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# Liquid metal experiments on FTU

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**Abstract**. Experiments were performed on FTU with a cooled liquid lithium limiter (CLL) and subsequently with a cooled liquid tin limiter (TLL) (end 2016) aimed at testing liquid metals (LM) under reactor relevant thermal loads of up to 10 MW/m$^2$ nearly stationary conditions. In the European framework of coordinated actions, a cooled sample of Sn Capillary porous system (CPS) type envisaged for the TLL in FTU has been tested on Pilot-PSI linear device. A power handling of 18 MW m$^{-2}$ has been demonstrated under stationary conditions and without apparent damage of the Sn sample, giving early indications that the TLL will be effective. In this paper an overview of the main activities of the last two years will be presented followed by the experimental results obtained on FTU with the new CLL system. Then, the preliminary work with the tin liquid limiter (TLL) and the results on Pilot-PSI with liquid tin samples will be described.

## 1. Introduction

In the framework of the European research for future fusion reactors, an important activity aims at testing liquid metals (LM) as a possible solution to the power exhaust problem and, in particular to evaluate constraints and limits of a LM solution, its compatibility with core performance and the link of both to the LM PFC properties (e.g. evaporation & erosion, stability).

In preparation of this program, improvements of the FTU facility started in 2014 with, 1) the extension of the pulse duration from 1.5 s up to 5 s and 2) feasibility studies to achieve diverted plasmas with the X-point near the CLL. The additional aim is to get the H-mode in plasmas heated by Electron Cyclotron Resonance Heating (ECRH) to study the impact of Edge Localized Modes (ELMs) on the CLL used as the main target. To characterize the CLL during plasma discharges, an important role has been played by the new fast infrared camera[1] looking at the CLL and by the spectroscopic signals in the visible range from Li and D line emission.

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[1] * See the appendix of G. Pucella et al., Proc. 25th IAEA FEC, Saint Petersburg, Russia, 2014

In this paper a review of the experimental results obtained in the previous (2014&2015) experimental campaigns and in the last campaign (July 2016) will be presented and discussed. Then the new Tin liquid limiter, under installation on FTU, will be described. Finally the results obtained on Pilot-PSI with liquid tin samples will be shown.

## 2. Experimental Results on FTU

This section describes the results obtained on FTU with the CLL. In the last campaign (July 2016) the shape of the limiter was modified, but due to the rupture of the Mo tube on the CLL head we performed experiments without the water cooling system. Nevertheless interesting results were obtained.

### 2.1. Experimental Campaign (2014&2015)

In order to extend the LLL operating regime up to 10 MW/m$^2$ with up to 5 s of plasma discharge duration, a CLL has been installed on FTU in 2014. The experimental program on FTU aims to test liquid metals (Li and Sn) by using the capillary porous system (CPS) that has proven to be the best configuration to confine liquid metal against MHD effects, by means of capillary forces [1]. In the CLL, shown in fig.1 a), water flows in the coolant circuit up to a temperature of about 200 °C playing a double role: it heats the lithium up to the melting point (180.6 °C) and removes the heat during the experiments.

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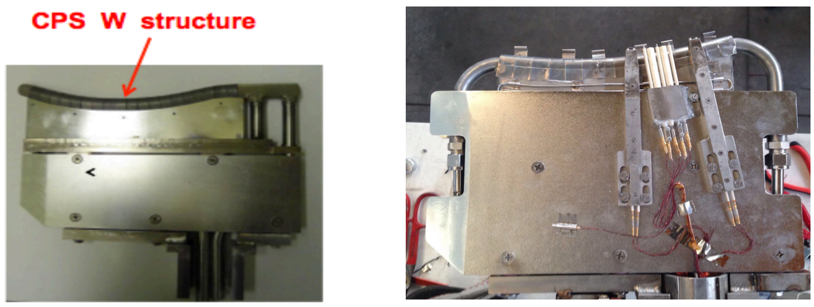


a) b)

Fig.1 a) The first version of the CLL limiter in which the red arrow indicates the W CPS structure and b) the latest CLL version in which are clearly visible the Langmuir and the ball pen probes.

