Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 152–156
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Erosion and transport of Sn and In in the SOL of MAST plasmas

A.R. Foster [a,*], G.F. Counsell [b], H.P. Summers [a]

[a] Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[b] Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK

Abstract

A satisfactory method for monitoring the erosion of vessel wall tiles in a fusion power plant remains an important missing diagnostic in the fusion program. Spectroscopic observation of embedded impurity layers may provide such a capability. In a preliminary experiment, Sn and In have been introduced to the scrape off layer of MAST plasmas by erosion from a target mounted on the reciprocating probe system, and have been successfully observed spectroscopically in the core and at the edge. The atomic transitions corresponding to each observed spectral line and feature have been predicted and then identified, with those in the visible region being used to estimate the erosion/influx rate. The confined plasma emission has been measured and modelled using the impurity transport code UTC-SANCO. The results show that eroded Sn and In emission is observable and distinguishable in MAST, and shows that the technique has promise for use in future devices.

PACS: 52.25.V; 52.70; 52.40.H

Keywords: MAST; Erosion and deposition; Impurity transport; Probes; Spectroscopy

1. Introduction/motivation

In a future fusion power plant erosion of the vessel walls will be a serious concern. Estimates of the erosion rates of the graphite divertor tiles in ITER range from 1 to 16 nm/s depending on the plasma regime [1,2], equivalent to up to 50 cm/burn year of erosion in ITER. This will only become worse in continuously burning power plants. One proposed method of monitoring this without resorting to frequent in-vessel inspections is to embed marker layers of non-intrinsic elements in the wall tiles. As the tiles erode these layers will be exposed to the plasma. If the marker elements enter the core and emit an observable characterising spectral signature then the location of the damage can be localised. A more detailed discussion of this technique is given in [3]. As a preliminary study of this technique, heavy elements (In and Sn, $Z = 49$ and 50, respectively) have been eroded from a probe into the SOL of MAST plasmas to observe the release and transport of these impurities in the SOL and core, and the distinguishability of their emission.

* Corresponding author. Fax: +44 1235 466379.
E-mail address: adam.foster@ukaea.org.uk (A.R. Foster).

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.01.056

2. The materials probe

A new materials probe head, shown in Fig. 1, has been designed for use on the MAST reciprocating probe system. The probe is constructed with removable boron nitride mushroom shaped tips which are coated with the material to be studied. The radius of the probe is 5 cm, with the mushroom being 5 cm in radius and 1 cm in height (0.5 cm for the upper surface, 0.5 cm for the stalk). In these experiments, a coating thickness of 0.7–1.0 μm was used (the layer is not completely uniform due to uneven deposition on the curved surface). The mushroom shape maximises the area of material exposed to the plasma, and also reduces the C redeposition onto the upper surface.

Embedded in the tip are two Langmuir probes, one on the very front and one 2.5 mm further back and towards the edge. These have been used mainly in ion saturation current mode to give a measure of the local particle flux at the probe tip.

The reciprocating probe system on MAST is located on the outboard midplane, and can reciprocate inwards up to 10 cm in 100 ms. It has interchangeable heads, including the newly designed Gundestrup Probe [4]. This has been used in similar plasmas to provide a comparison with Sn/In free plasmas.

3. Experimental setup

Two impurity spectrometers were used to monitor the released elements in the plasma. SPEX, a visible spectrometer, was setup to observe the probe tip by mounting a lens almost directly opposite the probe tip, as shown in Fig. 2. The angle was such that it allowed use of a lens with a very narrow field of view. This ensured that all the emission at the tip was captured but relatively little of the background plasma light. SPEX was used to observe the neutral, singly and doubly ionised stages which ionise close to the probe tip and so can provide an influx estimate.

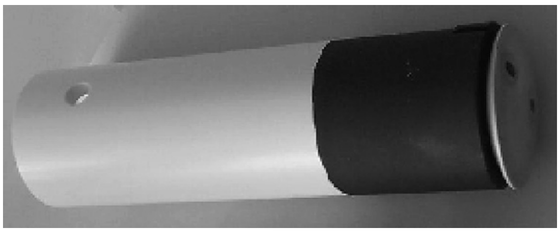

Fig. 1. The new materials probe head for the MAST reciprocating probe system.

