Test of Lithium Capillary-Pore Systems on the T-11M Tokamak

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Abstract. The ITER project development has shown that the divertor plates and first wall protection from disruption events are the most critical problems. A replacement of the divertor plate material (W, Be, CFC) by the material with a lower Z would become an evident step to a decrease in Z_{eff}. Such a material is Li. The possible technical solution of such a plate on the basis of Li capillary-pore system (CPS) has been proposed and realized. These plate specimens have been tested by electron beam and plasma flow. The first successful experiments in T-11M tokamak have been performed. In this work the divertor plate behavior has been simulated in the quasi-stationary condition. The T-11M tokamak up-grade allowed its performance to be increased as follows: plasma current up to 100 kA, pulse length ~0.2-0.3 s. Unlike the previous versions, the new Li limiter has a thermal regulation system which permits a Li surface initial temperature. This provides an increase in test parameter range: sorption and desorption of plasma-forming gas, Li emission into discharge, Li erosion, limiter deposited power and so on. Tests of the new Li limiter on T-11M tokamak are presently started.

1. Introduction

Li filled **C**apillary-**P**ore **S**ystem (CPS) application as a plasma facing material for a tokamak reactor has a number of advantages in comparison with other materials and, probably, will help in solving the important problem of a considerable increase of an operational resource of divertor plates without essential increase in Z_{eff} of a plasma column [1,2,3]. CPS with Li proposed as a divertor plate surface structure [1,2], which provides a means for solving the liquid Li surface stability problem. However, the use of liquid Li in tokamak raises some other problems: 1) energy removal ability from plasma by radiation, 2) Li erosion due to: arcs, ion sputtering and evaporation (thermal emission), 3) Li behavior in a plasma column, 4) Li deposition on the surface of vacuum chamber, 5) modification of surface getter properties (gas recycling decrease). The tests (~ 2000 experimental shots) of liquid Li surface stability have been performed and plasma interaction processes with Li CPS rail limiter have been studied in the T-11M tokamak [4]. This paper contains analysis of the last experiments with Li CPS-based limiters. The new design of Li limiter with an active cooling system is presented. The tests of new limiter were started in the T-11M up-grated tokamak, the pulse length of which was approximately trebled in comparison with the previous tests.

2. Interaction of Plasma with Li Capillary-Pore Structure in Tokamak T-11M

Experiments in T-11M tokamak have been performed in order to prove compatibility of a Li CPS with boundary plasma in tokamak conditions close to the quasi-stationary plasma parameters expected in reactor. The main task was to ascertain whether spontaneous Li bursts from the liquid wall to the chamber volume were an important effect or not. Besides, Li interaction with working gases, Li migration in plasma, technology of Li application in tokamak and rehabilitation of the facility after Li tests have been studied.

The performance data of the small tokamak device T-11M was the following: R=0.7 m, a=0.2 m, B_T=1 T, plasma current $J_p \approx 100$ kA (q(a)=3-4)., discharge pulse duration about 0.1 s. The heat load to limiter is about 10 MW/m^2, similar power density is expected to be on the ITER divertor plates. Taking into account a strong dependence of the heat load on electron temperature (as $\propto T_e^{\alpha}$, where α can vary between 7/2 and 3/2 depending on plasma collision near divertor plates) one may suppose that boundary plasma temperatures T_e=20-30 eV that are characteristic of modern tokamaks will be of about the same level or lower (for higher density) in a reactor machine. All negative effects occurring at the wall that are known at present, namely, arcs, emission bursts, ion sputtering, micro-capillary waves etc. are functions of sheath potential and, finally, of T_e. High recycling condition regime could not be simulated exactly in T-11M. However, it corresponds too lower T_e<5 eV that seems preferable for Li divertor plates. Therefore, we suppose that T-11M modeling experiments were carried out in the conditions close to or even more severe than those of a reactor periphery.

