EUROfusion

EUROFUSION CP(15)04/33

N. Gierse et al.

Time Resolved Imaging of Laser Induced Ablation Spectroscopy (LIAS) in TEXTOR and Comparison with Modelling

(18th May 2015 – 22nd May 2015)
Aix-en-Provence, France

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.

Time resolved imaging of Laser Induced Ablation Spectroscopy (LIAS) in TEXTOR and comparison with modelling

N. Gierse[a,*], M. Z. Tokar[a], S. Brezinsek[a], T. F. Giesen[b], M. Hubeny[a], A. Huber[a], V. Philipps[a], A. Pospieszczyk[a], G. Sergienko[a], J. Wegner[c], Q. Xiao[d], U. Samm[a], Ch. Linsmeier[a] and the TEXTOR team[a]

[a]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, 52425 Jülich, Germany
[b]Laborastrophysik, Universität Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany
[c]Present address: Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[d]Present address: Space Basic Science Research Center, Harbin Institute of Technology, Harbin, 150001, China

*) Email address: n.gierse@fz-juelich.de

Abstract

Laser based methods are investigated as in situ diagnostic for plasma facing materials (PFMs) in magnetic fusion research to study PFM composition and retention.
In Laser Induced Ablation Spectroscopy (LIAS) the wall material is ablated by a laser beam. The released material enters the edge plasma region of a fusion experiment and the resulting optical emission is observed. To conclude from the observed photons to the number of ablated atoms, a detailed knowledge of the velocity distribution of the ablated material is required.
In this work the LIAS emission in discharges at TEXTOR was studied using an Ametek Phantom v711 camera. In this paper a method is developed to conclude from the observed emission to velocity distribution of the ablated species. The obtained velocity distribution is used for our numerical LIAS model, demonstrating good agreement. Implications are discussed.

PACS, Keyword	
79.20.Eb	Ablation, laser impact on surfaces
06.30.Gv	Velocity, measurement of
89.30.Jj	Nuclear Fusion Power
52.40.Hf	Plasma-material interactions
34.80.Dp	Atoms, excitation and ionization by electron impact
28.52.Nh	Fusion reactors reactor safety
82.80.-d	Spectroscopy in chemical analysis

1. Introduction

The performance of the first wall in fusion reactors is critical for economic exploitation of fusion power [**Error! Reference source not found.-Error! Reference source not found.Error! Reference source not found.**]. There is an urgent need to develop means to measure plasma-wall interaction (PWI) processes in situ: understanding of the influence of plasma operation scenarios on material migration on the one hand and the monitoring of the tritium content of the first wall as an immediate safety application.

Laser based methods are investigated as candidates [**Error! Reference source not found.**], as they provide powerful tools to study fuel retention, deposition and material transport. Laser induced ablation spectroscopy (LIAS). [**Error! Reference source not found.-Error! Reference source not found.Error! Reference source not found.**] is a promising candidate.

In LIAS, a small area of the plasma-facing component surface (PFC) (diameter < 1 cm) is ablated by a laser pulse and the material is injected into the plasma edge region. There the species are excited and ionized by electron impact. Radiometrically calibrated spectroscopy provides the number of atoms in the ablated layer. This has been quantitatively demonstrated for hydrogen isotope containing layers in TEXTOR [**Error! Reference source not found.**].

However, the measured photon efficiency for D_α from a-C:D layer ablation is at least 3.5 times larger than expected from ADAS values for an atomic hydrogen beam for the TEXTOR edge region [**Error! Reference source not found.**]. Possible reasons for this discrepancy are molecular hydrocarbon dissociation, which for example in case of a pure D_2 source is known to reduce the photon efficiency for D_α by a factor of 2 for TEXTOR conditions [**Error! Reference source not found.**] and plasma perturbation caused by the material injected in a short time [**Error! Reference source not found.**].

For quantitative modelling of LIAS the velocity distribution of the ablated species is a required input parameter. The laser ablation process is known to be highly material dependent

[**Error! Reference source not found.**, **Error! Reference source not found.**] and the ablation rate has been found to dramatically increase in the presence of a magnetic field [**Error! Reference source not found.**].

