Development of Liquid Lithium Limiter for Stellarator TJ-II

A.V. Vertkov 1), I.E. Lyublinski 1), F. Tabares 2), E. Ascasibar 2)

1) FSUE “Red Star”, Moscow, Russia
2) CIEMAT, Madrid, Spain

E-mail contact of main author: avertkov@yandex.ru

Abstract. A new step in an improvement of TJ-II Heliac plasma performance is a development of two mobile poloidal liquid lithium limiters (LL) allowing further progress in achievements of enhanced energy confinement owing to effective impurity and particle control. Main parameters, structural scheme and materials of LL are presented and discussed. The possibility of LL positioning relative to last closed magnetic surface, gas puffing through limiter, biasing and equipment with Longmuir probes and thermocouples, electrical heaters are ensure wide operation window. Study of gas release from lithium surface is stipulated in special volume included to the LL structure. An analysis of LL behavior in TJ-II plasmas produced with 400 kW ECRH power is presented and demonstrates possibility of its long term and flexible operation.

1. Introduction

Stellarator concept is considered as an encouraging approach for fusion reactor development because it basically free from extreme thermal load events. However, the potential problem of impurity accumulation must be taken into account because stellarator plasmas has distinct features in their interaction with plasma facing materials (PFM) and in transport characteristics of the core comparing to tokamaks. The promising way in solution of this problem is application of low Z PFM and an appropriate wall conditioning procedure development. Among low Z elements lithium is the most attractive owing to its very low radiation power, strong hydrogen retention and getter activity to residual gases in vacuum chamber.

From 2007 the TJ-II has been operated with lithium coated wall [1, 2]. In comparison with other high and low Z PFM very promising results in density control, plasma reproducibility and confinement characteristics have been obtained, significantly enlarging the operational window of the machine even when only partial wall coverage with Li was achieved. As it has been shown a uniform coverage of the inner wall of vacuum chamber with lithium film is very important condition for beneficial effect. Vapor deposition method with ovens not satisfy this demand in case of rather complicated geometry of stellarator.

A new method of achieving the above in TJ-II is the insertion into the chamber of two movable poloidal liquid lithium limiters (LL) based on capillary-pore systems (CPS). These lithium limiters will serve as an emitter of lithium atoms by thermal emission and ion sputtering during interaction with plasma. In addition it may be used for wall conditioning (lithiation) in glow discharge before the experiments. It will allow further progress in achievements of enhanced energy confinement owing to effective impurity and particle control. Concept of LL is based on the surface tension forces in capillary channels that provide required shape of lithium surface, continuous lithium renewal, liquid lithium surface stabilization under MHD force effect in magnetic field etc. These features of CPS have been confirmed in series of experiments in tokamaks [3-6].

Lithium limiter of TJ-II represents a line of limiters intended for plasma device with relatively short plasma discharge duration (up 1 s) and power flux to the PFM up to 5 MW/m^2. The distinctive feature of this line is using of heat capacity of limiter structure for surface temperature stabilization insuring the lithium atom flux to plasma on reasonable level.

2. Main parameters and experimental capabilities of LL

Design of LL will provide it proper operation at TJ-II conditions presented in Table I. Two equivalent LL will be installed in lower vertical ports of opposite sections of TJ-II chamber (FIG.1). They are able for moving from the position for storage, preparation and tests in special vacuum volume to the position for operation. Each of LL consists of four lithium elements with semi-cylindrical plasma facing surface aligned tangential to the last closed magnetic field surface (LCFS) in poloidal section. LL is electrically insulated from vacuum chamber and has possibility for biasing. Both of LL are equipped with tube for gas puffing, two Langmuir's probes and eight thermocouples.