Movable rail limiter with plasma contacting surface made of Li CPS (two versions of CPS were studied – with pore radius R_{eff}=100 and 30 μm) was inserted into plasma to about 5 cm thus limiting plasma column aperture. Conventional graphite limiter was placed in the opposite port for comparison with the Li one. Thermocouples were fitted in Li limiter close to its surface to measure total energy absorbed by the limiter during the discharge. Standard optical diagnostics was applied to observe Li penetration into the plasma near and remote from limiter. A 15-channel bolometer system was also set up and special infrared diagnostics was developed to measure the limiter surface temperature during the discharge and to calculate the deposited power [3]. The local heat deposited was shown to achieve 10 MW/m^2 in a quasi-stationary discharge for effective heat pulse length equal to 50 ms. The limiter temperature rise during this discharge was 100^o–250^{o}C. A heater incorporated in the limiter structure enabled higher temperatures to be obtained (up to 400^{o}C by preheating).

Lithium erosion. No catastrophic events leading to abundant Li injection in the MHD- stable discharge conditions within the whole Li temperature range (T_{lim} from 20^{o}C to 600^{o}C) was observed in the T-11M experiments. Li and graphite limiters worked practically in a similar way if additional heater was not used. Heating of the Li limiter gave rise to Li injection into plasma detected by an increase of Li line radiation (LiI-670.8 nm) and visible integral light emission (usually, proportional to LiI intensity) in the vicinity of the limiter. It is evident that while T_0 increases Li flux begins to grow in time. Li light peak during the current decay (T_0=300^{o}C) may be explained by recombination process (MARFE) because it coincides with decrease of plasma heating and it is not followed by a growth of plasma density and cannot be explained by a simple additional Li influx to the plasma. Estimation of total Li emission (erosion) from limiter was performed by use of electrical biasing method. It is shown that for limiter temperatures T_0<500^{o}C erosion remains in the limits expected for sputtering by D^+ and Li^+ ions with sputtering yield from 0.5 to 1. (For T_{lim}>500^{o}C conventional evaporation appears to become the main channel of Li emission). This is in correlation with the known data on Li-sputtering. The monotonic rise of Li flux during the discharge for T_0>200^{o}C may be attributed to self-sputtering by Li^+ ions accumulated in the plasma periphery. However, the last PISCES-B experiments [5] and some measurements of J. Allain [6], where Li^+ accumulation effect was excluded, show the same kind of fast increasing dependence of Li erosion on initial target temperature as it was in the T-11M experiments. This is possibly the result of some new mechanism of enhanced liquid Li sputtering, which depends on the Li temperature [5]. The T-11M results support this explanation. In *FIG. 1*, in arbitrary units, we have presented the intensities of total light and LiI emission in the vicinity of T-11M CPS limiter as function of its surface temperature T_{lim} for a middle part of discharge. We conclude that Li emission from CPS limiter in tokamak discharge behaves much like pure Li sputtering in simulated experiments. Future investigations are planned for T-11M, because these results are very important for choosing of Li-divertor parameters.

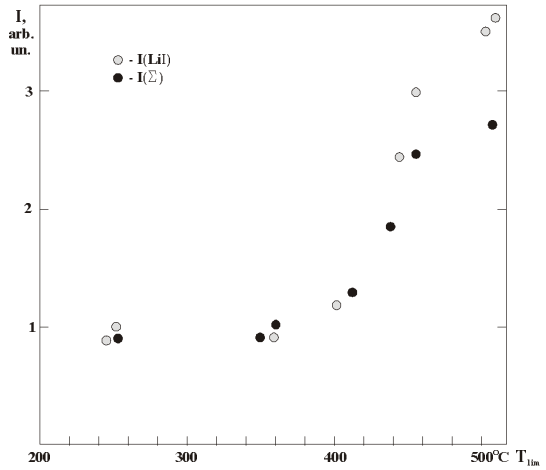


FIG. 1. Total light and LiI intensity as function of CPS temperature.

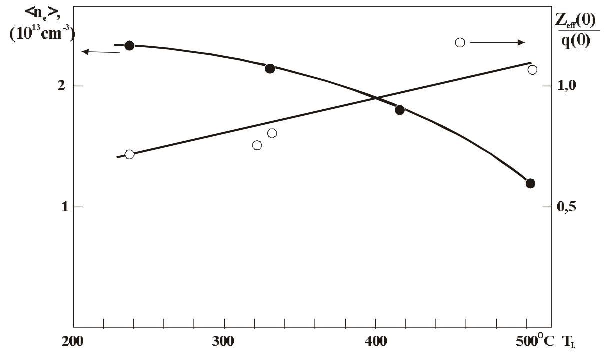


FIG. 2. Behaviour of $<n_e>$ and $Z_{eff}(0)/q(0)$ during experiment with Li limiter heating.