As it is the goal of LIAS to study material modifications of PFCs during plasma impact as well as mixed materials forming during operation, material properties are unknown by definition. Thus for LIAS modelling to work the velocity distribution of the ablated species must be determined in situ. A first approach was done in [**Error! Reference source not found.**] which is advanced here. A description for the laser ablated particles can be done in form of the stream modified maxwellian velocity distribution as used in [**Error! Reference source not found.**] of the form

$$f(v_x, v_y, v_z) = \frac{1}{2\pi\, T_0}\left[(v_x - u_s)^2 + v_y^2 + v_z^2\right].$$

Here the surface on which the laser beam is incident is assumed to be in the y-z plane. The width of the distribution is described by a temperature T_0 and the particles have a velocity distribution shifted by a stream velocity u_s in the x-direction.

2. Methods

2.1. Experimental Methods

LIAS was studied in the tokamak TEXTOR [**Error! Reference source not found.**] in ohmic discharges, r_{LCFS}=463 mm, $T_{e,LCFS}$=(33.7±.5) eV, λ_{Te}=49±3 mm, $n_{e,LCFS}$=(6.6±.2)*10^{18} m^{-3}, λ_{ne}=15.1±.7 mm [**Error! Reference source not found.**]. The radial location of the Tungsten sample was fixed at r=500 mm. In all experiments LIAS was performed during the current and density flat-top phase of the discharge.

The ablation was carried out with Innolas Spit Light laser system with the parameters E_p=1.5 J, λ=1064 nm, τ_p=7 ns. From the area of the laser A_{spot}=16 mm^2, and the total transmission of the optical system t=.64 [**Error! Reference source not found.**] an average target pulse energy density F_{target}=6 J/cm^2 is determined.

The emission was observed from Limiter Lock 1 in the horizontal observation [**Error! Reference source not found.**] by an Ametek Phantom v711 using the fast option. The WI transition 5d5(6S)6s □ 5d5(6S)6p at λ=400.9 nm [**Error! Reference source not found.**] was observed by a narrowband interference filter (010FC06-50/400.9nm AM-31527 S/N-01). A sample of the background subtracted signal for the first laser pulse of TEXTOR discharge #119779, the 5th laser pulse onto the tungsten sample is shown. The time shown at the top of each frame indicates the elapsed time from the laser trigger. The recording interval was 2.56 μs with an exposure time of 2.18 μs, recording 64 pixels in radial and 128 pixel in toroidal location. As the camera was free running relative to the TEXTOR timing system the relationship between the laser trigger and the start of the frame recording interval does not have a fixed relationship for each laser pulse.

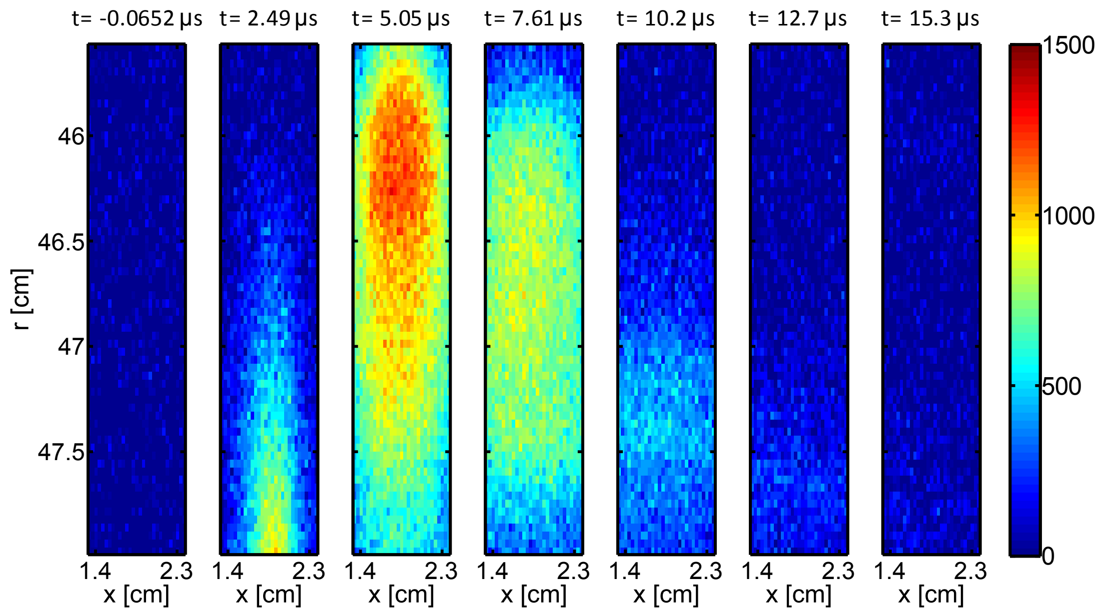

Figure 1: Background subtracted LIAS WI 400.9nm frame images from before the laser pulse until 15.3μs after the laser pulse.

