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Section 6. Advanced materials and plasma surface interaction in future fusion devices

Liquid lithium surface research and development

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Abstract

A liquid metal surface made with a capillary porous structure (CPS) (solid base) filled with lithium (liquid) has been offered for application in a magnetic confinement fusion reactor. The approach is investigated experimentally for divertor and first wall relevant conditions. The CPS ensured stability of the liquid surface under pulsed plasma impact in disruption simulation and tokamak experiments. Continuous operation of lithium capillary target was studied under electron beam load in stationary thermal conditions in the range 1–10 MW/m^2 of energy flux in steady state. Lithium evaporation was shown to dominate at temperatures higher than 400 °C and it removed up to 0.7 of incident power. Heat flux redistribution at the liquid lithium surface was analyzed. Lithium ionization, lithium plasma parameters near the liquid surface were evaluated. The importance and possibility of prompt lithium removal from the near surface layer in divertor conditions are emphasized.

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1. Introduction

The rising difficulties are encountered when we consider the solid plasma facing materials being used now in large tokamaks and those adopted in projects for their application in future fusion reactors. The requirements of a steady state operation under increased heat loads (compared to existing devices) make it difficult to find appropriate engineering solutions and to create long-life components. On the other hand, an intrinsic property of a liquid surface to be replenished under plasma bombardment is potentially a very attractive one to be used in the development of long-term plasma facing components. Liquid lithium is actually finding a particular attention in practical plan of experimental work as the last low *Z* candidate plasma facing material that should be investigated for tokamak reactor divertor and first wall application [1–3]. Different aspects of plasma–surface interactions on liquid lithium should be investigated extensively to advance the approach. These are search for liquid surface practical implementation options, study of heat control on a liquid surface, plasma contamination with the wall material, extension of database on lithium interactions.

An experimental research program is being carried out for the last several years in Russia to study liquid lithium surface for the development of lithium plasma facing components. The program explores liquid lithium surface under high heat flux and plasma conditions relevant to divertor and first wall of a magnetic confinement fusion reactor. We report here on an alternate solution of liquid lithium surface based on capillary structure and on the results of experimental research with the focus on steady-state operation conditions.

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2. Liquid lithium surface stability

A liquid metal surface made with a capillary porous structure (CPS) filled with lithium has been offered by the authors as a plasma facing material for application in a magnetic confinement fusion reactor [4,5]. Different aspects of this option are investigated experimentally and by supporting calculations. Liquid surface stability is one of the most important problems. A free liquid metal surface will be subjected to the forces of mechanical and electromagnetic origin that may lead to its' instability in magnetic field and to undesirable effects as splashing, waving, hydrodynamic instabilities. For tokamaks, it is the case of magnetic field pulsed operation, transition regimes, disruption events etc. If we fill a solid CPS with a liquid then due to the wetting effect we obtain a liquid surface confined by the structure where surface tension counteracts other forces and stabilize the surface. A convincing result of suppression of droplet erosion of liquid lithium has been demonstrated in disruption simulation experiments [5] with CPS target. Lithium loss was found to achieve 1–3 mm per pulse (200–500 μs, 5 MJ/m^2) for a free surface, it was reduced to 100 μm by the use of CPS with pore size 200 μm. Further reduction was shown for CPS with even smaller pore size (5 μm of lithium loss per pulse for 15 μm mesh). Fig. 1 illustrates these observations in the form of lithium mass loss vs effective pore size of CPS. Another example of lithium surface stabilization was shown in T-11M experiments with lithium CPS limiter where splashing effect was completely suppressed and experiments were performed without spontaneous bursts of lithium from the limiter surface [5]. Thus, in these experiments lithium-filled CPS exhibited excellent properties as to formation and confinement of the liquid surface and as to stability under pulsed plasmas impact.

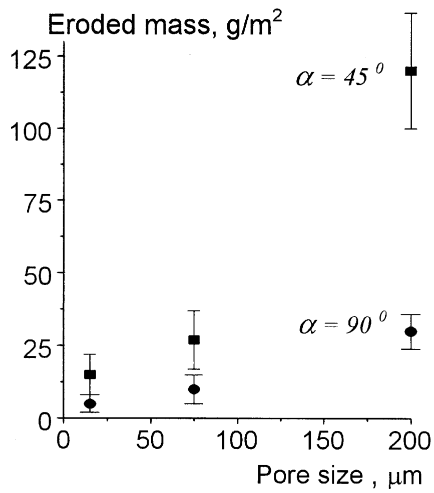

Fig. 1. Lithium mass loss vs CPS effective pore size (disruption simulation experiment at 5 MJ/m^2, pulse duration 200–500 μs, hydrogen plasma), α-plasma flow incidence angle.

