Journal of Nuclear Materials 386–388 (2009) 821–823

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Lithium capillary porous system behavior as PFM in FTU tokamak experiments

M.L. Apicella [a], V. Lazarev [c], I. Lyublinski [b], G. Mazzitelli [a], S. Mirnov [c], A. Vertkov [b,*]

[a] Associazione EURATOM-ENEA sulla Fusione, Centro Ricerche di Frascati, Frascati, Italy
[b] FSUE "RED STAR", 1A Electrolitniy proezd, 115230 Moscow region, Russia
[c] TRINITY, Troitsk, Moscow, Russia

A B S T R A C T

Liquid lithium use on the base of capillary porous systems (CPS) application as plasma facing material (PFM) of tokamaks is advanced way to solve the problems of plasma contamination with high Z impurity, PFM degradation and tritium retention. In frame of joint program between ENEA (Italy) and FSUE 'Red Star' & TRINITI (RF) started at the end of 2005 the test of passive cooled liquid lithium limiter (LLL) with CPS in a high field, medium size, carbon free tokamak FTU have been performed successfully. The LLL has been inserted in ohmic plasma discharges and at additional heating with LH and ECR at power levels in the MW range without any particular problem (B_T = 6 T, I_p = 0.5–0.9 MA, n_e = 0.2–2.6 × 10^{20} m^{-3}, τ = 1.5 s, P ~2–5 MW/m^2 at a normal discharge). The behavior of lithium CPS based on stainless steel wire mesh and its surface modification in normal discharges and at disruptions has been studied. Results of microscopic analyses of CPS structure after experimental campaigns are presented. The possibility to withstand heat load exceeding 5 MW/m^2 without structural damage, lithium surface renewal, mechanical stabilization of liquid lithium against MHD forces have been confirmed. Application of W, Mo as the base material and possible structure types of CPS have been considered for operating parameters improvement of long-living plasma facing components.

1. Introduction

The development of plasma facing elements (PFE) for ITER, DEMO and next generation fusion reactors presents serious problems. PFE structural materials should satisfy numerous demands for providing of appropriate lifetime under high power and neutron fluxes. The key problems of plasma facing materials (PFM) (i.e., damage, property degradation, plasma pollution and tritium retention) may be overcome by application of liquid lithium as the best candidate with low Z and low activation. The alternative version for realization of lithium advantages for PFE creation is based on the use of so-called lithium capillary porous system (CPS) – essentially new material in which liquid lithium is concluded in a matrix from a porous material. Lithium CPS application will allow: to create a self-renewal surface of the in-vessel devices possessing practically unlimited resource of work; to stabilise liquid metal surface under MHD forces at disruption owing to the capillary effect; to reduce power flux due to intensive re-irradiation on lithium atoms in plasma periphery that will essentially facilitate a problem of heat removal from plasma facing devices; to reduce effective charging number of plasma to minimally possible level close to 1, that will essentially increase plasma parameters of a reactor; to exclude tritium accumulation, that is provided with absence of dust products and an opportunity of the active control of the tritium contents in liquid lithium. The metal fiber-based materials are the most preferable in this respect. Thermal gradients will not give rise in stresses in the lithium filled CPS; consequently, no thermal induced cracking and no fatigue will occur unlike the conventional solid materials. Maximal allowable heat flux on the CPS surface is >100 MW/m^2 (for pore radius ~15 μm, at surface temperature ~1200 °C) owing to heat removal by lithium evaporation which is limited by CPS melting point (maximal surface temperature) and capillary pressure (lithium renewal limit). The CPS damage mode in principal had a character of local fiber damage instead of crack propagation in a monolith and did not affect all structure integrity. Its impact toughness exceeds the monolithic material a 10 times. The CPS attachment technology to supporting and heat sink structures is not a problem owing to the CPS excellent relaxation ability. Moreover, this material has a wonderful shock-absorbing ability. The problem of radiation and swelling resistance practically does not arise for CPS based on the metallic fibers from radiation resistant alloys.

Lithium CPS advantages as plasma facing material has been confirmed by the experiments with lithium targets in modeling conditions on electron beam facility 'Sprut', plasma accelerators QSPU, MC-200-UG and in T-11M tokamak conditions [1–8].

* Corresponding author. Tel.: +7 495 6138311.
E-mail address: avertkov@yandex.ru (A. Vertkov).