2.2 Analysis

Due to the plane of observation the intensity is integrated in poloidal direction. If the velocity distribution from #EQ1# is assumed, a twofold integration has to be performed [**Error! Reference source not found.**] yielding the resulting radial velocity function for the velocity along the normal component v_n of the target

$$f(v_n) = A_0 \ \exp\left[-\frac{(u_s - v_n)}{2\ v_{th}^2}\right],$$

with thermal velocity $v_{th} = \sqrt{\frac{k_B T}{m}}$, normalization constant A_0 and stream velocity u_s. In a simple description, the intensity observed is the result of two competing processes: Emission due to excitation by the plasma electrons of the impinging neutral tungsten atoms on the one hand and ionization by the electrons on the other hand which prevents further excitation. Additionally, for a single pixel a given solid angle is observed which means that the recorded signal has to be scaled with the velocity v of the observed species to account for the transition time. In this work the effect by ionization with the penetration length $\lambda = \frac{v}{n_e k_{ion}}$ in case of a homogeneous plasma is not accounted for, as the entering tungsten can be a case of local plasma perturbation, so that the electron density is a function of space and time over the duration of the laser pulse. In consequence, the method will be limited in reliability specifically for slow velocities.

2.3. LIAS modelling

For modelling of the LIAS emission a numerical model has been developed which provides a self-consistent description for the spreading of ablated particles and the modifications caused in the tokamak plasma. The model is based on the shell-model approach developed for impurity penetration [**Error! Reference source not found.**] and has been adapted to the much shorter time scales of the laser ablation process relevant for LIAS [**Error! Reference source not found.**]. The present status is described in [**Error! Reference source not found.**]. For the tungsten emission considered here data from the ATOM database was used. While the plasma interaction is modelled in detail, the velocity distribution of the species injected due to the laser ablation process is a required input. Thus in the following the results for the experimental determination of the velocity distribution of tungsten atoms are given. Then this velocity distribution is used to model the LIAS emission.

3. Results

Processed data from the raw data presented in fig. 1 is shown in fig 2. The plot shows the velocity corrected intensity binned in the x-direction as a function of time and distance to the target. The assumption of a point source located at d=0 instantaneously releasing the particles at t=0 is a reasonable assumption, as the laser pulse penetration depth < 1μm/pulse and the observed emission time τ_{em}~10 μs>>τ_p=7 ns.

