WPDTT1-PR(17) 19015

G Apruzzese et al.

# First spectroscopic results with tin limiter on FTU plasma

Preprint of Paper to be submitted for publication in
Plasma Physics Reports

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.

# FIRST SPECTROSCOPIC RESULTS WITH TIN LIMITER ON FTU PLASMA

G.M. Apruzzese[1,*], M.L. Apicella[1], M. Iafrati[1], G. Mazzitelli[1], L.Gabellieri[1], J.P.S. Loureiro[2], A. Romano[1] and FTU Team[1]

[1]*ENEA, Fusion and Technologies for Nuclear Safety Department,*

*C.R. ENEA Frascati, via E. Fermi 45, 00044 Frascati (Rome), Italy*

**e-mail:* gerarda.apruzzese@enea.it

[2]*Instituto de Plasmas e Fusão Nuclear, IST, Universidade Técnica de Lisboa*

*1049-001 Lisboa, Portugal*

**Abstract –** Since the end of 2016 experiments were performed on FTU with a tin limiter, for testing liquid metals under reactor relevant thermal load up to 17 MW/m$^2$ in nearly stationary conditions. FTU is the first tokamak in the world operating with a liquid tin limiter and one of the pioneers in liquid metal application. 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 UV ranges. The experimental observation of the tin spectral lines represents a new goal for extending the database of atomic nuclear data in the plasma tokamak research. In particular, 607.8 nm and 645.3 nm spectral lines of SnII have been observed. In addition, all the expected spectral lines in UV range have been detected, 20.4 nm of SnXXI and 21.9 nm and 27.6 nm of SnXXII..

In this paper the preliminary results obtained during these experiments with the tin limiter in FTU will be presented.

## 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. Since 2006, a liquid lithium limiter has been tested on FTU [1] and the successful experiments and the promising results have pointed out the importance to explore other liquid metal materials for the limiter such as tin whose operating window is much larger than lithium [2]. The boiling points of these two metals are quite different: 2602 °C for the tin and 1342 °C for the lithium.

The possibility to increase the operation temperature allows increasing the steady state heat load on the limiter surface up to very high values.

The tin limiter has been tested on FTU in the experimental campaign started at the end of 2016. FTU is the first tokamak in the world operating with a liquid tin limiter and one of the pioneers in liquid metal application. 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 production and 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.

## 2. EXPERIMENTAL SETUP

In fig.1 it is shown the Tin limiter installed on FTU and its CPS configuration, which is the best configuration for confining liquid metal against MHD effects by means of capillary forces. The TLL is provided by an actively cooling system by flowing air and water in a copper tube inserted in the molybdenum tube. The TLL limiter is equipped with several thermocouples and four Langmuir probes two for each side, for the local measurement of the plasma electron temperature and density. Besides, in order to characterize the TLL during plasma discharges, a fast infrared camera observing the whole limiter surface has been used [4]. 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.

In details, the visible spectroscopic diagnostic is performed by using a spectrometer, Ocean Optics HR4000, covering the bandwidth 380 - 830 nm with a maximum time resolution of 10 ms. 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 [3]. Both the collecting optical system for the visible spectrometer and the infrared camera [4] are placed on the top of machine at the same vertical port of TLL, placed at the bottom side. The presence of Sn inside the plasma column is detected by the SPRED UV-spectrometer. The spectrometer is equipped with two interchangeable diffraction gratings; spectral ranges and resolutions are 10–30 nm with 0.14 nm and 16–170 nm with 0.7 nm respectively and the acquisition time is 0.02 s.

## 3. EXPERIMENTS

In the first tin limiter campaign (autumn 2016), the experiments were performed with a standard ohmic discharge, $I_p$ = 0.5 MA, $B_T$ = 5.4 T and $n_e = 6x10^{19}$ $m^{-3}$, in which the tin limiter has been inserted, progressively, in the FTU plasma 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, $n_e = 1.0 \times 10^{20}\ m^{-3}$, both in ohmic regime and with additional heating power by using LH and ECRH systems.

