Visible spectroscopy with Tin liquid limiter on FTU plasma

G.M. Apruzzese, M.L. Apicella, M. Iafrati, G. Mazzitelli,

F. Bombarda, L. Gabellieri, A. Romano and FTU Team*

ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Frascati (Roma), Italy

**See the appendix of G. Pucella et al, Proceedings of the 26th IAEA Fusion Energy Conf., Kyoto, Japan, 2016, OV/P-4*

Introduction In the framework of the liquid metal research it has been taken into account the use of liquid metals as plasma facing materials in fusion devices. Two different materials have been studied in the Frascati Tokamak Upgrade (FTU): lithium and tin. The successful experiments with liquid lithium limiter [1], started since 2006, have pointed out the importance to explore other liquid metal materials for the limiter such as tin, whose operating temperature window is much larger than for lithium [2]. The possibility to increase the operation temperature allows increasing the steady state heat load on the limiter surface up to very high values. The liquid tin limiter, TLL, has been tested on FTU in the experimental campaign started at the end of 2016. The preliminary analysis of the experimental data has been focalized to detect the presence of tin in the discharge: suitable monitors are the spectroscopic diagnostics in the visible and VUV ranges. The analysis of the spectroscopic signals has been carried out considering the processes of tin release into the plasma. In this framework, the data from the infrared fast camera for monitoring the TLL surface temperature are of particular importance. In this paper experiments with tin limiter exposed to the plasma will be described and the first preliminary analysis of experimental spectroscopic data will be illustrated.

Experimental setup In Fig.1 it is shown the Tin limiter installed on FTU. It employs the Capillary Porous System (CPS), which was proved to be very suitable for the confinement of liquid metals against MHD effects by means of capillary forces. The TLL limiter is equipped with several thermocouples and four Langmuir probes for the local measurement of the plasma electron temperature and density. The surface temperature of the TLL limiter is recorded with a fast infrared camera [3] observing the whole TLL surface from the top of the FTU machine with a spatial resolution of ~ 1 mm and up to 1200 frames/s of acquisition rate.

A 3D finite-element code ANSYS has been used to reproduce the TLL surface temperature limiter and to calculate the maximum heat load withstood by the TLL, taking in account a 3D real design of the limiter and the plasma shape as reconstructed from the magnetic measurements.

For detecting and monitoring the presence of Sn in the plasma during the discharge, the spectroscopic diagnostics, in the visible and VUV ranges, have been used. The collecting optical system for the visible spectrometer is placed on the top of machine at the same vertical port of TLL, placed at the bottom side. In detail, the visible spectroscopic diagnostic is performed by using a spectrometer, Ocean Optics HR4000, covering the bandwidth 380–830 nm. The HR4000 is equipped with grating with 600 g/mm, an entrance slit of 25 µm and a detector with 3648 pixels that provide a spectral resolution of 0.51 nm (FWHM). The spectrometer is connected, through an optical fiber, to a telescope collecting the light coming from the tin limiter [4]. A 20 mm diameter spot on the TLL surface is observed through a single line of sight. The presence of Sn, and of any other impurity, in the FTU plasma core is monitored by means of a survey spectrometer SPRED equipped with two interchangeable diffraction gratings with 290 g/mm and 2100 g/mm that cover the 20–170 nm and 10–30 nm spectral range with a resolution of 0.7 nm and 0.14 nm, respectively [5].

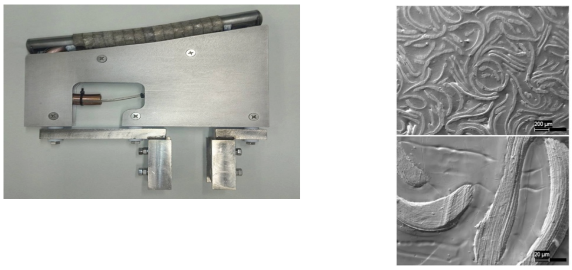

Fig. 1. On the left, the tin limiter, TLL, is shown. At the top of TLL is visible the molybdenum tube with CPS stripes, made by tungsten felt filled with tin. On the right, the CPS surface is shown in two pictures with different magnification.

Experimental results and discussion In the first tin limiter campaign (autumn 2016), experiments were performed with a standard ohmic discharge, $I_p = 0.5$ MA, $B_T = 5.4$ T and $n_e = 6\times10^{19}$ m^{-3}, in which the tin limiter has been inserted, progressively, in the FTU plasma up to a position very close to the last closed magnetic surface (LCMS). In the second tin limiter campaign (spring 2017), the experiments were performed with discharges characterized by the same values of I_p and B_T but with higher electron density, $n_e = 1.0\times10^{20}$ m^{-3}, both in ohmic regime and with additional heating power by using LH and ECRH systems. The experiments have been performed in repeated discharges characterized by very clean conditions. In the first TLL experimental campaign, the Sn spectral lines in the visible range were successfully observed [6]. In Fig.2 for the discharge #41215, the spectrum is shown with the Sn spectral lines.

