High Resolution EUV Spectroscopy on FTU with Tin Liquid Limiter

F. Bombarda[1], G. Apruzzese[1], L. Carraro[2], L. Gabellieri[1], M.E. Puiatti[2], A. Romano[1], M. Valisa[2], B. Zaniol[2], M.L. Apicella[1], E. Giovannozzi[1], A. Grosso[1], M. Iafrati[1], G. Mazzitelli[1], V. Piergotti[1], G. Rocchi, A. Sibio[1], B. Tilia[1], and the FTU team*

[1]*ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy*

[2]*Consorzio RFX, Corso Stati Uniti 4, 35127, Padova, Italy*

Introduction

FTU is an all-metal limiter machine characterized by an extremely low level of impurities of any kind, therefore it is particularly well suited for investigating the performances of liquid metal limiters under high thermal loads (in FTU up to 18 MW/m^2). During recent experimental campaigns the plasma behaviour has been studied with a Tin Liquid Limiter (TLL, Fig. 1), while previous tests were carried out with a Lithium Liquid Limiter [1]. Both are based on the innovative Capillary Porous System [2], with or without active cooling. Liquid metals have high evaporation temperatures, but once those are reached, the onset of the "vapour shielding" phenomenon provides further cooling of the plasma edge. So far, the experiments demonstrate that liquid materials can withstand the same heat loads as solid limiters, with the advantage of self-healing mechanisms. The resulting contamination of the plasma core remains to be more precisely documented in the case of TLL, due to lack of absolute intensity calibration of the VUV and XUV spectrometers.

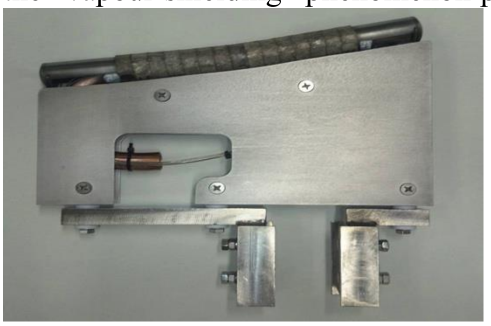

Fig. 1. The new TLL module installed on FTU

Spectroscopy of Tin in FTU plasmas

A 2m grazing incidence *Schwob-Fraenkel* XUV spectrometer [3] was recently installed on FTU, with a fixed equatorial line-of-sight, to observe the plasma emission in the range from 20 to 340 Å. Experimental data of Tin spectra from high temperature plasmas are scanty; for this reason, our first goal was the identification of the main spectral features, to support further studies of transport of Tin in the plasma core, and to complement previous observation regarding vaporization and plasma contamination.

Considerable effort was devoted to updating and expanding a comprehensive list of theoretical and experimental wavelengths for all the ions to be observed in our tokamak plasmas. FTU is a circular machine with a stainless steel AISI 304 Vacuum Vessel of 33 cm minor radius, Fe and Ni being its dominant elements, and a Mo toroidal limiter of 29 cm; the vessel is routinely boronized. Oxygen is hardly present, and C is also low; occasionally N is detected, while Ne is injected at times for diagnostic purposes.

TABLE I – *Partial list of the most prominent identified Sn lines**

Ion	λ (Å)
SnXXII	55.56
Sn IX-XVI	135
SnXX	139.8
SnXIX	144.6
SnXXI	162.85
SnXXI	203.2
SnXXII	219.0
SnXXII	276.0
SnXXI	301.7

*Experimental values

The high spectral resolution of the Schwob instrument when equipped with a 600 g/mm grating has allowed the identification of several spectral lines of Sn ionization stages up to SnXXIV. The Tin lines have been isolated against the metal-dominated background spectrum typical of FTU plasmas in a limited range of plasma parameters (B_T=5.3 T, I_p=0.5/0.7 MA, $T_e \leq 1.5$ keV, $n_e \leq 10^{20}$ m^{-3}). The vertical position of the TLL was varied on a shot by shot basis from being flush with the VV totally in the shade of the toroidal limiter to be almost at the LCMS. Many more lines remain to be identified, and higher ionization stages are not to be excluded. Line identification in the newly recorded high resolution spectra has highlighted an issue of instrumental absolute wavelength calibration that is especially critical when exploring the almost unknown Tin spectrum. In some instances, where the spectrum is especially crowded with lines, the spectral comparison with the lower resolution, survey spectrometer SPRED (100-300 Å), was not trivial even for the same discharge at overlapping wavelength ranges.