FIG. 2 illustrates the change of $<n_e>$ and $Z_{eff}(0)$ during experiment. It should be primarily noted a decrease in $<n_e>$ as a limiter temperature increases. This means that in spite of an increase in Li flux from the limiter into the plasma, deuterium and Li fluxes from the walls (recycling) decrease so, that a balance is biased to a decrease direction of $<n_e>$. This is a common tendency for all the experiments with Li limiter in T-11M. A level of deuterium plasma contamination by Li can be estimated according to $Z_{eff}(0) = 1+\alpha Z^2/1+\alpha Z$ ($\alpha= n_{Li}/n_D$) behavior at the column centre. To determine this parameter it must be taken into account as follows: electron temperature at the centre - $T_e(0)$, loop voltage - V_p, current density - j(0), or safety factor on axis - q(0). The two last-mentioned parameters are unknown, whereas measured $T_e(0)$ (by SXR) and V_p allow $Z_{eff}(0)$/q(0) parameter to be defined. Its variations during limiter heating are given in *FIG. 2*. Under normal conditions $q(0)\approx 1$. Therefore, the above parameter is the qualitative assessment of $Z_{eff}(0)$ change, namely, its growth 1.5 times on limiter heating from 200 to 500°C. To reduce a systematic error its value can be normalized in case of high density ($<n_e>\approx 5.10^{13}$cm^{-3}), where $Z_{eff}(0)=1$. The $Z_{eff}(0)$ value estimated such a way turned out to vary approximately from 1 to 1.5 (*FIG. 2*). Then for a limiting value of T_{lim} = 500°C a Li relative content n_{Li}/n_D accounts for about 0.1.

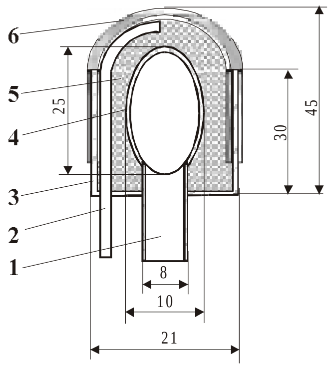
Radiating cooling. Therefore, Li emission into the discharge could be controlled by an increase of initial limiter temperature in T-11M. One could expect to obtain a growth of periphery radiation and, by this, to reduce the heat load to the limiter. It was really reduced by approximately a factor of two by these manipulations in the helium discharge [4]. Even larger fraction of the heat flux is supposed to be radiated with the increase of heat pulse duration and that will be closer to the limit of Li radiating mantle. Thus, a step to Radiation Improved (RI) conditions with a smaller impurity contamination of the center in actually operating tokamaks [7] and to radiating divertor in a reactor may be done. Li confinement time in the periphery layer (τ) may be taken as a governing parameter. If it is small then Li ions will not reach a coronal equilibrium before they return to wall. In this case the Li radiation intensity becomes much higher than that expected for coronal equilibrium. For example, the Li radiation may be by two orders higher than the coronal equilibrium level for T_e=30 eV, $n_e=10^{13}$ cm^{-3} and $\tau=10^{-3}$s that is quite realistic for plasma periphery. The radiating mantle also appears realistic in these conditions. Principle possibilities of $n_e\tau$-control are just known: ergodic magnetic fields at the plasma boundary, controlled ELMs, local excitation of MHD activity etc. Further development of these methods is needed.

Deuterium capture in Li and desorption effect. One of the most evident, though expected, consequences of Li introduced into real tokamak machines (TFTR, T-11M, CDX-U) was the high growth of sorption of D^+ and H^+ on the wall. Moreover, helium sorption was discovered in T-11M experiments as well [8] with a slow desorption during 20-100 s after the discharge. However, in order to avoid this effect of helium sorption it was sufficient to heat the T-11M vessel wall to 50-100^{o}C. For deuterium, even the highest attainable wall temperature of 250-300^{o}C turned out to be insufficient. At the same time the Li limiter could be heated up to 450^{o}C. The captured deuterium is desorbed from Li at temperatures >320^{o}C. Li hydrides are supposed to decompose at temperatures ≥600^{o}C. Therefore, one may conclude that considerable part of deuterium was captured by Li not in the form of deuteride but it was dissolved in Li. It means that a simple heating to 370-500^{o}C [9] seems sufficient to desorb deuterium. The character of Li interaction with hydrogen isotopes should be studied in more details.