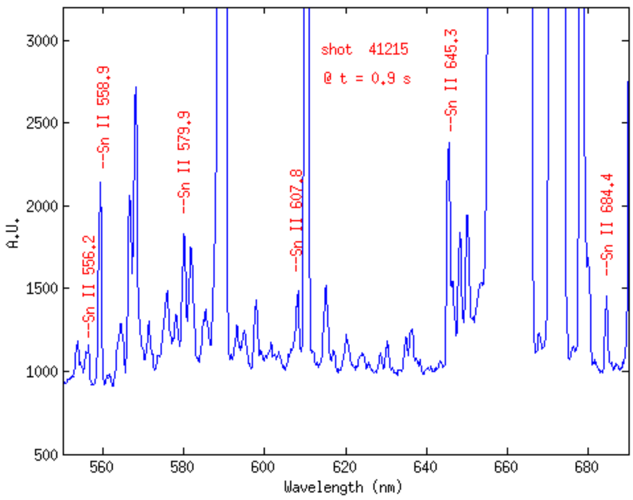

Fig. 2. Visible spectrum in experiments with tin limiter in the FTU plasma discharge #41215.

This line identification was performed using the listed wavelength in the NIST database [7]. All the Sn observed lines belong to the first ionization state and are given by transitions in the configuration $5s^2nl$, that is the same configuration of the ground state $5s^2\,5p$, term $^2P^o$. The wavelengths of the observed lines are, in nm: 645.35, 684.4, 553.2, belonging to the terms of transition $^2S - {}^2P^o$, 556.2 of $^2P^o - {}^2D$, 558.9 , 579.7, 579.9 of $^2D - {}^2F^o$ and 607.8 , 608.0 of $^2F^o - {}^2G$. No Sn II spectral lines from 5s5pnl configuration are observed because their intensities are below the minimum detectable values, as expected from the theoretical calculation [7]. The most intense lines of Sn II have the wavelengths 558.9 nm and 645.3 nm. Some lines are unresolved, due to the spectral resolution of the spectrometer. It is under investigation the absence in the spectrum of the neutral Sn lines, although the most significant line of Sn I at 452.473 nm has the same relative intensity of the observed Sn II lines. In addition, the presence of small amount of carbon and boron in FTU discharges does not permit to clear identify some observed lines, such as the 614.9 nm line of Sn I. In these experiments no tin spectral lines in the VUV region have been observed, on neither of the two gratings [5,6]. For this discharge with TLL very close to the plasma (#41215), the experimental temperature is well simulated by ANSYS with a maximum heat load of 11 MW/m^2 in the hottest region of the Sn limiter, see fig.3. In order to increase the heat load on the TLL surface, the second tin limiter experimental campaign has been performed operating with high electron density. For these discharges Sn lines have been successfully observed both in the

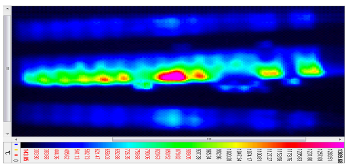

Fig.3 Image of the Tin limiter surface as recordered by fast infrared camera.

visible range and in the VUV region. For the discharge #41546, in the hottest region of the TLL surface, the experimental temperature reaches 1700 °C, as shown in Fig. 4. This temporal trend is well simulated by ANSYS code with a value for the heat load of 18 MW/m^2 in the temporal range 0.4-1.5 s. In this discharge, characterized by the highest heat load reached up to now on FTU, the quantity of tin released into the plasma does not significantly change the plasma performances as the Zeff and the energy confinement time. For the Zeff signals both the evaluation from Bremsstrahlung radiation and from electrical resistivity has been taken in account. The observed lines in the VUV region are: 20.48 nm of Sn XXI and 21.8 and 27.6 nm of Sn XXII [5,6].

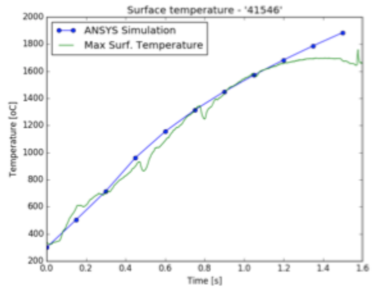

Fig.4 Reconstruction by ANSYS (blu line) of TLL experimental temperature (green line).

Conclusions FTU is the first tokamak in the world operating with a liquid tin limiter and one of the pioneers in liquid metal application. Experiments with tin as plasma facing material have been successfully performed on FTU device. Most of the predicted spectral lines in the visible region have been successfully observed. In conditions of high heat load, up to 18 MW/m^2 on the hottest region of TLL, when its maximum temperature value reaches 1700 ºC, the Sn spectral lines have been clearly detected also in the VUV spectrum.

References

1. M.L. Apicella et al.., J. Nucl. Materials **363–365,** 1346 (2007).
2. G. Mazzitelli et al., IAEA, '*Liquid metal experiments on FTU*', (2016) Ex/P8-21.
3. G. Mazzitelli et. al, J. Nucl. Mater. **463**, 1152 (2015).
4. G.M. Apruzzese et al, Fusion Eng. Design **117** 145 (2017).
5. F. Bombarda et al., EPS Proceedings (2018)
6. G.M. Apruzzese, Plasma Phys. Rep., to be published (2018)
7. NIST Data Base, www.nist.gov/pml/atomic-specta-database.

Acknowledgement

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.