Comparison between liquid lithium and liquid tin limiters in FTU

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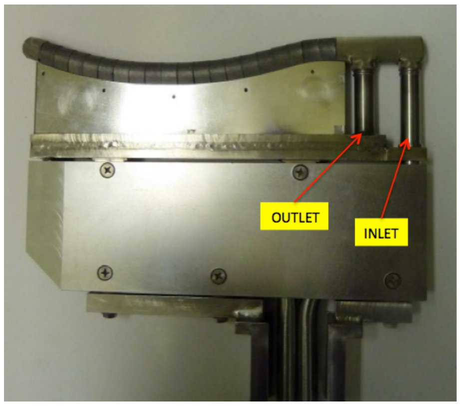
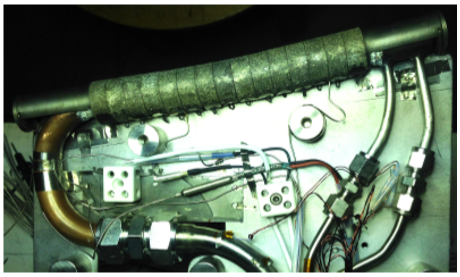
Introduction

The Frascati Tokamak Upgrade (FTU) is a medium-size metallic machine: the toroidal limiter is TZM (98% Mo), the vacuum chamber is stainless steel. Estimates of the power flux at the LCMS show that high parallel heat loads can be easily achieved. Therefore it is possible to perform significant experiments with liquid metals in order to test their behaviour and compatibility in a magnetically confined plasma scenario. Since 2006, several liquid metal limiters were installed on FTU: the first Liquid Lithium Limiter (LLL)[1], is shown in figure 1(a). Later, in order to investigate higher heat loads on the liquid surface, an advanced version of the lithium limiter with active cooling (CLL) [2] has been developed, figure 1(b). Several layouts of the CLL have tested on FTU. Finally, for the first time, a liquid tin limiter (TLL)[3] has been installed a few months ago, as shown in figure 1(c). All tested liquid metal limiters use the innovative Capillary Pore System [1]. The limiters have been exposed to many plasma discharges and several disruptions with no observable damage of the tungsten mesh, by visual inspection, after their respective experimental campaigns. In this paper the preliminary comparison between the results with the lithium and the tin limiter without active cooling are presented.

(a)



(b)



(c)

Figure 1: (a) Liquid lithium limiter; (b) cooled lithium limiter; (c) liquid tin limiter.

Systems and diagnostics description

A short description of the three systems follows:

- The LLL was the first liquid metal limiter ever used on FTU. The main purpose of that system was to test the CPS compatibility with tokamak operation and its use as evaporator in order to investigate lithization [5] of the first wall. The system was composed of three different modules, each one equipped with a lithium reservoir, the CPS target, and an electrical heater to melt lithium.

- The CLL was developed to increase the heat load on the limiter keeping the surface temperature under the evaporation threshold. Overheated water was used both to heat the lithium up to operating temperature and to remove the heat during the plasma pulses.

- The TLL represents the most recent layout. In this system an electric heater provides the operative temperature, while an atomizer allows the dispersion of a water-gas mixture. This technique promises very high cooling rate but it is still under investigation. Experiments with active cooling will not be discussed in this paper.

The limiters have been equipped with dedicated diagnostics in order to measure the relevant parameters in our investigations. Particularly significant are the surface temperature monitor, the electron temperature and electron density close to the limiter itself and the fast dedicated D-alpha monitor. The LLL was equipped with three single point IR-sensors (HgCdTe) [1], one for each module; the complete surface temperature has been acquired for the CLL and the TLL using a fast IR-thermocamera. Starting from the measured temperature data it has been possible to compute the power flux on the liquid surface using the heat equation and the Fourier law with the semi-infinite body approximation. Different computation methods have been used for the numerical evaluation of the heat load, i.e. Cook and Ferland method, the direct convolution formula and one self-developed algorithm based on the Discrete Fourier Transform [7]. Furthermore the data from the four Langmuir probes (LP), located close to the limiter, is congruent with the IR-camera measurements. The heat load profile, as computed by the Langmuir probe using the Stangeby theory [9], is shown in figure 2. The above mentioned methods have been applied to the data from the three limiter types (LLL, CLL and TLL) and the results are in agreement with the expected heat load. Data comparison between the two diagnostics, for a typical discharge, is shown in figure 3.

The shape of the FTU Langmuir probes allows the shot by shot verification of the molybdenum electrodes status. Before each plasma shot a sinusoidal voltage is acquired at the end of the probe: if the probe head is interrupted a warning signal comes out. This procedure allows to detect any modifications in the collection probe area after an abnormal event such as a disruption.

Comparison

Lithium and tin have several physical and chemical differences, i.e. the atomic weight (directly related with the plasma compatibility), thermal, corrosion [3] and retention [8] properties. Lithium must be manipulated in vacuum or in an inert gas atmosphere (i.e. argon), while tin can be handled with less stringent rules at room temperature. Thus lithium chemical reactivity must be taken into account when designing a possible future lithium-based reactor. Tin corrosion at high temperature may be a problem in a possible future tin-based reactor and requires a thorough investigation.

The limiters have been exposed to several different plasma discharges with transient heat load up to ten MW/m^2, without damages on the CPS surface.