Disruption shielding. As was shown in special disruption simulation experiments [3], a dense plasma layer was formed during high energy plasma interaction with Li CPS target. The major part of the plasma energy (~97-99%) is absorbed and radiated in this layer which plays the role of a shielding layer. This result has been confirmed later experimentally in a T-11M tokamak: only 30-50 J of about 0.7 kJ of total plasma energy loss has been found to reach the rail limiter during disruption events while under normal discharge condition the energy loss to the limiter is equal to 50% of total flow from plasma column [10].

3. Limiter Design and Parameters in Quasi-Stationary Operation Conditions

The T-11M tokamak up-grade provided an increase in discharge time up to 0.2-0.3 s. This allowed for starting an experimental program of Li limiter simulation tests under steady-state approximated conditions. The main physical problem, which should be solved in studies of heat transfer from thermonuclear plasma to Li CPS, is the controlled Li exchange between plasma boundary and divertor plates during all reactor regimes by choice of temperature and CPS technical parameters for realization of stationary liquid Li divertor. A thermophysical analysis has shown that the stationary heat removal of heat fluxes of >10 MW/m^2 at a Li surface temperature of <500^{o}C can be ensured at Li target plate optimal geometric parameters. This is possible by use of liquid (water, phenyls mixture, sodium, Na-K) or gaseous (helium) coolant force circulation or by evaporation of working fluids (water, ethanol, phenyls mixture) in limiter cooling system. To realize the first step of this program the design (*FIG. 3a*) has been developed and lithium limiter with active cooling by gas or organic coolants has been manufactured (*FIG. 3b*). The CPS of target plate with a thickness of ~1.5 mm and efficient pore radii of 30 μm has been made from type 18-8 stainless steel. The limiter has been placed in the T-11M tokamak and the first step of experiments has been started.



1 - heat transfer medium input/output channel;
2 - thermocouple;
3 - limiter case;
4 - heat exchanger;
5 - lithium supply volume;
6 - lithium surface of limiter

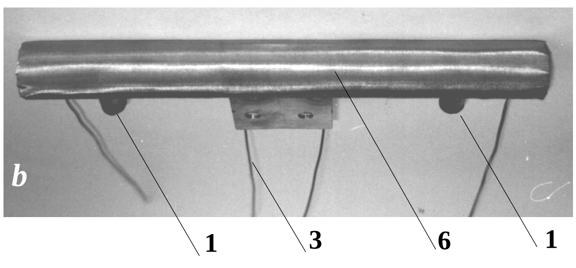


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Fig. 3. Design (a) and general view (b) of the new version T-11M tokamak lithium limiter.

4. Summary

A series of experiments on T-11M tokamak has proven compatibility of Li CPS limiter with plasma in all operating conditions. No spontaneous burst injection of Li at heat load close to that of reactor at a level of 10 MW/m^2 has been observed. Estimates have revealed that at T_{lim}=500^oC a lithium relative content at the plasma column center n_{Li}/n_D accounts for about 0.1.
High level of Li radiation has been detected including the case of disruption events so that solid basis of CPS limiter had no damages after more than $2 \cdot 10^3$ of plasma shots.

These experiments have shown that hydrogen (deuterium) and helium ions bombarding Li wall or limiter in normal conditions in the tokamak periphery ($T_e \approx$10-30 eV) are captured by Li. The difference in desorption temperature was shown to exist for hydrogen isotopes (320-350^oC) and helium (50-100^oC). These effects may be used for D-T separation from He.

By the next step T-11M program will be a repetition of investigations in upgraded T-11M regimes with enlarged discharges up to 0.2-0.3 s and Li-limiter active cooling to provide the quasi stationary regime. To realize this program the design has been developed and lithium limiter has been manufactured. The limiter has been placed in the T-11M tokamak and the first step of experimental studies has been started.

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