To characterize the CLL during plasma discharges the following means have been used: 1) a fast infrared camera observing the whole limiter from the top of the machine (≅ 1.5 mm of spatial resolution and 300 full frames/s of acquisition rate), 2) the spectroscopic signals from Li and D atom emission 3) thermocouples for the measurement of the inlet and outlet water temperature on CLL surface and 4) Langmuir probes for the local measurement of the electron temperature and density. The actively cooled lithium limiter (CLL) has been tested for ohmic and ECRH heated plasmas ($P_{ECRH}$ =500 kW), with circular and elongated shape (k ~1.2) and for different CLL positions under the TZM toroidal limiter shadow up to 1.8 cm inside the last closed magnetic surface in elongated discharges [2]. The CLL emerging from the bottom side of the vacuum chamber is clearly seen in fig. 2 where is shown the image of the FTU plasma relative to one frame of a visible CCD camera. For almost all the conditions, the Li surface temperatures monitored by the fast infrared camera was maintained below the threshold of Li evaporation (~500 °C).

Heat loads up to 2 $MW/m^2$, as found by ANSYS code simulations, have been withstood by the limiter surface for all the duration of the plasma discharge (1.5s) [3]. In the simulations, the shape of the plasma as reconstructed by the equilibrium code, the power to the SOL ( $P_{ohm}$- $P_{rad}$ ) and $\lambda_q$=1cm have been taken into account. A water pressure of 2.9MPa and a flow rate of 0.06Kg/s (v=0.44 m/s) are generally set corresponding to an initial Li temperature of 190°C.

As an example, fig. 3 shows an IR image of the lithium limiter as seen by the infrared camera and corresponding to the end of flattop of plasma current for an ohmic discharge ($B_T$=6T, Ip=0.5MA, ne=$1.0x10^{20}$ $m^{-3}$ time duration =1.5s). The temporal evolution of the temperatures on the three points indicated in fig. 3 and located on the top of the surface do not reveal a clear trend to the thermal equilibrium. It is shown in fig. 4 for the cases of the experiment (on the left) and of the ANSYS simulation (on the right) pointing out the importance to extend to longer pulses the FTU experiments with CLL.

In elongated plasmas, a different behaviour occurred [2]. Hot spots localized on the joint points of the strips of CPS structure (maximum heat load of ~2$MW/m^2$) and Li evaporation (500 -570°C), as monitored by visible spectroscopy, have been observed. Despite of the deep CLL insertion, no plasma disruption due to Li evaporation occurred and no damage of CLL surface was observed by a visual inspection in situ from the optical window of CLL volume.

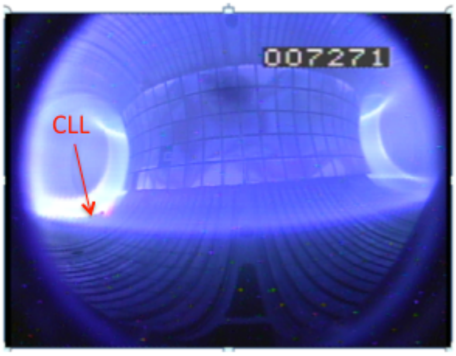


Fig.2 Image by visible camera of a plasma discharge with CLL emerging from the bottom side of the vacuum chamber.

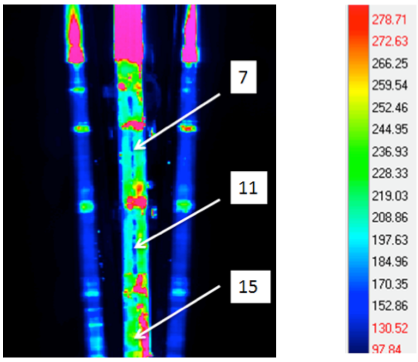


Fig. 3 IR image of the CLL as seen by the infrared camera. The surface of CLL facing the plasma is visible in the central region, while the lateral bands are due to the limiter radiation reflected by the lateral sides of the port.