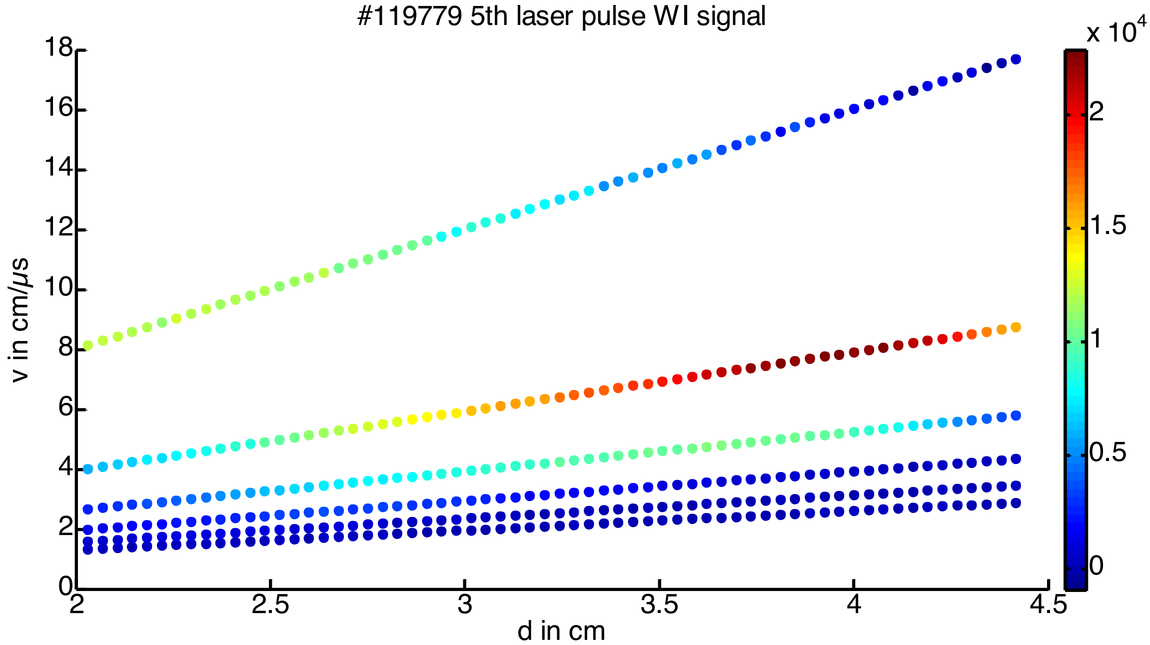

Figure 2: Mapping of the camera signal integrated in toroidal direction, mapped to distance to target- and velocity space.

To minimize the effect of signal loss due to ionization of slow species the velocity profile was determined for the region d=(2.15±.1) cm off the surface. The resulting data points for three laser pulses, the 5th, the 6th and the 10th on an untreated target as well as the performed fits are shown in figure 3. In the upper graph the actual corrected intensity together with the fit is shown. In the lower graph the fit residual is shown as a fraction of the peak intensity.

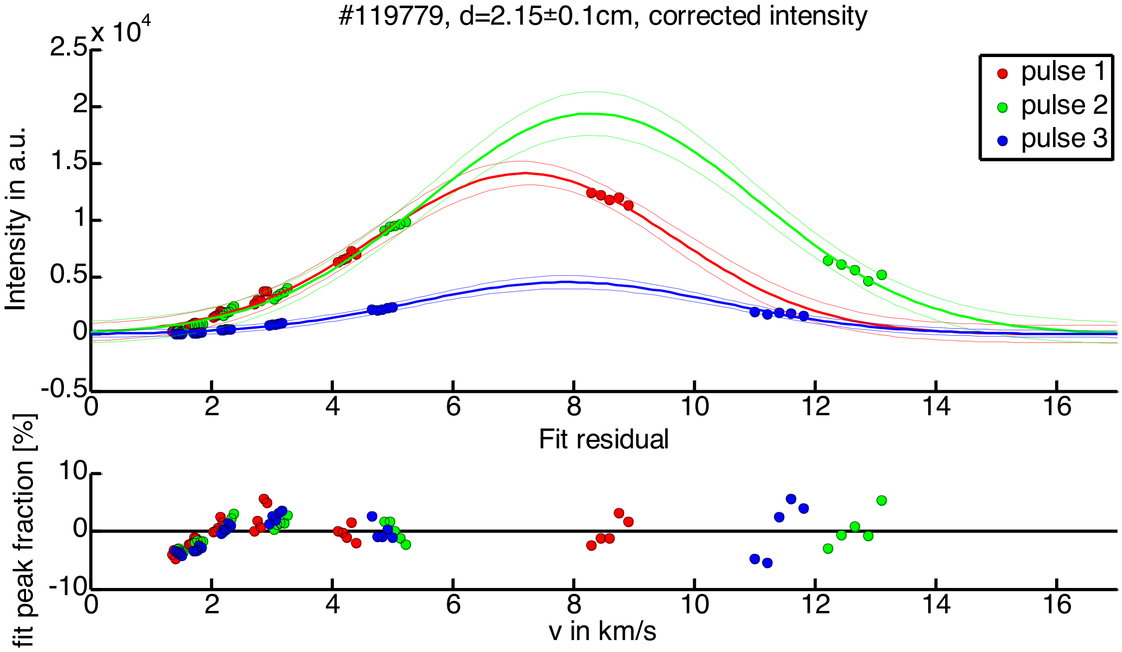

Figure 3: Fitting of stream modified Maxwell-Boltzmann velocity distribution to camera data.

The obtained fitting parameters are presented in table 1.