TABLE I. TJ-II OPERATION CONDITION

Parameter	**Value**
ECRH power	~ 400 kW
NBI power	~ 800 kW
Power flux to surface	~ 0.8 – 2.5 MW/m^2
Time of plasma-limiter interaction	~ 200 ms
Toroidal magnetic field	~ 1 T
Electron density on LCFS	1-2 10^{18} m^{-3}
Electron temperature on LCFS	~ 30–60 eV

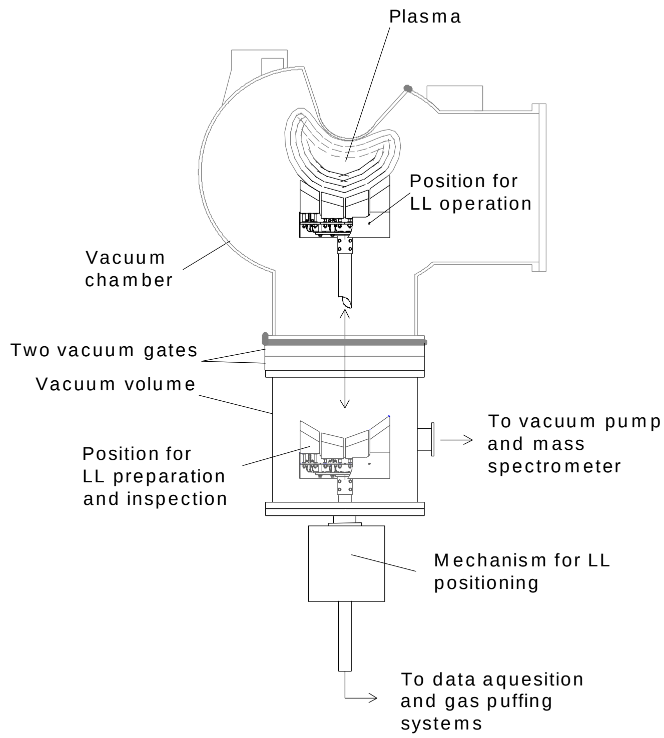

FIG.1. Main scheme of LL

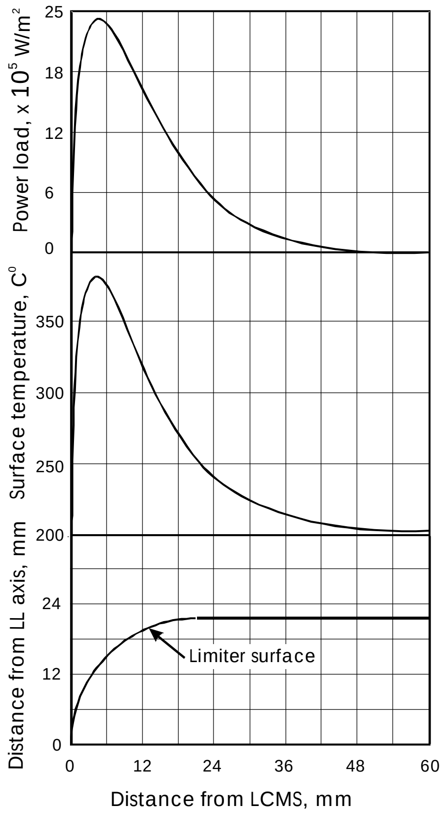

FIG. 2. Power flux and temperature distribution on LL surface

Special vacuum volume equipped with two vacuum gates, own pumping system, heater of the walls and mass-spectrometer provides the possibilities of easy LL installation and preparation, protection of LL from contact with air during TJ-II vacuum chamber opening, carrying out the experiments on hydrogen and helium sorption – desorption process study on lithium surface. The functional capabilities of LL allows for essential expansion of window for experimental researches.

Possibility of LL plasma facing surface to withstand high power loads without damage, provide continuous lithium supply and stabilization of liquid lithium surface under electromagnetic force effect are ensured by CPS. Capillary force in this structure should satisfy the condition when $Pc \geq \Delta P_L + \Delta P_G + \Delta P_F + \Delta P_{MHD}$, where Pc – CPS capillary pressure; ΔP_L - hydraulic pressure drop in CPS; ΔP_G - hydrostatic pressure drop; ΔP_F – pressure drop on evaporating surface due to liquid – vapor phase transition; ΔP_{MHD} – pressure due to MHD effect. Sum of pressures $\Delta P_L + \Delta P_G + \Delta P_F$ for TJ-II conditions is estimated as 500 Pa. For ΔP_{MHD} estimated value is less than $1 \cdot 10^3$ Pa. So, even capillary structure with pore radius of 250 µm will satisfy this demand. Application of CPS with pore radius of 15 µm where estimated pressure is significantly higher (about $5 \cdot 10^4$ Pa at 550°C) will ensure proper LL operation.