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To better assess the CLL behavior, an analysis tool based on Cellular Neural Networks [4] has been developed in collaboration with the University of Catania with the aim of applying emissivity correction to the thermographic images. Furthermore, in order to refine the prediction provided by ANSYS, which does not takes into account the real behavior of the device (including the role of material imperfections), an identification procedure has been performed too. The refinement of prediction performance, in fact, may reveal to be

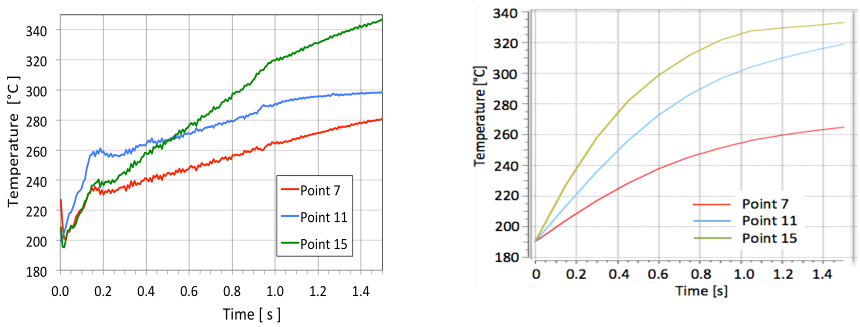


Fig.4 Temporal trend of temperature from the experiment (on the left) and from the ANSYS simulation (on the right) relative to the points of CLL shown in Fig. 3

fundamental to improve the CLL performance, namely allowing a more accurate control of the temperature distribution over the CLL. To act as main limiter in long pulses it is important that the limiter surface is uniformly wetted by the plasma, i.e. the shape of the last closed magnetic surface has to fit as much as possible the limiter curvature

The model identification has been performed on the basis of data-driven methods, i.e. analyzing the thermographic data and comparing them with other process variable, such as the actual geometrical features of the plasma ring. After preliminary phases during which correlation between the considered data have been estimated candidate inputs for the data-driven model have been selected, the functional relationship between the selected inputs and the thermal distribution of the CLL surface has been identified.

The correlation analysis between each selected candidate variables with respect to the CLL thermal distribution as measured by the infrared camera has been performed and plasma shape related variables, namely the elongation and upper radius, have been selected as model input. Furthermore, being the heating a diffusion process, the thermal evolution of a CLL point is supposed to be driven by its neighbours in the previous time steps. Thus, the 8-neighbours pixel connectivity has been adopted and considered as model inputs too.
Once chosen the model input variables, three different model structures have been considered , namely a linear autoregressive model (ARX) with three poles and two zeros, a nonlinear autoregressive model (NARX) with three poles and two zeros realized by mean of an Artificial Neural Network (ANN) with 8 neurons, and an Hammerstein model (HM) with three poles and one zero. The analysis of the models performance leads to assess the suitability of the three approaches, which produce good results as it is shown in fig 5. However, the Hammerstein model shows better statistical properties of the error dynamics along with a relatively simple structure in which only static input nonlinearities are considered. Furthermore, the Hammerstein model is able to predict temperature behaviour also in presence of abnormal plasma experiments, i.e. those experiments in which the plasma ring shows instabilities leading to an early end.

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**Comment [1]:** Logic - "something" may have revealed that the control of the limiter surface is fundamental in order to improve the CLL performance. What is that "something"? I am also not quite sure what this means. Of course the performance is limited by the surface temperature. I would argue the other way around that performance improvements will result in a lower (better controlled) surface temperature.

Holger Reimerdes 22/9/2016 21:20
**Comment [2]:** Not clear what this is. I would have thought that ANSYS is perfect to predict the thermal behaviour of the CLL, isn't it?

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Holger Reimerdes 22/9/2016 21:21
**Comment [3]:** What are the target variables?

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**Comment [4]:** What are these?

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**Comment [5]:** What dataset? The measured surface temperature?