3. Liquid surface in steady state

Experimental research of liquid lithium surface under high power load in steady state conditions has been performed in the beam-plasma linear machine SPRUT-4 [4]. An electron beam with maximal power 40 kW in a magnetic field 0.3 T provides power flux 1–100 MW/m^2 at the target. Lithium targets of different design were tested at the previous stage of the research [6,7]. Here we report the recent data obtained with the target shown schematically in Fig. 2. It has a capillary working surface, a transport system and forced water-cooling. This target design ensured continuous feeding of the working surface with lithium, compensation of lithium loss and regeneration of the liquid surface. A water-cooled flange served to stabilize thermal conditions at the CPS surface and in the target structure and to evacuate the heat absorbed by the target. A thermocouple was placed in the target body just behind the CPS to measure its temperature in the center of the hot spot. Calorimetric measurements were carried out to obtain the heat absorbed by the target.

The following processes are excited during interaction of the liquid lithium surface with electron beam in

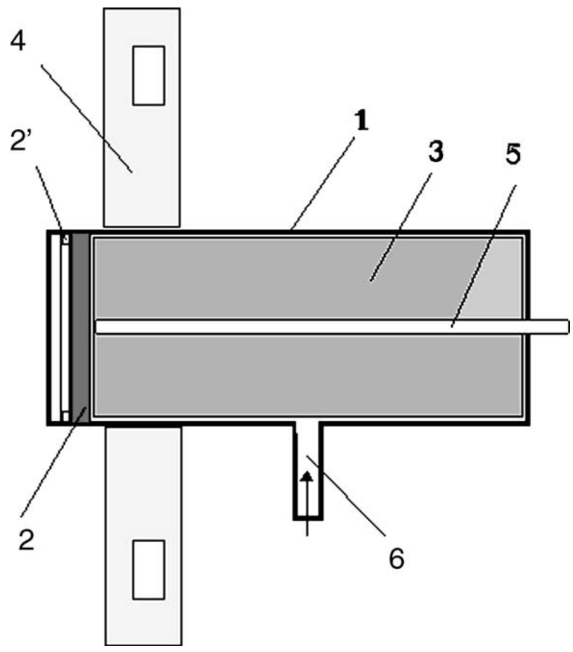

Fig. 2. Lithium target with CPS: 1 – casing; 2 – CPS (d = 40 mm); 2′ – clamp; 3 – transport structure; 4 – water cooled flange; 5 – thermocouple; 6 – lithium supply.

stationary conditions: heating of the target, lithium evaporation from the surface, lithium plasma generation in front of the target, plasma induced surface processes, lithium plasma and vapor condensation on the surrounding structure. We have investigated energy balance in the target and around it, mass balance of lithium emission, plasma parameters and the role of plasma effects in redistribution of the incident beam energy and plasma radiation.

Lithium loss rate was directly measured by level gouge in the feeding vessel and it was compared with lithium accumulation in the condenser surrounding the target [7]. The result of lithium emission evaluations is summarized in Fig. 3 as lithium loss rate plotted as a function of the incident power flux. Shown also in the figure is the limiting curve calculated for the condition when the incident heat is totally spent on evaporation. The data were obtained in stationary operating conditions when thermal fields in the target and all operating parameters were stable during the time period of 10 min to several hours. The range 1–10 MW/m^2 has been covered by this experimental series. Lithium loss rates are shown for capillary structures with different capillary sizes (mesh $\Delta = 0.15$ mm and perforated plate $r = 0$, 3 mm). No difference of lithium loss for these two types of structures was found. Therefore, we may suppose that the size of capillary was not of great importance in the studied range of power flux. Corresponding surface temperature values are shown in Fig. 4. The values measured with thermocouple are lower than corresponding surface temperatures calculated from balance by 100–200 °C, and this may be explained by thermocouple location in the body of the target and temperature gradient near the surface (see Fig. 8). Lithium emission from the target is easily explained by evaporation process for the obtained surface temperature values (see calculated curve in Fig. 3).

The role of lithium evaporation is very important in the power absorption by the target. Energy balance measurements were performed by calorimeter in the target cooling and lithium heat deposit in the condenser. It showed that the fraction of energy removed by evaporated lithium always exceeded 0.1 and it was higher for higher incident power flux achieving 0.7–0.8 at 8 MW/m^2. Efficiency of evaporative cooling of the target surface is illustrated in Fig. 5 showing the ratio of the removed to incident power as a function of the incident power load.