In both experimental campaigns the tin limiter has been used without the actively cooling system. The experiments have been performed in repeated discharges characterized by very clean conditions, due to the only presence inside the plasma of Mo impurity, coming from the TZM toroidal limiter.

## 4. EXPERIMENTAL RESULTS AND DISCUSSION

In the first TLL experimental campaign, the Sn spectral lines in the visible range were successfully observed. In fig.2 the spectrum is shown with the Sn spectral lines which identification is reported in table 1. This line identification was performed using the listed wavelength in the NIST database [5]. Some lines are unresolved, due to the spectral resolution of the spectrometer. All the Sn observed lines belong to the first ionization state and result by transitions in the configuration $5s^2nl$, that is the same configuration of the ground state $5s^25p$, term $^2P^o$. The terms of the observed transition are: $^2S$ - $^2P^o$, $^2P^o$- $^2D$, $^2D$ - $^2F^o$ and $^2F^o$- $^2G$.

No Sn II spectral lines from 5s5pnl configuration are observed because the expected intensity is too low for detection.

Generally, in spectra dominated by oxygen the line at 558.882 nm is not useful for spectroscopic analysis because of its overlapping to the 559.237 nm line of O III.

No lines of the neutral Sn have been observed, although we expect to observe the line 452.473 nm since its expected intensity is comparable to the intensity of the observed Sn II lines.

In these experiments no tin spectral lines in the VUV region have been observed, on both the two gratings.

Although Sn limiter surface reaches, in a limited central region, as shown in fig.3, temperatures up to 1300 °C, not far from the exponential increase of the evaporation rate, the plasma performances do not significantly change.

For this discharge, the numerical simulation performed with ANSYS code shows that a maximum heat load of 11 $MW/m^2$ has been achieved with the Sn limiter very close to the LCMS.

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 and with additional heating power. In these conditions, the temperature of the TLL surface exceeded and evaporation became important. For these discharges Sn lines have been successfully observed both in the 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. The temporal trend is well simulated by ANSYS code by assuming, as input data, a value for the heat load of 17.2 MW/m$^2$.

In this discharge, characterized by the highest heat load reached up to now on FTU, the quantity of tin is below the critical value of the radiative collapse and the plasma performances, as the Zeff and the energy confinement time, does not significantly change.

The spectrum in the VUV region is shown in fig.5 and the identified spectral lines are listed in table 2. The observed lines are: 20.48 A of Sn XXI and 21.8 and 27.6 nm of Sn XXII. There is also an unresolved multiplet at 13.5 nm that will be accurately investigate in the near future with a high resolution SWHOB spectrometer. The indentified Sn lines in the VUV region have been also detected in similar experiments on MAST [6], [7].

In order to explore a wider spectral region, the SPRED has been used also with the 20-180 nm grating. The fig.6 shows the spectra recorded in two discharges with and without TLL inserted. Besides the lines already observed with the other grating, no more spectral lines have been observed at other wavelengths.

## 5. CONCLUSION

Experiments with the tin as the plasma facing material have been successfully performed on FTU device.

Spectroscopic measurements have been made in the visible and VUV regions and most of the predicted spectral lines have been successfully observed. An effort will be made in the future to investigate the absence of the neutral Sn spectral lines in the visible range.

The spectral lines in the VUV region have been observed when the tin limiter has been exposed to the plasma with a heat loads up to 17.2 MW/m$^2$. In this condition, the tin limiter surface reaches the maximum temperature value of 1700 °C and the quantity of tin released into the plasma, due to the evaporation, can be detected by VUV spectroscopic diagnostic. In future an effort will be made to explore other spectral region at lower wavelength as the extreme ultraviolet, EUV, in order to study the behavior of the Sn highly ionized.


