Commissioning and First Results of the OLMAT facility

Francisco L Tabarés[1], Eider Oyarzabal, Daniel Alegre, David Tafalla, Kieran J. McCarthy, Alfonso de Castro, Enrique Ascasíbar, Alfonso Soleto, Ivan Fernández-Berceruelo, Ricardo Carrasco, Fernando Martin, José A Sebastián, Jesús Gómez-Manchón, Augusto, Pereira, Angel de la Peña and the OLMAT team*

Laboratorio Nacional de Fusión (LNF) - Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain.
[1]Corresponding author: tabares@ciemat.es

Abstract.
The OLMAT (Optimization of Liquid Metal Advanced Targets) facility has recently undergone the commissioning and start-up phases. Solid Titanium-Zirconium- Molybdenum (TZM) alloy and liquid tin (Sn) metallic targets were exposed to a hydrogen neutral beam injector (NBI) particle flux with power densities up to 58 ±14 MW/m$_2$, pulse duration up to 150 ms, and repetition rates up to 2 pulses/minute. These beam parameters are well above the estimates based on the typical performance of this NBI system when used for heating plasmas in the TJ-II stellarator. The parameters of the plasma generated through the interaction of the fast (32.5 keV) neutrals and ions and the solid were characterized by spectroscopic methods while surface temperature and total absorbed power were followed using pyrometry, infrared (IR) thermography, and calorimetry, respectively. Targets were visually monitored during the exposure and microscopically analyzed ex-situ. Electrical isolation of the target permitted recording the floating voltage during irradiation as well as for active biasing tests. In this work, a description of the facility, its operating parameters, and firsts results are provided and assessed as a new High Heat Flux (HHF) Facility for testing solid and liquid metal divertor targets under reactor-relevant heat load conditions.

Keywords: HHF facilities, target materials, liquid metals, DEMO, ITER, CPS, OLMAT, vapor shielding.

* The OLMAT technical team.
Miguel Navarro, Andres Jimenez-Denche, Francisco Miguel Honrubia, Luis Alberto Bueno, Jose A Sebastian, Emilio Sánchez, Ana Portas.

1. **Introduction.**

Power exhaust still represents a major challenge on the road to a commercial fusion reactor [1]. In contrast to other cases with similar values of magnitude to be handled, a fusion plasma exhibits a unique pattern, with a combination of steady-state and fast transients loads, which makes thermal fatigue of any material exposed to the divertor plasma a critical issue when it comes to selecting a suitable material for the high heat flux region of the reactor divertor [2]. Furthermore, neutron irradiation and embrittlement add to the challenge [3].

Although material testing in a realistic scenario, i.e., in a real fusion experiment, is always preferred, as it provides all the actual components of the problem, this is not usually available due to the risk associated with machine integrity and deployment of the scientific program. This is why several types of laboratory simulators have been developed over recent decades for that goal [4]. Even though none of them provide all the elements in play, the combined information extracted from their operation represents a highly valuable tool for the evaluation of candidate materials for the Plasma Facing Components (PFCs) at critical locations.

For the upcoming ITER operation, tungsten has been selected as the armor material, and extensive testing of this material and its alloys has been carried out under several HHF scenarios [5]. Still, many questions remain unanswered and no guarantee about its use in a future reactor exists. Although in a lower state of maturity, alternative solutions based on the use of liquid metals (LM) have been proposed as a substitute [6]. However, few tests in divertor plasma simulators are available at present, mostly due to the more challenging handling and integration of LM concepts in their final configuration.

In this paper, the first results of a new facility for testing solid and liquid metal divertor candidates under DEMO-relevant heat loads, OLMAT, are presented. Although the Facility has been described in general terms in a previous publication [7], its actual performance was unknown by then. Here, the first results of TZM and Liquid Sn/W Capillary Porous System (CPS) targets exposed to heat fluxes up to ~ 60 MW/m_2 and to series of up to 100 consecutive pulses are reported, and its capabilities and limitations as an HHF facility within the EuroFusion (EF) Road Map [1] are addressed.