For a long-time operation of LL without damage it is necessary to have in store sufficient amount of lithium and keep lithium in the liquid state ($T_{lim} > T_{melt} = 180^oC$) that lithium surface will be self-recovering due to the capillary forces. Moreover the proper operation of LL as lithium emitter requires providing a sufficient integral quantity of lithium atoms during the plasma-limiter interaction estimated as ~ $2 \cdot 10^{21}$ atoms (for lithium coating with 10 monolayers). It seems that LL should have a sufficient surface temperature and plasma interacting area. Estimated distribution of maximal power flux and temperature on the LL surface in TJ-II conditions are presented in FIG.2. Analysis of ion sputtering and thermal evaporation contribution to lithium flux for LL surface temperature in the range of 200 – 550^{o}C indicates prevalence of ion spattering process and possibility of flexible control of lithium flux by preliminary heat. From this point all lithium element of LL has own electrical heater for initial temperature control in the rage of 20-550^{o}C and the following parameters are taken for limiter design (Table II).

TABLE II. MAIN PARAMETERS OF LL FOR TJ-II

Parameter	**Value**
Dimensions L x D x H	0.324 x 0.044 x 0.225 m
Lithium surface area	$2.24 \cdot 10^{-4}$ m^2
Initial temperature	~ 200 - 550 ^{o}C
Amount of lithium	~ 80 g (20 g x 4)
Lithium loss per discharge	~0.01 g
Number of lithium elements	4
Capillary pressure	~5 10^4 Pa
Power of heaters	up to 300 W
Total weight	5 kg
Operation campaign	> 1000 discharges

3. LL design

Development of all components of LL design is in a final stage. The results of this activity on lithium part of project are presented in FIG. 3 and 4.

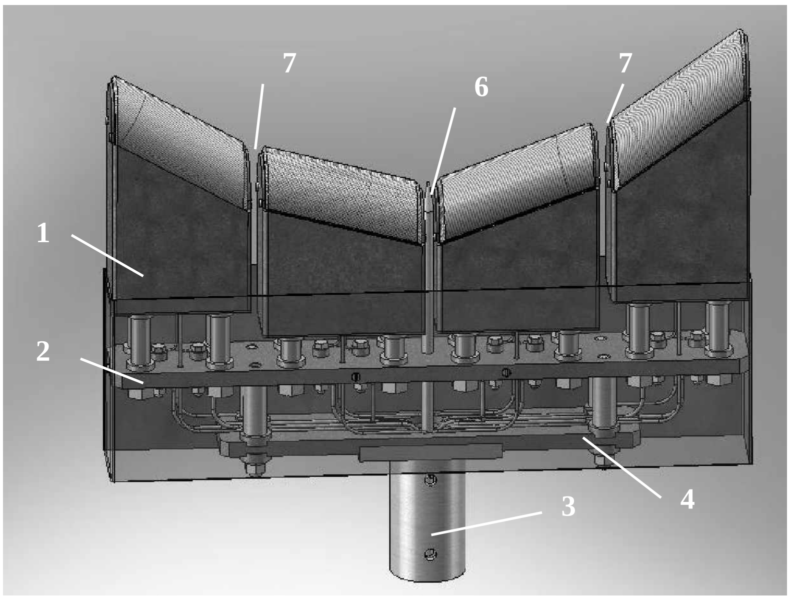

FIG. 3. General view of LL structure.