0022-3115/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2008.12.238

2. Liquid lithium limiter experiment on FTU

The experiments of passive cooled liquid lithium limiter (LLL) with CPS have been performed in a high field, medium size, carbon free tokamak FTU with TZM main toroidal limiter (B_T = 6 T, I_p = 0.5–0.9 MA, t = 1.5 s and average electron density n_e from 0.2 up to 2.6×10^{20} m^{-3}) under the joint program between ENEA (Italy) and TRINITI & Red Star (RF) started at the end of 2005 in particular aimed to confirm the lithium CPS compatibility with real tokamak plasma conditions, the surface capability for self-regeneration and lithium confinement during normal plasma operations and disruptions, the ability to withstand high heat loads without damage of limiter surface [9]. The experimental results on an important physical issue of the lithium effect on plasma discharge parameters are presented in [10].

The LLL inserted into lower vertical port of FTU have been tested in ohmic condition (up to 0.85 MW) and plasma-heated discharges with LH and ECR heating at power levels in the MW range. Its radial position can be varied from the wall to the last closed magnetic surface for providing of the power flux increasing. The LLL consists of three separated and electrically insulated units (Fig. 1(a)). The semi-cylindrical lithium surface of LLL units (Fig. 1(b)) with total lithium area of 170 cm^2 and actually plasma interacting lithium surface ~50–85 cm^2 is formed by a porous mat (9) with 1 mm thick and pore radius of 15 μm from stainless steel mesh (available modeling CPS base material) filled with lithium and in contact with a lithium reservoir (7) (total amount of lithium ≅80 g). Heat sink (3) from molybdenum is applied for CPS surface temperature stabilization during plasma interaction. LLL has been initially heated up to the liquid state (210 °C) and then exposed to the plasma.

3. Experimental results and discussion

The first stage of the lithium CPS behavior study as PFM has been performed with more than 60 discharges in ahmic heating condition for thermal loads exceeding 2 MW/m^2. The temporal evolution of the LLL surface temperature measured by IR sensors and found from the calculations of ANSYS code for power flux of 2 MW/m^2 is presented in Fig. 2. The average temperature on the Li surface has not exceeded 450 °C. There is evidence that the measured surface temperature has a tendency for stabilization and deviation from ANSYS data as it would occur probably owing to Li irradiation in front of the limiter surface. Calculation with TECXY code supports this hypothesis [9,10]. About 0.5–1.0 × 10^{21} Li atoms are produced by physical sputtering plus evaporation from limiter per discharge. No anomalous phenomenon like 'lithium bloom' occurs during plasma discharges.

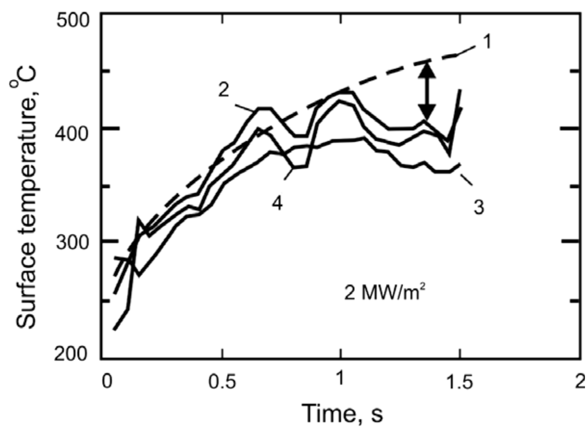

Fig. 2. The LLL surface temperature behavior (2, 3, 4 – IR date) under power flux of 2 MW/m^2 with ANSYS cod data (1).

No changes of the CPS surface have been found after the end of first experimental stage and no surface damage has been observed on the LLL after operations and also in the case of plasma disruption (Fig. 3). Lithium droplet generation due to $J \times B$ forces have not been observed in case of plasma disruption when LLL was well fastened. It is necessary to note, that significant decreases in residual gases and metallic impurities line intensity have been detected in plasma spectra during experiments with LLL in contrast with reference discharge without it. No spectral lines of CPS basing material have observed during experimental campaign and lithium lines are prevailing in spectra. It means that plasma does not interact with CPS basing material directly and lithium film exists on the surface. Thus the ability of capillary force in CPS with pore radius of 15 μm for Li surface renewal and liquid metal confinement during disruption is confirmed for high magnetic field (B_T = 6 T) tokamak condition that is in a contrast with free lithium surface behavior. The temperature in the local places on the limiter surface was less then stainless steel melting point in any case and CPS has not been damaged.