2. The OLMAT facility

The OLMAT facility was previously described in detail [7], and only a sketch is shown in figure 1a. A 3D CAT view is also displayed in Fig 1b for clarity. In brief, one of the two neutral beam injectors (NBI) operated on the stellarator TJ-II is used to irradiate samples in a separate, diagnosed chamber under high vacuum conditions. The sample, either solid or liquid metal held into a CPS, is installed on a manipulator with heating, biasing, translation, and rotation capabilities. In order to prevent overheating of the connecting valve between the OLMAT chamber and the TJ-II vacuum vessel, two retractable Mo plates are inserted behind the manipulator. These plates have thermocouples incorporated into them, these being placed on the back (unexposed to NBI) side of the plate so that a shot-to-shot recording of their temperature can be made. Infrared Pyrometry (OPTRIS, CTlaser 3MH1) and IR thermography [8] allow the temperature evolution of the exposed surface to be followed with 1 ms time resolution. Both types of temperature sensors together with embedded thermocouples are used to characterize the thermal response and to assess the incident heat flux. Optical diagnostics include a filter-scope arrangement for visible emission (Balmer Hα, impurities) and a CMOS-based spectrometer, with a 25 μm entrance slit that is coupled to an optical fiber to collect emission spectra from 236 to 812 nm. The absolute response of the fiber-spectrometer combination was determined for the range 310 to 812 nm using a calibrated light source. In addition, a 16-channel photomultiplier (PMT) array (Hamamatsu, mod: R5900U-L16) is used for recording the emission profile of selected species near the sample. Eventually, active spectroscopy is also used. It involves injecting N_2 close to the sample and applying the line ratio technique to evaluate microscopic plasma parameters. In the start-up phase, an 80 mm diameter and 7 mm thick TZM disc was selected as the first target (Figure 2b). The base material presents an average commercial composition of 99.4 wt. % Mo, 0.5 wt. % Ti and 0.08 wt. % Zr. For the subsequent liquid metal containing target, another TZM disc reservoir was machined to produce an array of 3 mm holes evenly distributed over its surface (Figure 2a). These holes are designed to act as LM reservoirs in liquid metal – CPS exposure experiments. This element acts as the primary substrate where a porous mesh (150 micron pore diameter, folded three times) is embedded. In this second target, the liquid tin spreads along the porous mesh and is confined therein by capillary forces. For these firsts experiments only part of the target was wetted with tin as can be observed in figure 2c. Two thin W wires are set across the mesh for preventing budging.

3. First Results

The TZM target was exposed to a series of NBI pulses with varying power, duration, and repetition rate. Visual inspection was eventually performed during and after the exposure to check for sample damage. The initial target temperature was also varied using a heating resistor on the back of the target, although a systematic increase of the temperature was always observed as a consequence of the absorbed NBI power and the very low thermal contact between the sample holder and the target. The target cooling rate was measured using two thermocouples inserted in the backside and a characteristic exponential decay with a time constant of 70 min was determined, i.e., significantly longer than the time between pulses. Therefore, a significant degree of accumulation of injected energy into the sample was produced, especially at temperatures leading to negligible radiation losses between pulses. In what follows, the results are sorted according to the relevant parameter of the facility under test.

3.1. Injected power and its profile.

The temperature increase in the target upon its exposure to the NBI shot was followed using the two thermocouples inserted in the backside. The duration of the pulse length was systematically increased along a series of constant nominal power shots from 30 to 100 ms. Linear behavior of the temperature increase versus pulse duration was recorded at all powers, with the slope increasing along with the nominal NBI power.

Figure 3 shows the results for two examples. As seen, an offset of ~10 ms was always detected, this providing evidence for a delay between the onset of the reference signal (voltage applied to the NBI source grid) and the development of full incident power on the target. Due to the thermal inertia and the limited time resolution of the thermocouples, the maximum temperature increase at the target was recorded a few seconds after the pulse.