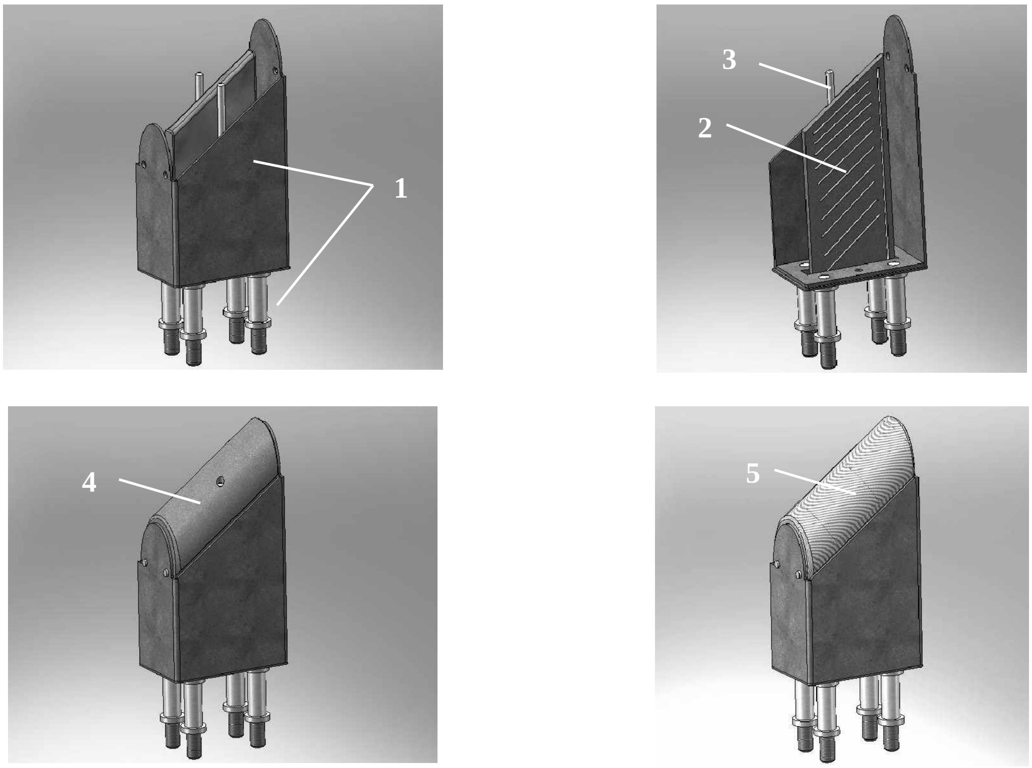

FIG.4. View of LL lithium element structure.

Each of LL (FIG. 3) includes four liquid lithium elements (LE) (1) which are fastened to a supporting plate (2) and is connected to the movable tube (3) of positioning mechanism by the fastening assembly (4) with electrical insulation. LL is provided with pipe for gas puffing (6) and two Langmuir's probes (7).

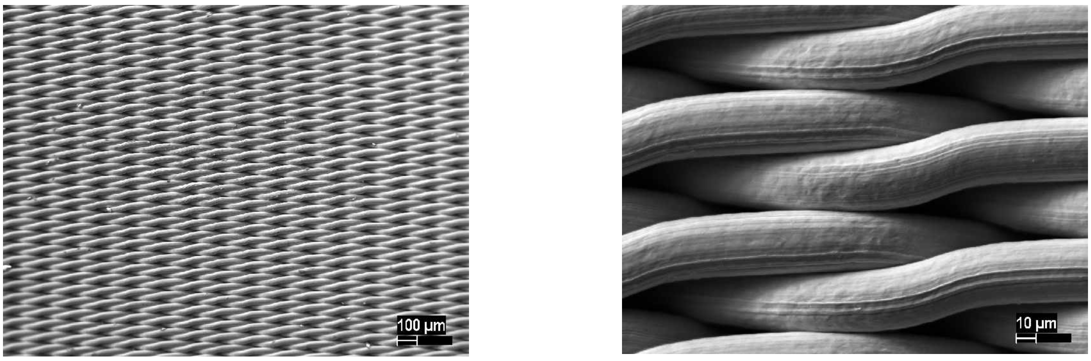

FIG. 5. SEM micrograph of SS mash for CPS of LE plasma facing surface.

Lithium elements (FIG. 4) consists of the following main parts: case (1) including all structure elements and lithium supply volume with CPS for lithium transport to the surface; electrical heater (2) situated in hermetical casing and providing the initial heating, two hermetical channels (3) with thermocouple for LE temperature monitoring; heat accumulator (4) for surface temperature stabilization; lithium filled CPS (5) of plasma facing surface.