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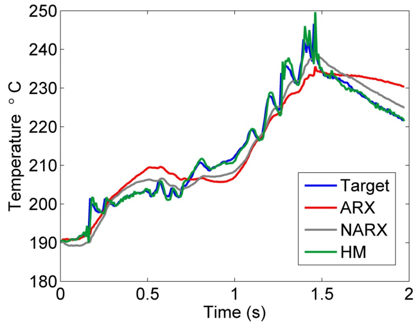


Fig 5. Temporal evolution of the temperature of a pixel of the IR camera during a plasma disruption. Comparison between the output of the three models with respect to the measured CLL temperature.

### 2.2. Experimental Campaign (2016)

Due to a rupture in the Mo tube, the modified CLL (see fig 1.b) was exposed to plasma without water cooling. Nevertheless it was inserted deeply into the SOL and in many discharges was tangent to the last closed magnetic surface. Three different experiments were performed: 1) discharges at plasma current $I_p$= 0.5 MA, $B_t$=4 T , $n_e \sim$ 6.0 $10^{19}m^{-3}$, pulse length 1.5 s, 2) shots at $I_p$= 0.3 MA, $B_t$=4T, $n_e$=4.5 $10^{19}m^{-3}$, pulse length 3 s, 3) discharges like those of point 2) but with variable plasma elongation k between 1.05 and 1.2 during the shot itself.

Totally were performed 32 shots with 14 disruptions but not due to the lithium limiter. The lithium limiter was dismounted at the end of the campaign and its surface was bright without any damage while the Langmuir and the ball pen probes were heavily damaged.

Data analysis is still on-going and here we present only the preliminary results regarding the first type of experiments in which the limiter was inserted up to 1 cm from the last closed magnetic surface. In fig. 6 the plasma current, the electron density and the evolution of the Li I emissivity as recorded by a visible spectrometer looking directly to the limiter, are shown. In these discharges we have collected data mainly from Langmuir probes moving the limiter shot by shot. The Langmuir probes were fixed very close to the limiter surface and in fig. 7 the heat load radial profile is shown. The no-cooled lithium limiter withstands at least a heat load of q=5MW/$m^2$ without any problem with an e-folding length of $\lambda_q$= 0.76 cm

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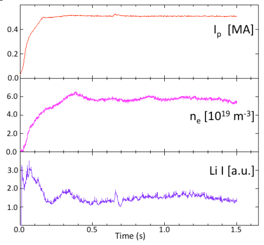
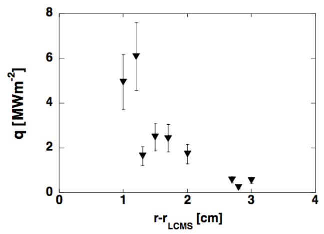
|  |  |
| Fig. 6 Plasma current, density and Li I emissivity. The limiter was 1.5 cm away from the LCM | Fig. 7 Heat load radial profile obtained shot by shot by Langmuir probes at t=1s |

## 3. TLL – Tin liquid limiter

In fig. 8 it is shown the new Tin limiter installed on FTU. CPS assembly has been made from the unified porous tungsten elements with overall dimensions of 70×11×1 mm.

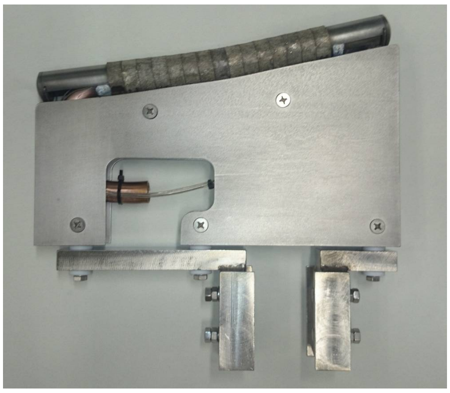


Fig. 8 The new Tin CPS limiter

The 16 tungsten elements have been wetted with high purity tin (Sn - > 99,8 wt. %, Si – 0.2 wt. %) at the temperature of 1050°C. The porosity of CPS elements is determined from the following equation and is equal to 0.33.

$$\varepsilon = 1 - M / \rho V = 0.33, \qquad (1)$$

where ε- porosity; M – mass of dry element; ρ- specific density of W; V- element volume.