Ionization of lithium vapor is another important effect in the interaction of electron beam with liquid lithium surface (see photo Fig. 6). The plasma was formed as a result of beam-plasma discharge [4]. It is important to consider this effect because, first, the incident energy of electron beam is redistributed between the target and the plasma. The plasma part is spent to ionization, to excitation of neutrals, to heating of particles; the energy is transferred by diffusion and

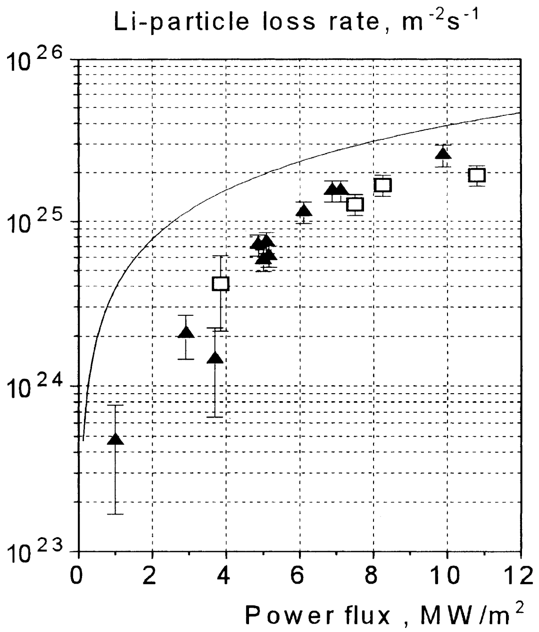

Fig. 3. Measured lithium loss rate versus incident power flux for two capillary structures: solid symbols – mesh $h = 0.15$ mm, open symbols – perforated plate $r = 0.3$ mm. The curve shows calculation of maximum lithium mass loss when the incident power is totally going to evaporation.

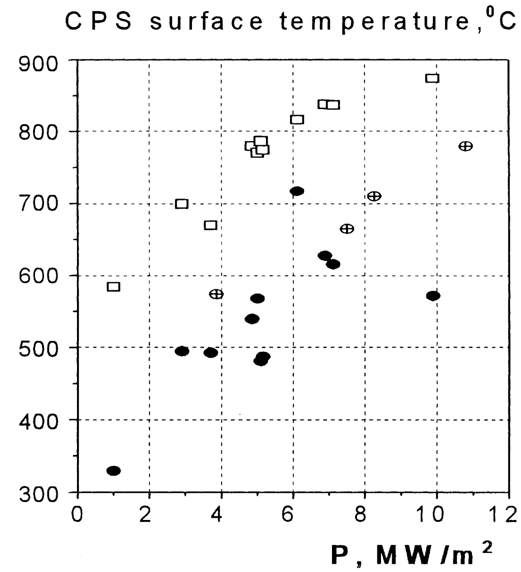

Fig. 4. Temperature at the CPS target surface as measured by thermocouple (closed circles – mesh, open circles – perforated plate) and deduced from lithium mass balance (squares).

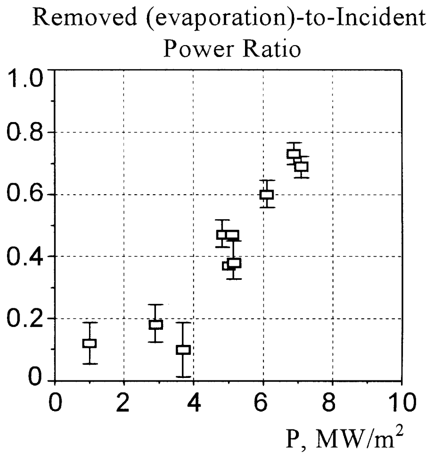

Fig. 5. Efficiency of heat removal from CPS target via evaporation vs incident power flux.

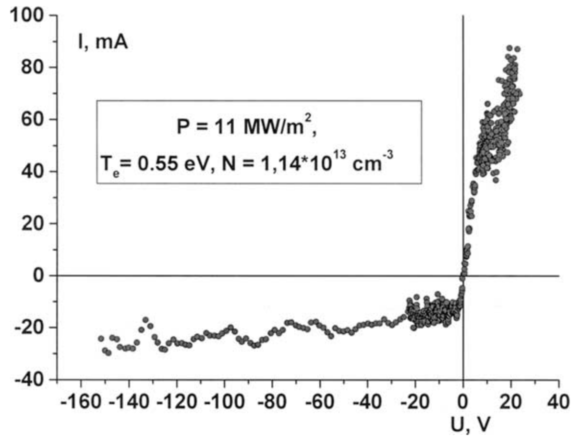

Fig. 7. Voltage–current characteristics of a single Langmuir probe taken in steady-state lithium plasma (heat flux and corresponding plasma parameters are shown).