LE is provided with protective shield serves for insulation of lithium surface from the interaction with atmospheric gases during fabrication, transportation and preparation of LL for operation. The shield is made of SS AISI 304 foil with 0.05 mm thick. Foil is soldered to CPS surface by lithium during manufacture process. It may be easily removed under spring pressure of the mechanism of opening when LE is heated up to lithium melting point in special vacuum volume just before the beginning of the experiments.

Most of LL parts are made from AISI 316 type austenitic stainless steel excluding heat accumulator made of pure molybdenum. CPS of plasma facing surface and for lithium transport from supply volume comprises a mat with 1 mm thick of wire meshes made of AISI 304. CPS outer layer is made of mesh with an effective pore radius of 15 μm (FIG. 5). The inner layers of mat are made of mesh with the pore radius of 50-100 μm. The mesh mat covers the heat accumulator surface and forms a plasma facing cylindrical surface of the LE. CPS of plasma facing surface is in hydraulic contact with CPS of lithium transport from the lithium supply vessel in the cavity of the case. Each of all LE are filled with ~20 g of pure lithium.

4. LL mock-ups manufacture and tests

Under LL project development two full-scale mock-ups of LE have been manufactured, filled with lithium and tested with the main goals to validate feasibility of design solutions and manufacturing process, conformity of their parameters with operating demands.

Developed processes of assembling, preparation and filling with lithium are successfully applied and ensured the warranted quality of LE, good wetting of CPS and uniform distribution of lithium on the surface. Steps of mock-ups assembling are presented in FIG.6.