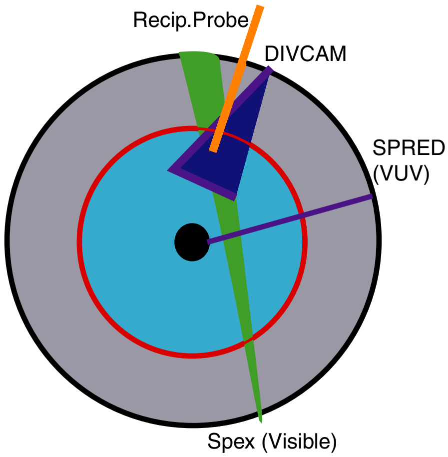

Fig. 2. The experimental setup showing the lines of sight of the spectrometers. All are mounted on the midplane except DIVCAM, which is below the midplane looking towards the upper divertor.

SPRED, a VUV grating spectrometer [5] mounted on the outboard midplane with a radial line of sight was used to monitor the higher ionisation stages of the impurity in the confined plasma.

A divertor imaging camera (DIVCAM) was fitted with a filter to show the Sn II line at 5333 Å. This camera has a wide field of view, which encompasses the probe tip, allowing a 2D picture of the Sn emission near the tip. The system has two CCDs recording the same view with different filters, allowing emission from two different lines to be observed simultaneously (D_α has been used as the additional line here).

Several different plasma types have been used for these studies to investigate heavy species SOL transport and core penetration in a variety of SOL conditions. Sn has been eroded into upper single null (USN, 13832-13835) and lower single null (LSN, 14479, 14480) ohmic plasmas. In has been introduced to identical lower single null, ohmic plasmas as for Sn. New scenarios have been devised to provide sawtooth free ohmic LSN and connected double null (CDN) plasmas, which are simpler for modelling. These have been used with In. Most of the work in this paper refers to the studies with Sn. Plasma parameters for these shots are shown in Fig. 3.

Simulations were made of the spectral line emission and envelope feature emission for Sn and In as a function of plasma conditions with code from the

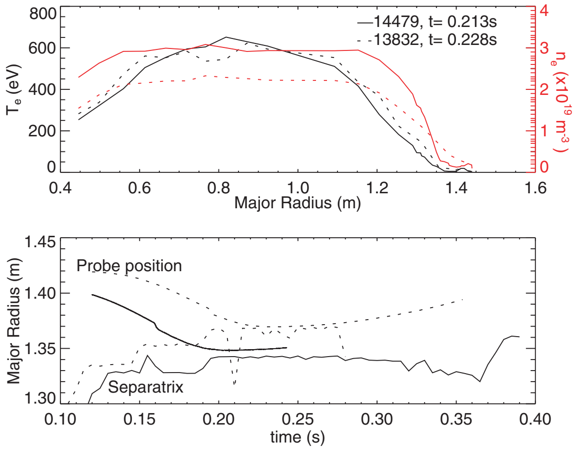

Fig. 3. The ohmic plasmas used for Sn in this study, USN plasma 13832 and LSN 14479.

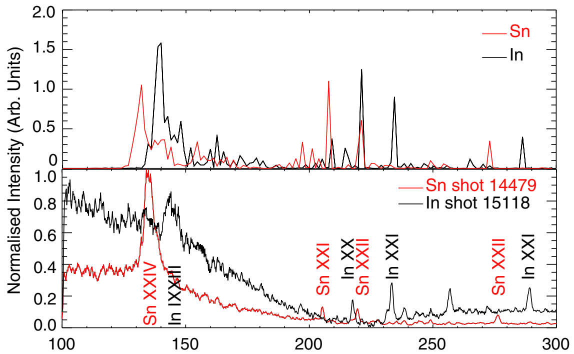

Fig. 4. (Top) predicted and (bottom) observed VUV spectra for In and Sn probe heads.

atomic data and analysis structure (ADAS [6]) and the atomic structure code of Cowan [7]. Useful visible lines were identified and their wavelength corrected using data from NIST [8] and other sources [9–11]. The predicted spectra in the VUV region are shown in Fig. 4.