Laser pulse	u_s [km/s]	v_{th} [km/s]
1	7.2±.2	2.4±.2
2	8.3±.1	2.7±.2
3	7.9±.1	2.6±.2

Table 1: Stream modified Maxwell-Boltzmann distribution fitting parameters.

For the LIAS model described in 2.3 the parameters us=7.8 km/s and vth=2.6 km/s were chosen based on the results presented in table 1. The simulated emission for different numbers of tungsten atoms injected is shown in figure 4. The observed time and scaling are reproduced from the experimental measurements presented in figure 1 for convenience.

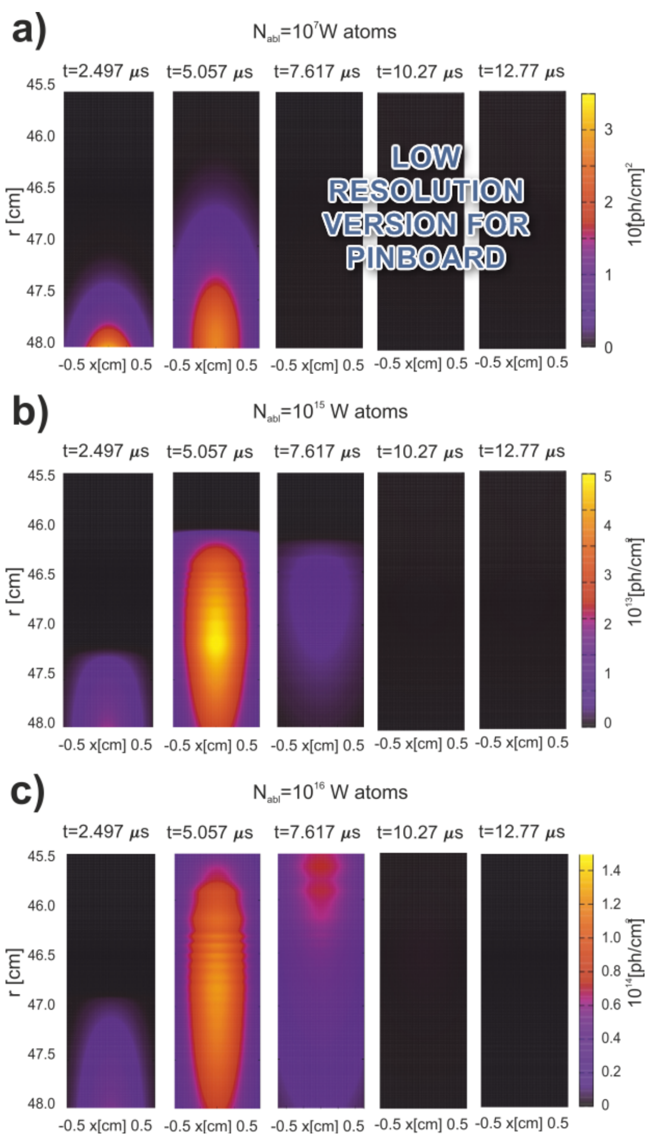

Figure 4: LIAS simulation for WI 400.9 nm emission, accounting for plasma perturbation by injected species. The number of atoms is increased from a) to c).

In a) only 10^7 W atoms are injected, causing only negligible local perturbation to the plasma. In b) and c) the emission for 10^{15} W and 10^{16} W atoms are shown, respectively which is the number of atoms typically ablated by the laser used [**Error! Reference source not found.**]. In these cases a strong local transient perturbation of the local plasma parameters is found, amounting in case of 10^{16} injected W atoms to $n_{e,cloud}$=3.29*10^{15} cm^{-3} and $T_{e,cloud}$=0.526 eV at t=3.78μs. The plasma shows full recovery to pre-laser pulse parameters within 10 μs after the onset of the laser pulse.

A good agreement between emission modelling and experimental observation is found, both in regard to shape and time scale.

4. Discussion and Conclusion

In this work time resolved fast camera measurements of the WI 400.8 nm emission from Laser Induced Ablation Spectroscopy (LIAS) is used to determine the velocity distribution of ablated neutral tungsten atoms. Then the obtained velocity distribution is used successfully for a comparison between our numerical LIAS model and the experimental observation.