The lines identified with reasonable confidence are listed in Table I. The unresolved transition array at about 135 Å [4] that was recorded previously with the SPRED instrument,

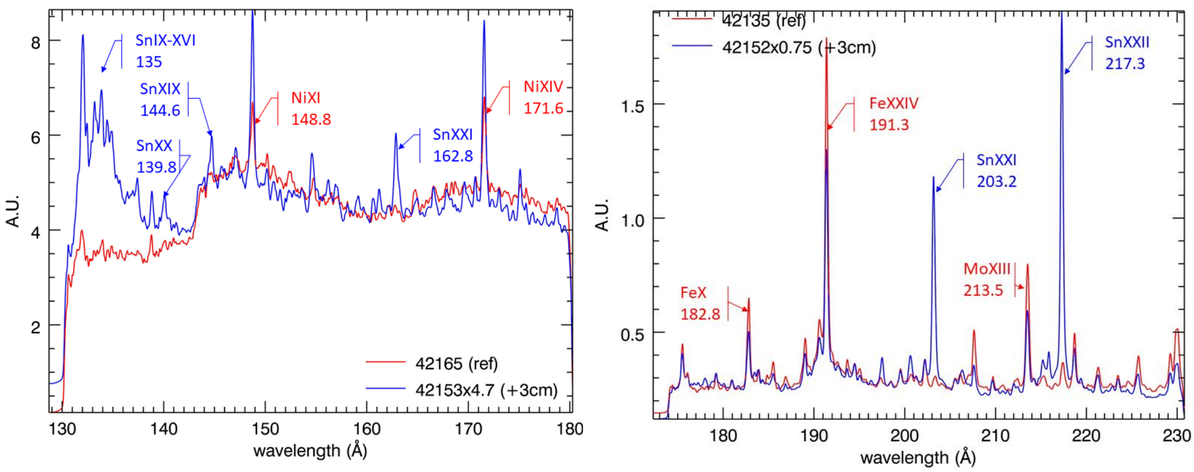

Fig. 2. Comparison of different segments of the observed spectral range for two discharges, one with the TLL fully retracted (in red), and the other with the TLL at + 3cm (in blue). The blue curves are normalized to the same background level.

is now clearly visible as a "bump" caused by Sn transitions, with a minor contamination by other metals (Fig. 2, left panel). Also the adjacent spectral range (right panel) is dominated by Sn and Mo lines, confirming the scarce presence of light impurities in the FTU plasmas.

The set of discharges where the Schwob spectrometer was active covered a rather limited range of plasma parameters and of thermal loads on the TLL. Tin in itself did not seem to be the direct cause of any plasma disruption for this limited set of experimental conditions, although some discharges did end with hard disruptions, more likely for other reasons.

The time evolution of two lines of SnXVI and SnXXI for one discharge where the TLL was placed at 2.5 cm inside the VV is shown in Fig. 3, to be compared to lines of CIV, FeXVI, and NiXVIII, all of them recorded by the Schwob spectrometer, and one SnII line in the visible range [5]. It can be observed how the rise of Sn lines, which move in phase, seem to follow the decrease of the C line, while Fe and Ni are not affected. The increase of line brightness from about 1.2 s is also reflected in the radiated power signal, but Z_{eff} remains constant at less than 1.2: in these conditions the plasma contamination is still contained; this is consistent with previous rough estimates, based on observations with instruments in the visible spectral range, which led to values of maximum Sn relative concentration of the order of 5×10^{-4} in the plasma core [1] in worse case scenarios. The moderate increase of signal over time, with some oscillations towards the end of the plasma current flat top, is observed also in otherwise extremely stationary discharges, such as those used for the spatial scans described below.