4. Experimental results

Sn and In were successfully observed with identified lines and features in both the visible and VUV spectra, in all plasma configurations. Typical recorded spectra are shown in Fig. 4. Table 1 shows the line identifications. As was predicted, the strongest lines in the VUV region were from the Cu and Zn like stages (4s and $4s^2$ respectively). There is also a strong quasi-continuum feature from Sn and In at 135 Å and 143 Å, respectively, due to the

Table 1
Line identification for Sn and In

λ (Å)	Species	Transition
205	Sn XXI	$4s4p\ ^1P_1 \rightarrow 4s^2\ ^1S_0$
219	Sn XXII	$4p^2P_{\frac{3}{2}} \rightarrow 4s^2S_{\frac{1}{2}}$
276	Sn XXII	$4p^2P_{\frac{1}{2}} \rightarrow 4s^2S_{\frac{1}{2}}$
5333	Sn II	$5s^26d^2D_{\frac{3}{2}} \rightarrow 5s^26p^2P_{\frac{1}{2}}$
5351	Sn III	$5s6p\ ^3P_1 \rightarrow 5s5d\ ^3D_2$
5370	Sn III	$5s6p\ ^3P_0 \rightarrow 5s5d\ ^3D_1$
5563	Sn II	$5s^26d^2D_{\frac{5}{2}} \rightarrow 5s^26p^2P_{\frac{3}{2}}$
217	In XX	$4s4p\ ^1P_1 \rightarrow 4s^2\ ^1S_0$
233	In XXI	$4p^2P_{\frac{3}{2}} \rightarrow 4s^2S_{\frac{1}{2}}$
289	In XXI	$4p^2P_{\frac{1}{2}} \rightarrow 4s^2S_{\frac{1}{2}}$

Exact identification for the visible In lines has yet to be made, hence they are omitted.

$4d^N \rightarrow 4d^{N-1}$ (5f + 6p) unresolved transition arrays [12].

Observation using DIVCAM (Fig. 5) showed that all significant Sn II emission occurred within 1 cm of the probe. This means that even with the narrow lens acceptance cone SPEX can be assumed to be observing the total plasma Sn II content.

Data from the Langmuir probes in the mushroom were recorded for the Sn plasmas in ion saturation (I_{SAT}) mode. These were found to agree well with measurements using the Gundestrup probe, suggesting that any perturbation to the SOL due to the presence of the probe is independent of the material.

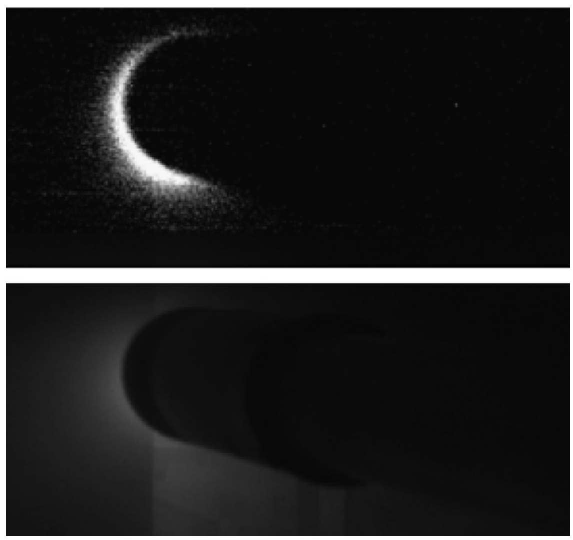

Fig. 5. DivCam picture of the rear of the probe during peak interaction showing (top) the Sn II and (bottom) the D_α emission.