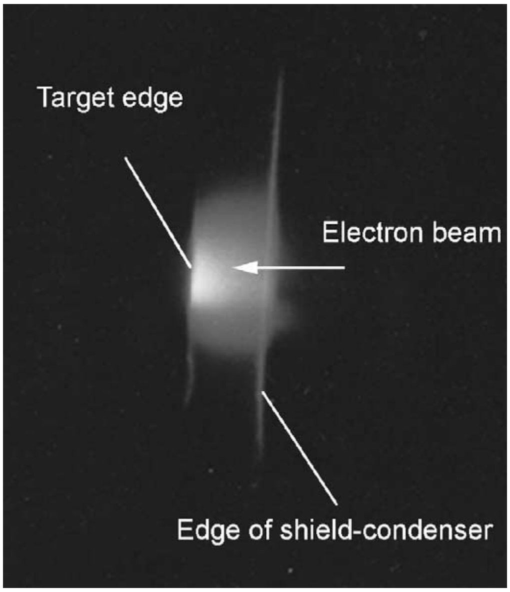

Fig. 6. Photo of lithium plasma near lithium CPS target at 4 MW/m^2 of incident power flux.

radiation. Second, heavy charged particles, ions, may achieve higher energies than those of evaporated neutrals in presence of electric field (sheath potential) leading to sputtering effects on the target surface.

Probe diagnostics technique has been developed for measurements in steady-state lithium plasma. Plasma parameters have been taken with a single Langmuir probe near the target. An example of current–voltage characteristics is shown in Fig. 7. The results reported earlier [7] have been completed in this study by direct measurements of electron temperature in the range of power loads 2–14 MW/m^2 carried out in conditions of high density of lithium neutrals. The values of electron temperature varied within a range of 0.5–20 eV and they correlated with the plasma density while power load was changed. Electron temperature was higher (15–19 eV) for lower densities $\sim 10^{12}$ cm^{-3} corresponding to 2–4 MW/m^2 of power load, and it decreased to 0.5–1 eV for densities of $\geqslant 10^{13}$ cm^{-3} at 10–14 MW/m^2. Maximal plasma density at the target surface evaluated by extrapolation was about 10^{14} cm^{-3}. Though energy absorbed by the plasma according to these measurements was not significant in comparison with the incident beam power at the level of the studied power loads (below 10%) we suppose it to become an important component at higher powers. Optical spectra showed a sharp growth (by more than an order) of linear radiation from the plasma in the visible and the near ultraviolet ranges for higher powers (increased plasma densities) when electron temperature fell below 1 eV. The observed spectra are supposed to signify the increase of the role of radiation in plasma energy balance and in the character of equilibrium conditions at power loads $\geqslant 10$ MW/m^2.

A detailed analysis of temperature distributions at the target surface and in the body was needed for better interpretation of experimental observations, for mass and energy balance and temperature measurements. Two-dimensional model of the target was elaborated for thermal analysis of the process of energy absorption by the surface. The model took account of CPS material, lithium filling, target transport structure and materials as well as of the incident power flux profile. A typical temperature field in the target is shown in Fig. 8 for 10 MW/m^2. We obtain high temperature in the loaded area (850 °C) and a high gradient in the near surface layer.

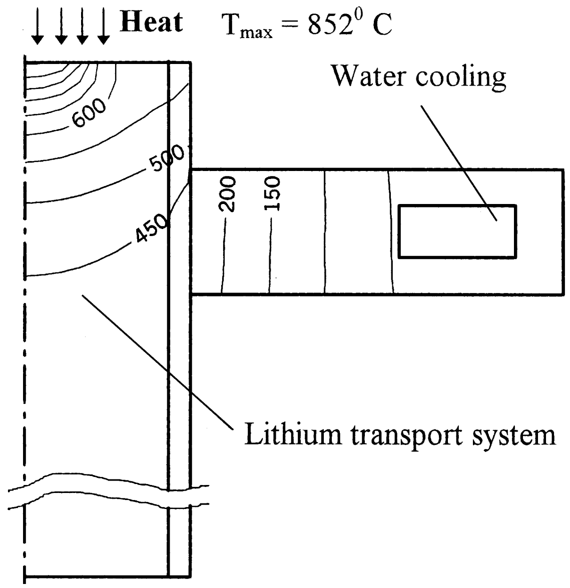

Fig. 8. Temperature field in the lithium target in steady state at 10 MW/m^2. Target diameter is 40 mm, heat loaded area diameter is 18 mm, heat sink is provided by water cooling through the cavity in flange.