A model to investigate the lithium vapour shield observed in FTU is currently under development [7]; similar effect with tin is reported in [6]. The lithium limiter has shown a flattening of the surface temperature, as shown in figure 4, which deviates from the heat conduction model provided by ANSYS code. The flattening of the surface temperature can be linked to the surface evaporation phenomena. Using the tin limiter, the deviation from the ANSYS model has been observed above relevant tin evaporation temperature, as shown in figure 5. Such effect has been achieved placing the TLL at a few millimetres from the LCMS: the temperature evolution has clearly moved from the ANSYS simulated at high temperature level. The operative temperature window, larger for tin than lithium, strictly depends on the respective vapour pressure curves.

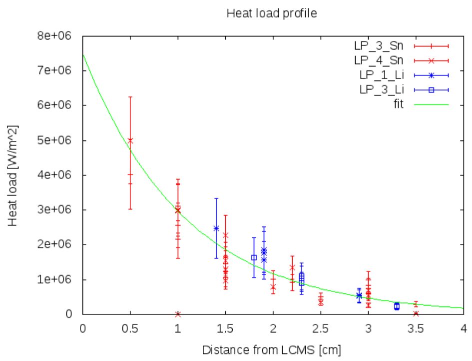


Figure 2: The probe measured profile.

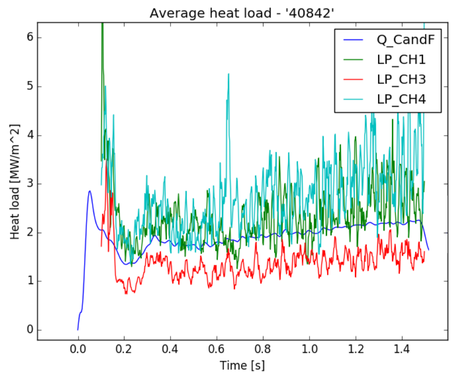


Figure 3: Comparison between the heat load computed by the LP and the average from the camera using the Cook and Ferland algorithm.

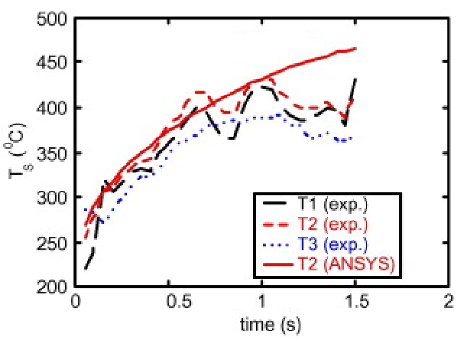


Figure 4: Experimental surface temperature evolution for the LLL compared with the ANSYS model.

It has been possible to provide an estimation of the impurity content in the discharge from the Z-effective measurement. From the UV spectra some pulses have been identified as completely dominated by lithium or tin. Assuming that lithium or tin are the only impurity the effective charge Zeff is $Z_{eff} = \frac{Z_{imp}^2 \cdot n_{imp} + Z_H^2 \cdot n_H}{n_{tot}}$. Substituting in the equation the values for the selected pulses we got respectively $n_{\%_{Li}} = (1.0 \pm 0.8)\%$ and $n_{\%_{Sn}} = (0.05 \pm 0.03)\%$. With the tin limiter we observed the absence of any impurity lines on the UV spectra until the surface temperature reached a sufficient high level, approximately $1500°C$, where evaporation becomes important.

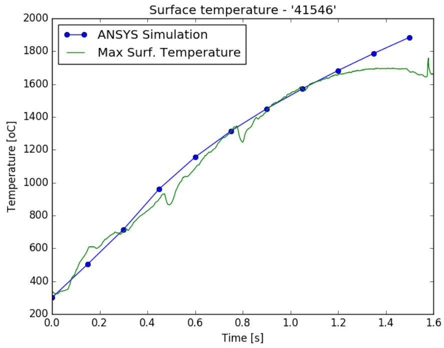


Figure 5: Ansys model vs the TLL experimental surface temperature.

Conclusion

In summary, the experiments performed so far demonstrate the possibility for liquid materials of withstanding high transient heat loads, with the added quality of self-healing properties. Technological improvements have followed the liquid metals experiments on FTU. Several CPS meshes have been tested, several layouts have been investigated and different diagnostic tools have been applied. The experience with lithium and tin fixes the physical (i.e. the operative window) and technological constrains for the next design phase.

Acknowledgments

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References

[1] A. Vertkov et al., Fusion Eng. Des. v. 82-15 p. 1627, (2007)
[2] M. Iafrati et al., Fusion Eng. Des. v. 117 p. 157, (2017)
[3] A. Vertkov et al., Fusion Eng. Des. v. 117 p. 130, (2017)
[4] J.W. Coenen et al., Phys. Scr. T159 (2014) 014037
[5] M. L. Apicella et al., Plasma Physics and Controlled Fusion, Vol. 54, N. 3, (2012)
[6] G. G. van Eden et al., Phys. Rev. Lett. 116, 135002 (2017)
[7] G. Mazzitelli, M. Iafrati et al., PSI-2016 Rome (2016)
[8] J. P. S. Loureiro, et al., Fusion Eng. Des.,117 (2017) 208-211
[9] P. C. Stangeby, Plasma Phys. Control. Fusion 42(2000) B271-B291