## ACKNOWLEDGEMENTS

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


## REFERENCES


1. M.L. Apicella,G. Mazzitelli, V. Pericoli Ridolfini, et al., *J. Nucl. Materials 363-365 (2007) 1346-1351*
2. G. Mazzitelli et al., *IAEA 2016,* ‘*Liquid metal experiments on FTU’,* Ex/P8-21
3. G.M. Apruzzese, et al.,*Fusion Eng. Des, 117 (2017) 145-149*
4. G. Mazzitelli, et al., J. Nucl. Mater. 463 (2015) 1152–1155
5. NIST Data Base, www.nist.gov/pml/atomic-specta-database
6. A. Foster, et al., *J. Nucl. Materials 363-365 (2007) 152-156*
7. A. Foster, ‘*On the behaviour and radiating properties of heavy elements in fusion plasmas*’, Thesis submitted for the degree of Doctor of Philosophy at the University of Strathclyde, 31st August 2008.


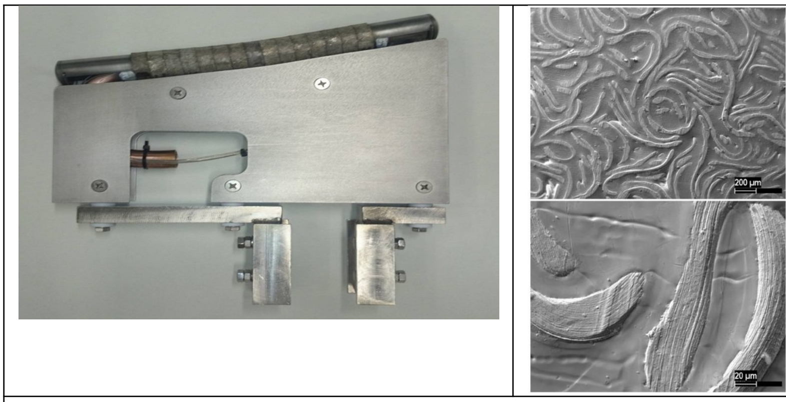


**Fig. 1.** On the left, the tin limiter, TLL, and its CPS (Capillary System Structure) configuration, on the right.

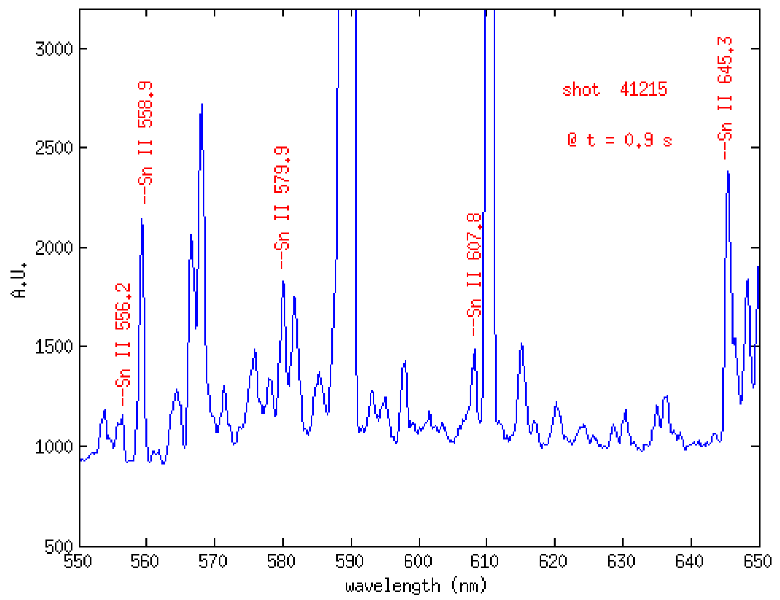


