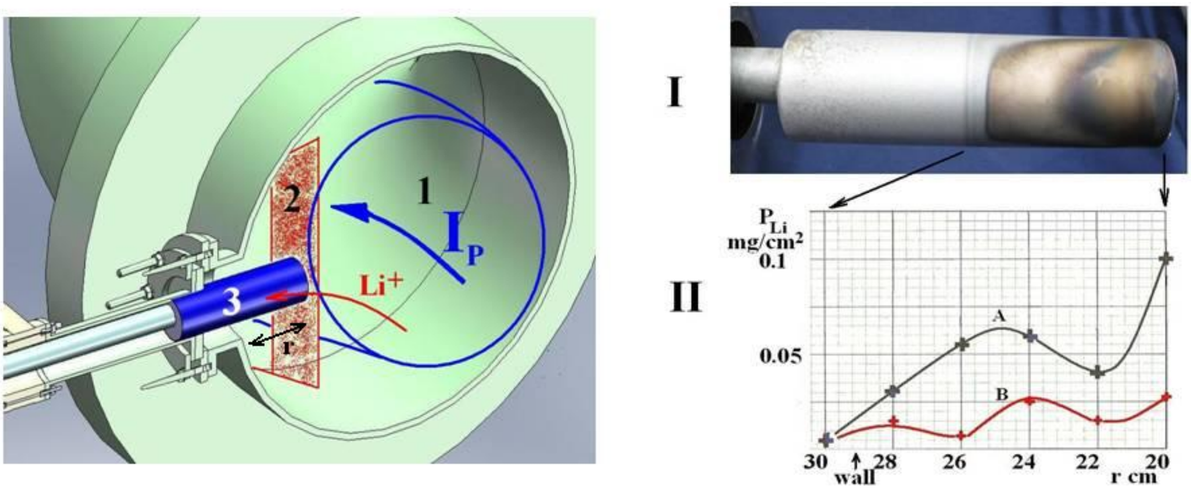

Figure 3. Left side- the cooled collector in shadow of vertical lithium limiter of T-11M. 1-plasma column, 2-limiter, 3- collector. Right side - -view of head of cooled lithium collector after 50 plasma shots exposition, II - the distribution of captured lithium along target on “ions”(A) and “electrons”(B) sides.

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