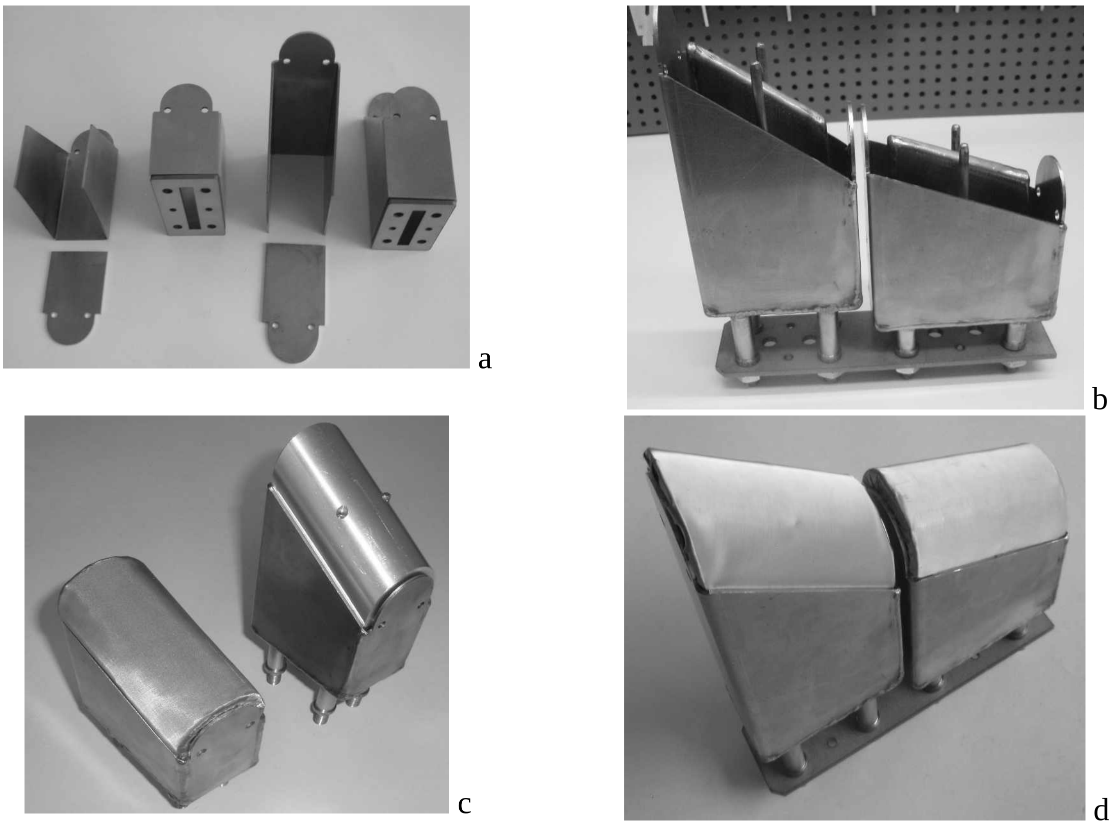

FIG. 6. Assembling of LE mock-ups

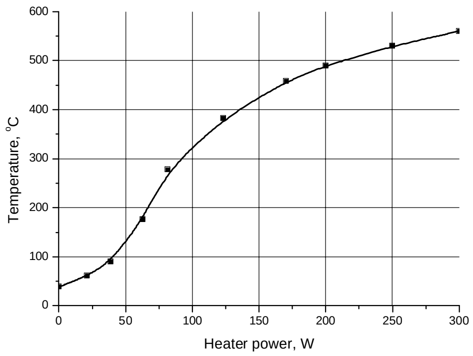

FIG.7. LE surface temperature & heater power

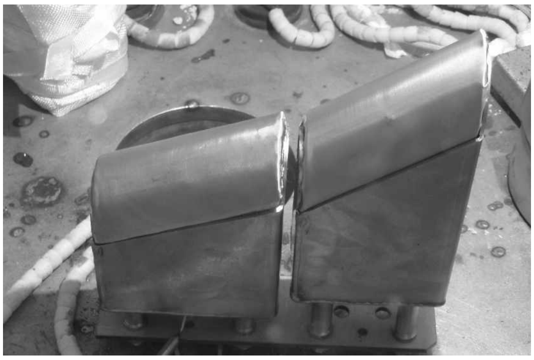
FIG.8. View of LE mock-ups after thermal tests

A result of mock-up thermal tests in vacuum (P < $1.3 \cdot 10^{-4}$ Pa) clearly demonstrates the possibility of electrical heater with power of 300 W for a long-term operation and maintaining of LL surface temperature in the range of 200-550°C (FIG. 7). No effects of thermal stress on LE structure have been found (FIG. 8). Vacuum tests with gas release control by mass-spectrometer have confirmed the fact that LL isn't a source of contamination for plasma at these conditions. Only hydrogen partial pressure increase with the mock-up temperature rise was observed and may be attributed to the result of chemical reaction of lithium with the residual water vapor in vacuum chamber.

5. Conclusion

Activity on the development of LL for stellarator TJ-II have clearly shown that design, manufacture process and preparation procedures provides correspondence of LL parameters to supposed experimental capabilities. The available possibilities allows for essential expansion of window for experimental researches with LL. Designing stage of the project has successfully finished and manufacture of LL components is in progress now. Installation of LL to the camera of TJ-II is expected in the first half of 2011.

References

[1] TABARÉS, F.L., et al., "The lithium stellarator experiment. TJ-II as a benchmark", Problems of atomic science and technology, 2008. № 6, Series: Plasma Physics (14), 3-7.

[2] TABARÉS, F.L.,et al., "Overview of TJ-II Plasma Performance under Lithiated Wall Conditions". Proc. of 1st Int. Workshop on Lithium Applications to Boundary Control and their Effects on Core Plasma Performance in Fusion Devices CRC-NIFS, Toki, Japan, 18-20 Jan. 2010.

[3] MIRNOV, S.V., et al., "Experiments with lithium limiter on T-11M tokamak and perspectives of the lithium capillary-pore system application in fusion", 20th IAEA FEC, Vilamura, Portugal, 1-6 November, 2004, IAEA-CPS-20/CD, EX/P5-25, IAEA, 2005

[4] VERTKOV, A.V., et al., "Technological aspects of liquid lithium limiter experiment on FTU tokamak", Fus. Eng. Des. **82** (2007) 1627-1633.

[5] APICELA, M.L, et al., "Lithium capillary porous system behavior as PFM in FTU tokamak experiments", J. Nucl. Mater. 386-388 (2009) 821-823.

[6] LYUBLINSKI, I.E., et al., "Application of lithium in systems of fusion reactors". Part 2. The issues of practical use of lithium in experimental facilities and fusion devices. Plasma Devices and Operations. Vol. 17, No 4, Dec. 2009, 265-285.