The in-vessel parts include the electrical heater and the cooling channel with a water atomizer. The electrical heater of in-vessel element provides heating up and maintenance of the TLL initial temperature at 250-300°C. Temperature stabilization of TLL plasma facing surface (maximal level of surface temperature) during plasma discharge is supposed at desirable level in the range of 300-800°C that prevents Sn evaporation and corrosion effect. Heat removal from plasma facing surface during plasma discharge is provided by intermittent injection of Ar - water spray from the atomizer to the cooling channel of TLL. The heat removal process is based on the evaporation of water spray on the inner surface of cooling channel. System will work at low pressure of Ar and water (~2 bar). The calorimeter is included into the system for estimation of power flux to the TLL surface. Calorimetric measurements are based on the conventional principles – heat transfer from the object (TLL) by heat transferring media to the heat capacity (water) in calorimeter and measurement of its temperature change. Out-coming flow of water vapour, Ar gas and water spray mixture from TLL comes to the fixed volume of water with fixed initial temperature in the calorimeter. A measured change in temperature of water in the calorimeter (by thermocouple) provides the possibility to estimate the power flux to the TLL from plasma. This calorimetric method has been developed in detail and successfully experimentally checked in laboratory tests.

It is worth while to note that FTU will be the first tokamak in the world to test liquid Tin as alternative solution to conventional solid divertors.

## 4. Experiments on Pilot-PSI

As part of the preparations to determine the expected power handling for the FTU Sn-limiter, a Sn-filled CPS target was exposed to plasma in Pilot-PSI [5,6] and compared to a reference W target. Both targets were exposed to He plasma at heat fluxes up to 18.1 MW $m^{-2}$. The following observations were made:

- XPS results indicate that the CPS surface remains wetted by the tin and that there is no apparent damage to the W CPS wire.
- No droplet production was observed, in agreement with expectations from stability analysis against Kelvin-Helmholtz and Rayleigh-Taylor instabilities
- Finite element analysis of the targets indicates that thermal conductivity of the mixed CPS layer can best be represented according to the rule of mixtures as $k_{CPS} \sim f k_{Sn} + (1-f) k_W$ where $f$ is the volume fraction of Sn and $k_i$ is the thermal conductivity of material $i$ (fig. 9).

This indicates that an actively cooled tin limiter can operate at much lower temperatures than 1000 °C for heat loads of 10 MW $m^{-2}$ as expected in FTU, sufficient to keep evaporation at an acceptable level.

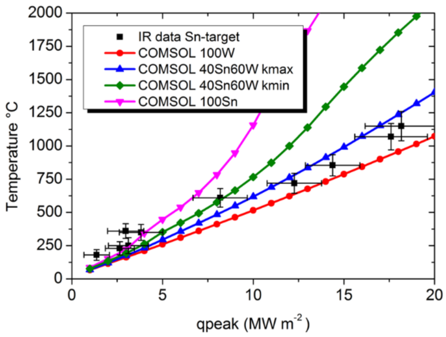



Figure 9: Equilibrium temperatures of the Sn-CPS target at the plasma centre compared to different COMSOL models treating the CPS layer in different ways according to the rule of mixtures limits ($k_{max}$ and $k_{min}$) or as pure Sn or pure W.

## 1. Final Remarks

The development of a reliable solution for the power and particle exhaust in a reactor is recognised as a major challenge towards the realisation of a nuclear fusion power plant [7]. To mitigate the risk that the conventional divertor solution adopted for ITER will not extrapolate to a robust fusion power plant (DEMO), the European fusion consortium (EUROfusion) is investigating alternative divertor solutions.

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In this framework, since 2006 FTU is the medium size tokamak in Europe in which experiments on liquid metals have been performed: as first step by using a liquid lithium limiter and then a Tin liquid limiter.

The main aim is to assess the capability of liquid Li/Tin to act as a plasma facing material under heat loads greater than 10 $MW/m^2$. This means to demonstrate the possibility to have an operational temperature window in which evaporation, specially for Li, is kept under control and in the case of Tin that the exposure to the plasma of a high Z material is compatible with plasma operations without strong influx or accumulation in plasma discharges.

**Acknowlegment**

*This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission*

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