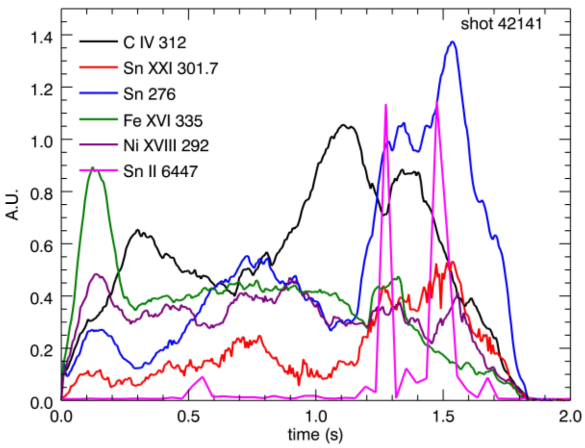

Fig. 3. Time evolution of four spectral lines from different ions recorded during a single discharge by the XUV spectrometer, together with one Sn line from the visible spectrometer. All wavelengths are in Å.

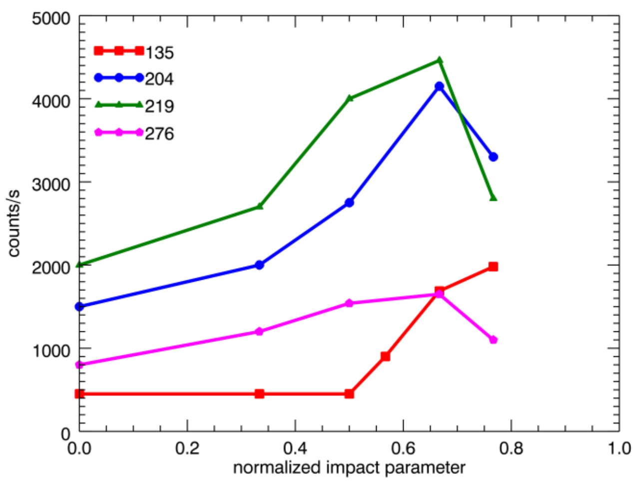

Fig. 4. Spatial scan of the plasma cross section in discharges with TLL at 3.5 cm

Radial distribution of Sn ions

Some of the Sn lines were also identified with the SPRED instrument and used to perform a spatial scan of the plasma cross section, on a shot-by-shot basis of repetitive discharges (B_T=4 T, I_p=0.5 MA, $T_e \leq 1.5$ keV, $n_e \leq 10^{20}$ m^{-3}). The instrument was tilted upward so that the impact parameter of its line-of-sight varied from 0 to 23 cm in steps of few cm at the time, while the TLL was kept at 3.5 cm. The lines used in Fig. 4 are all seen to be peaked off-axis, as to be expected for these intermediate ionizations stages. Lack of recommended and validated data regarding ionization equilibria for Sn has so far prevented more detailed analysis of these experimental results.

Conclusions

A full wavelength scan was performed with a high resolution *Schwob-Fraenkel* XUV spectrometer in order to identify spectral lines from Sn different ionization stages suitable for monitoring the performances and impact on plasma parameters of the Tin Liquid Limiter under investigation in FTU. Few more Tin lines have been identified, in addition to those previously observed with the low resolution, survey SPRED spectrometer. In these round of experiments the TLL was not pushed to its limit; the Sn line brightness is seen to increase towards the end of the discharge, but not to the point of causing a measurable variation in Z_{eff}. A more extended identification of the Tin spectra will be carried out in the near future, to further integrate the atomic databases, also by means of a higher resolution grating for the *Schwob-Fraenkel*. A more detailed study of the Tin effects on plasma performances over a wider range of plasma parameters is also planned

Acknowledgments

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.

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

[1] G. Mazzitelli, et al., 44th EPS 2017, O5.132.

[2] A. Vertkov et al., FED **82-15,** 1627 (2007)

[3] J.L.Schwob *et al., Rev. Sci. Instrum*. **58,** 1601(1981).

[4] G.M. Apruzzese, et al, *Plasma Phys. Rep*., to be published (2018).

[5] G.M. Apruzzese, et al., this conference, P4.1025