The second stage of the lithium CPS behavior study has been performed for thermal loads exceeding 5 MW/m^2 and in plasma-

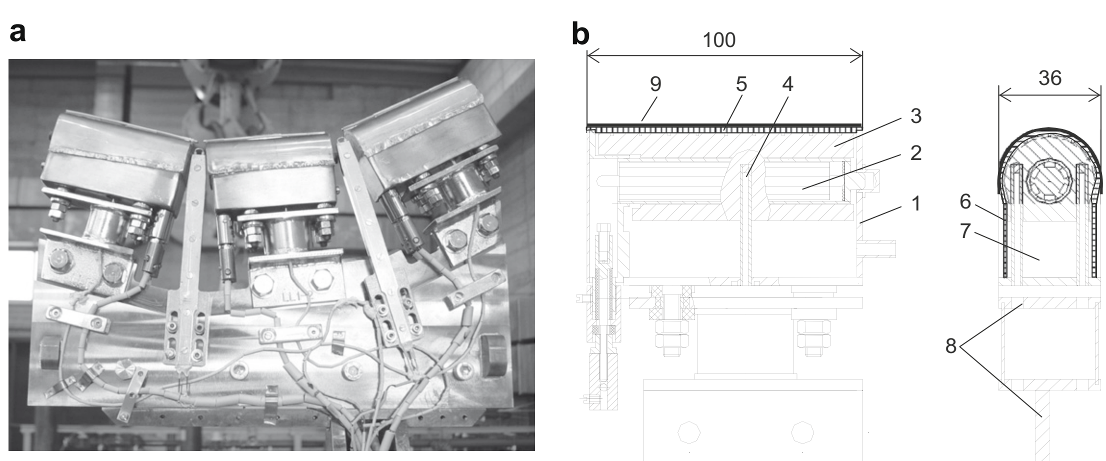

Fig. 1. View of complete assembled LLL before installation (a), structure of LLL unit (b): 1 – LLL case; 2 – heater; 3 – heat sink; 4 – thermocouple; 5,6 – CPS for Li transport to surface; 7 – Li supply volume; 8 – supporting structure; 9 – CPS of LLL surface.

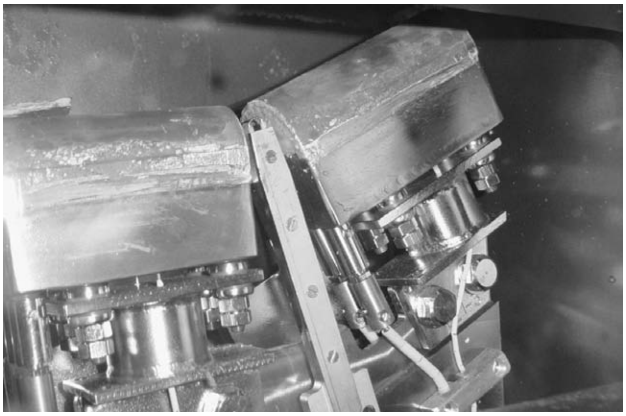

Fig. 3. View of LLL after series of discharges with disruptions.

Fig. 4. View of LLL surface after series of discharges with additional plasma heating.

heated discharges with LH and ECR heating in megawatt range. The behavior of CPS during this stage was analogous to the previous one as a whole. But the following effect has been observed. From the IR measurement data the maximal surface temperature reaches of 700 °C at the end of discharge and about 850–900 °C at disruption. Specific relief formation (waves on the surface) and evolution was revealed during tests (Fig. 4). This process was limited to the first layer of mesh mat and the height of relief elements (wave height) reached of 0.7–0.8 mm. Such behavior can be attributed to the low heat removal efficiency from the surface. Applied modeling CPS base material has low heat conductivity. Its value was evaluated by $k_{CPS}(T) = k_{Li}(T)(\beta-\varepsilon)/(\beta+\varepsilon)$, where $\beta = [1 + k_c(T)/k_{Li}(T)]\ [1 - k_c(T)/k_{Li}(T)]^{-1}$, ε is the volumetric porosity, k_c(T) and k_{Li}(T) is the CPS base material and lithium heat conductivity coefficient, respectively. High surface layer temperature in a combination with high thermal expansion coefficient ($\alpha = 18 \times 10^{-6}\ K^{-1}$) causes the thermal stresses exceeding CPS yield stress evaluated as $\sigma_{yCPS} = \sigma_{yc}(1-\varepsilon)^2$, where σ_{yc} is the yield stress of CPS basing material. Surface layer deformation leads to the further reduction in heat conductivity and progress in surface relief formation. Moreover it became evident, that stabilization of temperature of a surface by means of the thermal accumulator is not sufficient for such condition (power flux > 5 MW/m^2, t = 1.5 s). Despite of it no surface damage has been observed on the LLL after second stage.