5. Erosion rate calculations

Most SOL impurity transport codes make the assumption of toroidal symmetry, and of trace impurity contamination of the bulk plasma. A source such as the probe head used here is evidently not toroidally symmetric and it remains to be determined whether in the vicinity of the probe the impurity concentration remains a minority one. Full 3D modelling of the probe plasma interaction is planned for the future. In the present work two methods have been used to estimate the Sn erosion/influx rate from the probe tip.

The first method exploits the calculated number of ionisations per photon (S/XB) from ADAS for the Sn visible lines. The new edge Thomson scattering system [13] provides T_e and n_e information at the probe tip, on which the SX/Bs depend. These have been compared with the number of photons observed by the visible spectrometer. Making the assumption that all the Sn II and III ionises within the field of view of this spectrometer (Fig. 5), and that all the Sn released from the probe will either ionise to higher charge states than the Sn II/III or redeposit on the probe, but not both, we obtain the influxes shown in Fig. 6.

This model is simplified – Sn may erode from the probe and rapidly leave the plasma, without ionising through Sn III. Indeed, Fig. 6 shows a significant reduction (≈75–90%) in influx depending on whether it is measured using the Sn II or the Sn III lines, implying (a) escape from the SOL outwards, (b) escape from the field of view of the spectrometer, or (c) redeposition on the probe between the two stages.

The second method used for estimating the erosion rate is the SRIM [14] package. Assuming the ions (impurity and deuterium) in the SOL are moving at the ion sound speed, c_s, and have a Maxwellian velocity distribution, the expected Sn sputtering rates for Sn, C and D collisions have been calculated. The results are shown in Fig. 6. As can be seen, deuterium is very ineffective at sputtering Sn, however the C sputter and Sn self-sputter rates are almost equal. Therefore, the self-sputtering cannot be ignored.

The conditions at the probe tip during the peak interaction of shot 14479 ($\approx T_e = 30$ eV, $n_e = 3\times10^{18}$ m^{-3}) suggest an erosion rate of 9×10^{16} s^{-1} due to C sputtering and 2×10^{17} s^{-1} due to Sn self-sputtering if both have 10% impurity concentration; the value calculated spectroscopically using Sn II lines is 2.1×10^{17} s^{-1}. The USN shot 13832 was also studied in this way, and similar results were found. Using these techniques the total Sn erosion during the shot was found to be $\approx1\times10^{16}$ atoms.

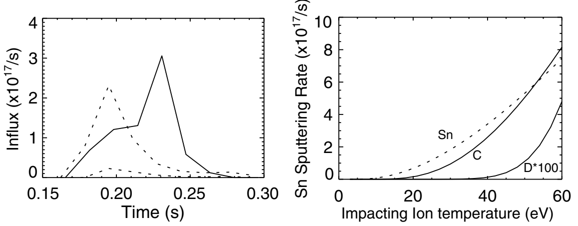

Fig. 6. *Left*: the influx calculated from the ionisations per photon (S/XBs) for Sn II in USN (shot 13832, solid line) and LSN (14479, dashed line). Also shown is the influx calculated using the Sn III lines in 14479 (lower dashed line). *Right*: the sputtering rate of Sn atoms from SRIM modelling. The graph shown assumes a deuterium density of 3×10^{18} m^{-3} in the SOL, and that the Sn and C are 10% impurities. All the ions are assumed to have a Maxwellian velocity distribution with $T_{ion} = T_e$. The SOL conditions in MAST indicate that the probe temperature was ≈30 eV. The deuterium data have been multiplied by 100 to make them visible on the graph.

6. Confined plasma

The confined plasma was modelled using the $1\frac{1}{2}$D impurity transport code UTC-SANCO [15]. The Sn influx was assumed to be that calculated using the Sn II lines above. The UTC-SANCO code allows the user to alter various plasma conditions, including the effective diffusion coefficient, D, and the convective velocity, v, across the plasma. The code parameters were adjusted to try to match the observed line integral Sn XX and Sn XXI line strengths measured by SPRED with those simulated by the UTC plasma reconstruction. Some results from these simulations are shown in Fig. 7. The composite line consisting of Sn X–XIV at 135 Å could not be simulated using this software due to the large number of overlapping transitions from different stages.