**Fig. 2.** Visible spectrum recorded by the HR4000 spectrometer in experiments with tin limiter in the FTU plasma.

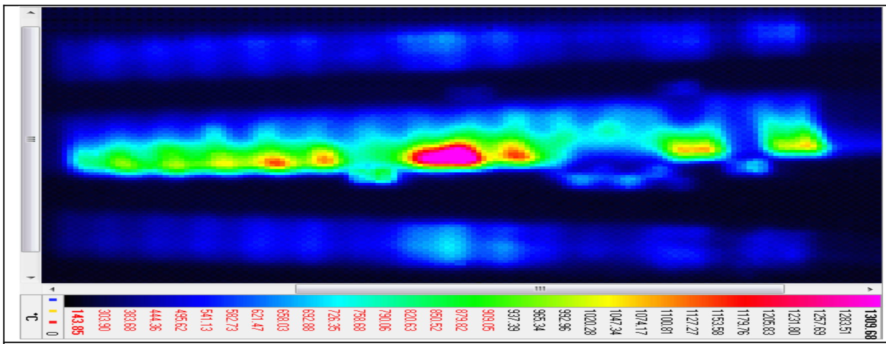

**Fig. 3.** Typical temperature distribution on the Tin limiter surface during the plasma discharge ( #41215) at 1.5 s, as measured by fast infrared camera. The central part of the image is the TLL, while the sides are the reflections from the port.

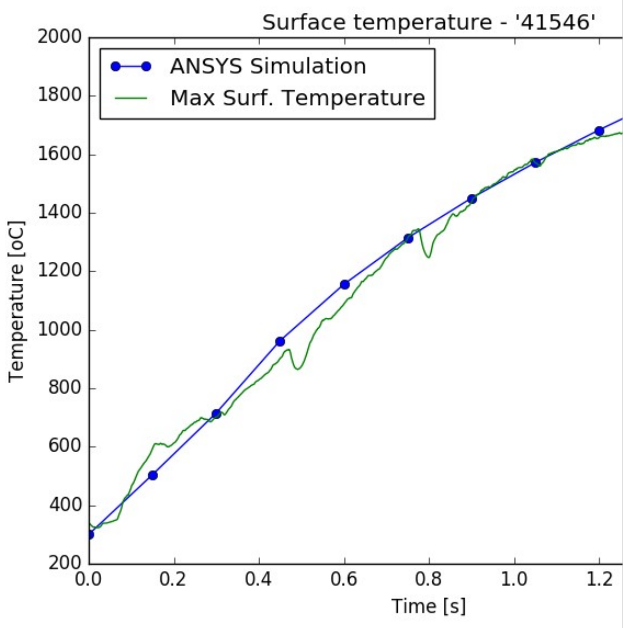


**Fig. 4.** Reconstruction by ANSYS (blu line) of TLL experimental temperature (green line), for FTU discharge #41546. As input data, a heat load of 8.6 $MW/m^2$ for t < 0.3 s and a heat load of 17.2 $MW/m^2$ for 0.3<t< 1.5 s have been considered.

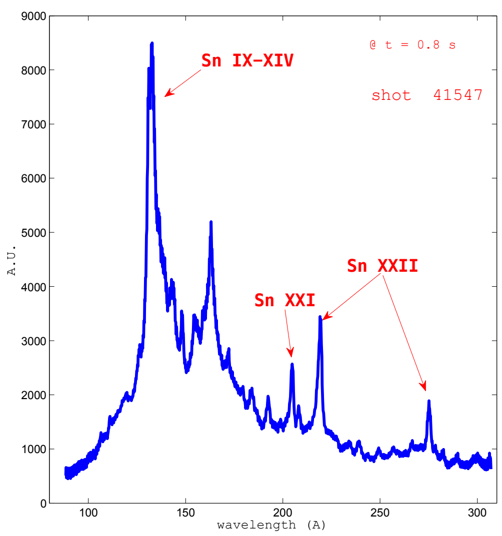


**Fig. 5.** Observed spectrum in the VUV region for the FTU discharge #41547. The spectrum has

been recorded with the SPRED spectrometer with the 10-30 nm grating.