Lithium filled CPS from stainless steel has shown the basic opportunities and advantages of this class of plasma facing materials. But it is clear that this modeling type of CPS has not an optimal structure and properties. In comparison with applied PFM the molybdenum and tungsten fiber-based CPS has considerably higher heat conductivity (5–6 times), melting point (1.5–2 times), mechanical strength (3–6 times), corrosion resistance to lithium, lower thermal expansion coefficient (~4 times lower). In addition the tungsten is the low activated material and considered as candidate PFM for fusion reactor application. These materials with pore size less than 10 μm can be applied for increasing of PFE performance. The technology of tungsten fiber-based CPS production exists and such porous material is available.

Heat removal system with active cooling should provide surface temperature stabilization on the level of 500–550 °C for limitation of lithium flux to plasma.

4. Conclusions

CPS-based passive cooled liquid lithium limiter has been successfully tested in high magnetic field tokamak FTU with thermal loads exceeding 5 MW/m^2.

Lithium filled CPS from stainless steel has shown the basic opportunities and advantages of this class of plasma facing materials. But it has not an optimal structure and properties. The above mentioned high power flux effect on limiter surface smoothness can be restricted by application of tungsten or molybdenum fiber-based CPS and more effective heat removal system with active cooling.

Strong wall pumping capability and low values of Z_{eff} and radiation losses have been obtained leading to improved plasma operations.

The further experiments with liquid lithium CPS as PFM and with tungsten-based CPS are stipulated next year in present devices in view of a possible use on a steady state fusion reactor.

References

[1] V.N. Mikhailov, V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov, A.N. Chumanov, Lithium for Fusion Reactors and Space Nuclear Power Systems of XXI Century, Energoatomizdat, Moscow, 1999.

[2] N.V. Antonov, V.A. Evtikhin, V.I. Khripunov, I.E. Lyublinski, V.B. Petrov, V.V. Shapkin, A.V. Vertkov, Steady-state lithium plasma and liquid lithium divertor experimental validation, Fusion Energy 1996, in: Proceedings of the 16th IAEA Conference on Fusion Energy, Montreal, 1996, vol. 3, IAEA, Vienna, 1997, p. 651.

[3] V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov, S.V. Mirnov, B.I. Khripunov, N.I. Ezhov, S.M. Sotnikov, Fus. Eng. Des. 49–50 (2000) 195.

[4] V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov, S.V. Mirnov, V.B. Lazarev, N.P. Petrova, S.M. Sotnikov, A.P. Chernobai, B.I. Khripunov, D.Yu. Prokhorov, V.M. Korzhavin, Lithium divertor concept and results of supporting experiments, in: Proceedings of IAEA/TCM on Divertor Concepts, September 11–14, 2001, Aix en Provence, France, Plasma Physics and Controlled Fusion, 44(6) (2002) 955.

[5] V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov, V.G. Belan, I.K. Konkashbaev, L.B. Nikandrov, J. Nucl. Mater. 271–272 (1999) 396.

[6] V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov, S.V. Mirnov, S.M. Sotnikov, A.S. Prokhorov, E.A. Azizov, V.B. Lazarev, V.M. Safronov, V.M. Kozhavin, Plasma Sci. Technol. 6 (2004) 2291.

[7] V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov, S.V. Mirnov, V.B. Lazarev, S.M. Sotnikov, Test of lithium capillary-pore systems on the T-11M tokamak, Fusion Energy 2002, in: 19th Conference Proceedings, Lyon, France 14–19 October, 2002, IAEA-CPS-19/CD, FT/P1-17, IAEA, 2003.

[8] S.V. Mirnov, E.A. Azizov, V.B. Lazarev, V.A. Evtikhin, I.E. Lyublinski, A.V. Vertkov, Experiments with lithium limiter on T-11M tokamak and perspectives of the lithium capillary-pore system application in fusion, Fusion Energy 2004, in: 20th IAEA Conference Proceedings, Vilamura, Portugal, 1–6 November 2004, IAEA-CPS-20/CD, EX/P5-25, IAEA, 2005.

[9] M.L. Apicella, G. Mazzitelli, V. Pericoli, V. Lazarev, A. Alekseyev, A. Vertkov, R. Zagorski, J. Nucl. Mater. 363–365 (2007) 1346–1351.

[10] V. Pericoli-Ridolfini et al., Nucl. Fusion 47 (2007) S608–S621.