From the slope, m (K/S), of the straight lines in figure 3, the power absorbed by the target can be estimated as Q (W)= Cp. M. m, where Cp and M are the specific heat capacity and target mass, respectively. Since there are two components with quite different thermal properties in the target, namely TZM and stainless steel (SS), the values of Cp and M to be considered for the evaluation of Q are not trivial. Due to the much lower thermal conductivity of the SS supporting ring (b in figure 2a), a higher temperature is achieved during the pulse at the holding ring. As the thermal contact between the SS ring and the TC support is hard to evaluate, two limiting cases were considered for the evaluation of Q. In the first case, only the TZM mass and exposed area are used. On the contrary, if full thermalization between all the target components is assumed, an effective heat capacity of $Cp_{eff} = (m_1. Cp_1 + m_2. Cp_2)/(m_1+m_2) = 255$ J/kg. K applies, with the subindex 1, 2 indicating each of the components . Then, the average power density at the target is given by Q (W/m^2) = $(m_1+ m_2) Cp_{eff}\, \Delta T/A.\, t_{pulse}$, where A is the target area. Since for the particle energies involved here, the energy reflection coefficient of H on Mo is of the order of 6%, [10] no correction for this was made when evaluating the incident NBI power from the calorimetric results. From the values of the mass and Cp of the target components, one gets Q (MW/m^2) = 20.m for the first case, and Q (MW/m^2) = 32.m if full thermal coupling is assumed. Figure 4 shows the deduced Q values with the associated error bars and Table I summarizes the NBI parameters used in the tests together with the results from calorimetry at the target. In the table, exposure conditions with and without activation of the NBI bending magnet are included, and referred as without/with ions, respectively. Values of average power density up to 58±14 MW/m2 are deduced at the maximum injected NBI power. These values are about a factor of 3 larger than those measured at the graphite calorimeter located within the stellarator TJ-II [8] and provided as an estimate in the previous publication [7] but this increase is to be expected considering the location of the OLMAT target, close to the beam focus. From the power density reaching the target, and neglecting the particle reflection coefficient at the involved energies, particle fluxes can be deduced as Γ ($m^{-2}.s^{-1}$)=Q (W/m_2)/<E_{kin}>.e, with e standing for the elemental charge and <E_{kin}> is in volts. Based on the beam composition, (1/2 E_0 + 1/4 E_0/2 + 1/4 E_0/3), as determined by Doppler spectroscopy, a value of <E_{kin}> ~E_0/1.5 is used for the particle flux evaluation shown in Table I.

So far, only values averaged over the exposed area have been shown. However, calorimetric measurements at the TJ-II graphite calorimeter location clearly showed a peaked profile, its width depending on NBI source parameters [9]. In order to characterize the beam profile at the target location, the target was displaced sideways from its central position in 1 cm steps on a shot-to-shot basis for a constant NBI power of 280 kW and 50 ms pulse length. The temperature at the target was recorded by the corresponding embedded thermocouples. Figure 5 displays the results. As seen in figure the target data, convoluted by the target width, can be fitted to a Gaussian of FWHM 11.7 cm.