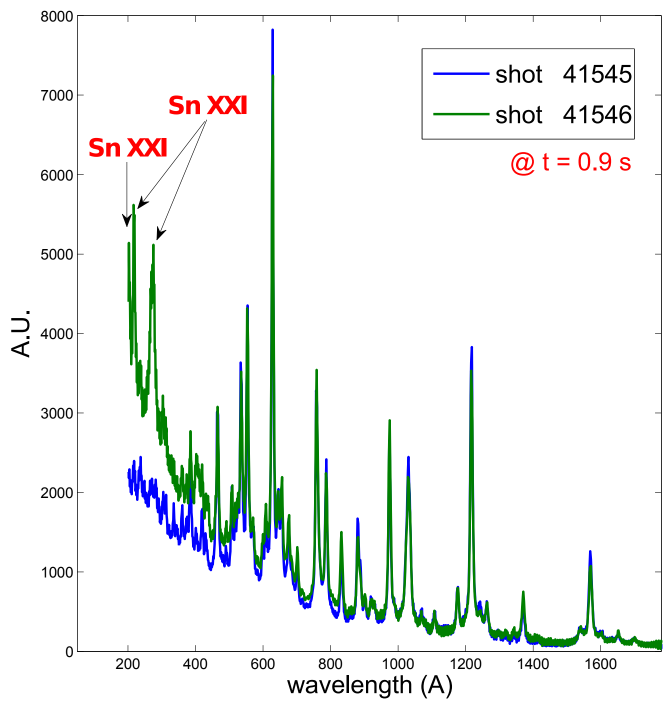


**Fig. 6.** VUV spectra on FTU plasmas with the 20-180 nm grating, for discharges without TLL inserted (blu line) and with TLL inserted (green line).

Table 1

Line identification for tin in the visible region

| $\lambda$ (nm) | Species | Transition |
|---|---|---|
| 553.234 | Sn II | $5s^2 6p\ ^2P^o_{1/2} - 5s^2 6d\ ^2D_{3/2}$ |

| | | |
|---|---|---|
| 556.191 | Sn II | $5s^26p\ ^2P^o_{3/2}$ - $5s^26d\ ^2D_{5/2}$ |
| 558.882 | Sn II | $5s^25d\ ^2D_{3/2}$ - $5s^24f\ ^2F^o_{5/2}$ |
| 579.691 | Sn II | $5s^25d\ ^2D_{3/2}$ - $5s^24f\ ^2F^o_{3/2}$ |
| 579.886 | Sn II | $5s^25d\ ^2D_{5/2}$ - $5s^24f\ ^2F^o_{7/2}$ |
| 607.763 | Sn II | $5s^24f\ ^2F^o_{7/2}$ - $5s^26g\ ^2G_{7/2}$ |
| 607.763 | Sn II | $5s^24f\ ^2F^o_{7/2}$ - $5s^26g\ ^2G_{9/2}$ |
| 607.977 | Sn II | $5s^24f\ ^2F^o_{5/2}$ - $5s^26g\ ^2G_{7/2}$ |
| 645.354 | Sn II | $5s^26s\ ^2S_{1/2}$ - $5s^26p\ ^2P^o_{1/2}$ |
| 684.419 | Sn II | $5s^26s\ ^2S_{1/2}$ - $5s^26p\ ^2P^o_{3/2}$ |

Table 2

Line identification for tin in the VUV region

x=2 for Sn XIV and x=7 for Sn IX

| λ (Å) | Species | Transition |
|---|---|---|
| 135 multiplet | Sn IX-XIV | $4p^5\ 4d^x$ - $4p^6\ 4d^{x-1}$ |
| 204.8 | Sn XXI | $4s4p\ ^1P_1$ - $4s^2\ ^1S_0$ |
| 218 | Sn XXII | $4p\ ^2P_{3/2}$ - $4s\ ^2S_{1/2}$ |
| 276 | Sn XXII | $4p\ ^2P_{1/2}$ - $4s\ ^2S_{1/2}$ |