A method to deduce the velocity distribution of the ablated particles from camera data is introduced. It is found that the velocity distribution of the ablated tungsten bulk material in TEXTOR can be described by a stream modified Maxwell Boltzmann distribution. Although the intensity of the integrated LIAS light differs between the shots, possibly due to surface conditioning effects the thermal velocity is found to be constant within the statistical errors of the fitting method. The stream velocity is found to vary by less than 20% between laser pulses.

The experimental method described here can be applied in principle to data obtained from a fast photodiode carefully aligned to the emission cloud. The analysis highlights the advantage of side-observation of the LIAS plume as interpretation is dramatically eased. In future work the simultaneous observation of different emission lines should be considered. This allows distinguishing between ionization and excitation effects of the respective species.

Furthermore, the 2D camera data allows for investigation of the penetration behaviour for different velocities and angular distribution measurements. This will be explored in the future.

The determined velocity distribution can be applied to our numerical LIAS model which is in good agreement with the experiment and is a first successful step for validation of the model. A significant local plasma perturbation due to LIAS is found which is very different from sputtering experiments under similar conditions [21]. The next step will be the quantitative validation of the predicted photon efficiencies. With the model a tool for LIAS with local perturbation is available, allowing a quantitative estimate on ablation amount based on emission shape. On the other hand, the model allows for the design of non-perturbative LIAS with shorter laser pulses and/or lower pulse energy and high repetition rates. Additionally, predictions for LIAS in other machines can now be made.

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. The authors Hubeny, Pospieszczyk, Wegner, Xiao and the TEXTOR team contributed to the measurements leading up to the analysis presented here.

References

[1] Ch. Linsmeier, C.-C. Fu, A. Kaprolat et al., J. Nucl. Mater., 442(1–3, Supplement 1):S834 – S845, 2013.

[2] A. Möslang, E. Diegele, M. Klimiankou et al., Nucl. Fusion, 45(7):649, 2005.

[3] H. Zohm, C. Angioni, E. Fable et al., Nuclear Fusion, 53(7):073019, July 2013.

[4] V. Philipps, A. Malaquias, A. Hakola et al., Nucl. Fusion, 53(9):093002, 2013.

[5] N. Gierse, PhD thesis, University of Cologne, 2014.

[6] C. Grisolia, A. Semerok, J.M. Weulersse et al., J. Nucl. Mater., 363–365(0):1138 - 1147, 2007.

[7] D.D.R. Summers, M.N.A. Beurskens, J.P. Coad et al., J. Nucl. Mater., 290(0):496 – 500, 2001. 14th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices.

[8] N. Gierse, S. Brezinsek, J. W. Coenen, et al., Physica Scripta, 2014(T159):014054, 2014.

[9] M. Zlobinski, V. Philipps, B. Schweer, et al., Fusion Eng. Des., 86:1332 – 1335, 2011. Proceedings of the 26th Symposium of Fusion Technology (SOFT-26).

[10] V. Philipps M. Z. Tokar, N. Gierse et al., Nucl. Fusion, submitted.

[11] E. Buttini, A. Thum-Jäger, and K. Rohr, J. Phys. D: Appl. Phys., 31(17):2165, 1998.

[12] A. Thum-Jäger, PhD thesis, Universität Kaiserslautern, 1998.

[13] Q. Xiao, R. Hai, H. Ding et al., Journal of Nuclear Materials, 2014.

[14] I. Konomi, T. Motohiro, T. Kobayashi et al., Appl. Surf. Sci., 256(16):4959–4965, June 2010.

[15] O. Neubauer, G. Czymek, B. Giesen et al., Fusion Sci. Technol., 47:76–86, Feb. 2005.

[16] B. Schweer, S. Brezinsek, H.G. Esser et al., Fusion Sci. Technol., 47(2):138 – 145, 2005.

[17] A. E. Kramida and T. Shirai, Journal of Physical and Chemical Reference Data, 35(1):423–683, 2006.

[18] M. Z. Tokar and M. Koltunov, Phys. Plasmas, 19(4):042502, 2012.

[19] V. Philipps U. Samm M. Z. Tokar, et al., in 41st European Physical Society Conference on Plasma Physics, 2014.

[20] Q. Xiao, A. Huber, G. Sergienko et al., Fusion Eng. Des., 88(9):1813–1817, 2013.

[21] S Brezinsek, D Borodin, JW Coenen et al., *Physica Scripta*, 2011(T145):014016, 2011.