The simulations show that all significant observed Sn emission occurs in the outer regions of the plasma ($\frac{r}{a} \geqslant 0.5$) where T_e is between 300 and 400 eV (in these plasmas this is at $0.6 \leqslant \frac{r}{a} \leqslant 0.7$), which results in the Sn accumulation further into the plasma being unquantified. Since the emission will be from the confined plasma it will be toroidally symmetric, eliminating the need for multiple diagnostics observing different zones of the tokamak.

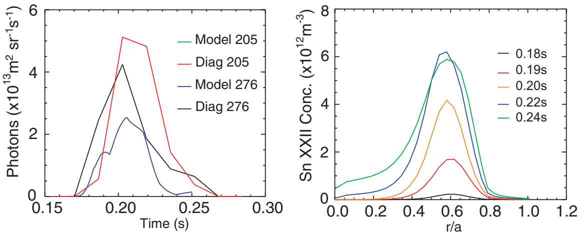

Fig. 7. The results of the UTC simulation for the LSN plasma 14479: (*left*) the modelled and observed Sn XXI and XXII signals, and (*right*). The Sn XXII concentration across the plasma.

The estimated peak core plasma Sn content for these shots is $\approx 1 \times 10^{15}$ ions, while the total erosion over the probe plasma interaction time is $\approx 1 \times 10^{16}$ ions. For successful observation emission of only 10% (or less) of that obtained here will be required. Using the estimates in [3], this means that 1 cm^2 of an exposed 1% doped layer in the divertor will provide a measurable signal in the core. While much more work remains to be carried out on this diagnostic these preliminary results imply that the technique should be viable in future devices.

7. Summary

Both Sn and In have been successfully eroded from a newly designed head for the MAST reciprocating probe system. Spectroscopic measurements have been made in the visible and VUV regions and the predicted Sn and In lines have been successfully observed. An attempt has been made to deduce the influx from the probe into the plasma, using both spectroscopic and ion impact sputtering calculations. For both USN and LSN plasmas with the probe in the SOL the agreement between the two was found to be good. UTC-SANCO modelling of the core indicates that there is strong emission from just inside the separatrix from Sn X–XIV, comprising a very strong composite line feature which would provide a clear indicator of Sn's presence in the plasma in a future diagnostic. The area of impurity-doped layer required to be exposed to observe the impurity in the core has been estimated at 1 cm^2, which implies that the technique should be viable in a future device, although more work is required to confirm this.

Acknowledgements

This work was funded jointly by the UK Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The view and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] R.A. Pitts et al., Plasma Phys. Control. Fus. 47 (2005) B303.
[2] D.G. Whyte et al., J. Nucl. Mater. 241–243 (1997) 660.
[3] G.F. Counsell, EU Task No. DV7A-T438, 1999.
[4] S.A. Tallents et al., J. Nucl. Mater., these Proceedings.
[5] R.J. Fonck, Appl. Opt. 21 (12) (1982) 2115.
[6] Atomic Data and Analysis Structure, online at <http://adas.phys.strath.ac.uk>.
[7] R.D. Cowan, The Theory of Atomic Structure and Spectra, University of California, 1981.
[8] NIST Atomic Spectra Database, <http://www.nist.gov>.
[9] C.M. Brown et al., Atom. Data Nucl. Data 58 (1994) 203.
[10] E. Biemont, Atom. Data Nucl. Data 39 (1988) 157.
[11] J.B. Green, R.A. Loring, Phys. Rev. 30 (1927) 574.
[12] W. Svendsen, G. O'Sullivan, Phys. Rev. A 50 (5) (1994) 3710.
[13] R. Scannell et al., Rev. Sci. Instrum. 77 (2003) 10E510.
[14] J.F. Ziegler, J.P. Biersack, U. Littmark, The Stopping and Range of Ions in Solids, Pergamon, New York, 1985.
[15] A.D. Whiteford, et al., Proceedings of the 31st European Conf. (ECA), London, 2004, p. 1.159.