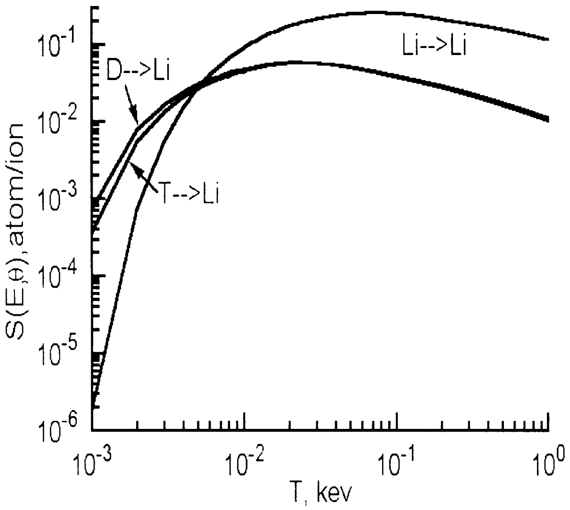

Fig. 9. Physical sputtering of lithium surface by hydrogen, deuterium and lithium ions (calculated values average over ion energy and incident angle, $\delta = Z_i e\varphi/T_i = 3$, Mach number = 1).

4. Discussion

The results of steady-state experiments here above should be considered in more details with respect to the processes on the liquid lithium surface. The power flux on the surface was the governing parameter in these experiments. Surface temperature rise to 400–850 °C was shown to be the reaction of the liquid surface to the heat load that has led to high evaporation rate. Sputtering contribution to lithium loss has been evaluated on the basis of calculations shown in Fig. 9 (see also [8,9]). Taking our experimental values of T_e and n_i for the lithium plasma near the target we find lithium ion flux bombarding the surface to achieve 10^{20} ion/cm^2 s. Therefore, the sputtered flux corresponding to the $Li^+ \rightarrow Li$ yields (10^{-6}–10^{-2} in the range below 10 eV) is lower than evaporative loss (2.5×10^{21} at/cm^2 s at maximum, see Fig. 3) by two to three orders. On the other hand, evaporative cooling of the liquid surface is so significant that it removes an important part of incident energy. If we would like to put limit of target temperature at about 400 °C (to limit lithium emission) then in presence of a high temperature gradient in the surface layer (our results are indicative of about 200 °C/cm) we would need more intensive cooling and lower temperatures in the target body. Note that the rise of liquid lithium viscosity would complicate lithium transport in the target at temperatures below 300 °C. Therefore, a liquid lithium surface operating under high heat loads in steady state at temperatures lower than 400 °C where evaporative loss is not predominant seems hardly realistic.

Considerable lithium influx appears to be one of the most serious problems of a liquid lithium divertor which will be feasible if lithium removal from the divertor volume is about at the level of emission from target plate. Lithium divertor is supposed to operate in conditions of low temperature ($\leqslant 1$ eV) and high density plasma similar to gas divertor where high collisionality would facilitate lithium transport to the walls and its removal by condensation. Lithium condensation from plasma has been demonstrated by the authors at specific mass flow rate 3×10^{23} m^{-2} s^{-1} in experiments reported in [6] and that seems to be at the level needed for divertor.

5. Conclusions

Experimental investigation of liquid lithium surface shows that the problems of stability and of wall structure resistance to pulsed and steady state power loads can be solved if we take CPS as a solid base of plasma facing material. Liquid lithium CPS targets have been elaborated and investigated in high heat flux and plasma conditions. CPS ensures stability of liquid metal surface under pulsed and stationary loads. The targets exhibited good resistance of the CPS material to heat load in stationary thermal conditions at 1–10 MW/m^2. Significant surface temperature (400–850 °C) was the most important target reaction to the incident power, it resulted in high evaporative lithium loss and efficient heat removal from the surface (70%). Lithium loss due to sputtering in high density and low temperature plasma (supposed in lithium divertor) has a negligible effect.

The most important issues of the further research and development of the liquid lithium divertor appear to be lithium emission, confinement and removal in the divertor channel. Direct experiments in divertor tokamak devices are needed to clarify the problem. We believe that lithium penetration to the SOL from the divertor region can be limited at the level tolerated by the core plasma.

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