Finally, pyrometry was also used for the assessment of the beam power incident over the target. The 1 cm spot seen by the pyrometer was projected at the target center under the same experimental conditions as those described before. Figure 6a shown an example for a nominal injected power of 623 kW and several pulse durations. For a simple slab model, $\Delta T = 2Q.\sqrt{t}/\alpha$, with Q in W/m^2, t in s and α is a thermal parameter, characteristic of the material, $\alpha=\sqrt{\kappa\rho Cp.\pi}$, the increment ΔT should linearly follow the squared root of the exposure time. This functionality was indeed observed as plotted in figure 6b. However, the values of Q (MW/m^2) deduced from the linear fitting are systematically lower than the averaged ones deduced from calorimetry (Fig 4) if the bibliographic values of Cp, ρ, and κ for TZM (250 J/kg. K, 10.2 g/cm_3 and 139 W/m. K at room temperature, respectively,) are assumed. Although some evolution of these parameters with temperature exists [11] in the range explored, the deviation of the deduced figures for Q based on pyrometry cannot be accounted for by using T dependent thermal parameters alone. Analytical expressions [12] and Finite Element Analysis (FED) indicates that for a solid with finite thickness, the slab model has limited application and deviations could be expected. For the case of SS and TZM, the corresponding, calculated heat penetration depths are significantly lower than their thickness, thus validating the application of the slab model. Therefore, pyrometry would support the lowest Q values given above, corresponding to the absence of thermal coupling between the two target's elements. However, possible changes in surface emissivity during the temperature ramp-up, are not considered here, and they could also contribute to the observed mismatch between pyrometry and calorimetry. In any case, a two-color pyrometer and calibration by a single-element calorimeter is intended for the next campaign for a more accurate evaluation of the incident heat fluxes.

3.2. Plasma Characterization

The interaction of a high-energy beam with a solid leads to the generation of a plasma plume at its surface [13]. Although the specific mechanism of the generation of such plasma is out of the scope of this work, its characterization opens the possibility to perform plasma-wall interaction studies under a well-controlled scenario. These studies include the deployment of vapor shielding effects, of direct impact on the effective energy deposited into the target [14] as well as the recycling and sputtering properties of the exposed material. For this reason, and as a specific feature of the new facility, a set of devoted diagnostics was implemented in OLMAT. Plasma spectroscopy and electrical characterization of the target upon beam exposure were used in the reported experiments. A survey spectrometer in the UV-visible-near IR range that viewed the target provided information about the plasma composition and its microscopic parameters, while a Balmer Hα (656.3 nm) monitor and a 16-Channel PMT array were used for the characterization of particle recycling and the plume's spatial structure. Moreover, the floating voltage and saturation current developed at the target was monitored on a shot-to-shot basis.

Figure 7a shows a typical spectrum of the plasma emission in the range of 280 - 810 nm for a TZM target. As seen, some characteristic lines are identified, including the Balmer hydrogen series and some Mo I emission lines. From the ratio of intensities of the Balmer lines [15], an electron temperature of ~ 4 eV is deduced by comparing absolute intensities of the non-shifted Hα, Hβ and Hδ lines, as seen in the figure (the Hγ is contaminated with other lines, thus it is not used for this). This value has to be taken with care since line ratio-based diagnostics are prone to large errors and are rather qualitative. In addition, a blow-up of the Hα region is displayed in figure 7b. Peaks, corresponding to the Doppler-shifted energy components of the beam, E, E/2, and E/3, can be identified together with a peak corresponding to non-shifted hydrogen plasma emissions. Moreover, a shoulder is visible on the blue-shifted side of the Hα spectrum when the observation is performed with a component parallel to the propagation of the beam, corresponding to the H atoms reflected from the target (particle reflection coefficient ~10% [10]).

At high-injection powers, strong visible-IR radiation from blackbody emission was seen at the wavelengths routinely recorded. Temperatures up to 2100 K were deduced from the radiation spectrum. Since no complete discrimination between the TZM and SS parts of the target is possible from the perpendicular viewing direction, and due to the different thermal properties of both materials addressed above, it can be assumed that these high temperatures are indicative of SS heating by the beam. Serious melting of theSS ring was indeed observed after high power injection and pulse duration above 50-70 ms. Figure 8a shows the spectrum with a strong contribution of blackbody radiation while in fig 8b a photograph of the target with the molten SS ring can be seen.

The observation from a window perpendicular to the target allows for the reconstruction of the plasma plume emission profile along the beam direction. By using the 16-Channel PMT array and a Hα transmission filter, the profiles depicted in Figure 9 are recorded. A characteristic decay length of ~1 cm is obtained from the intensity decay shown in the figure. Also, higher intensities are seen for beams generated without the activation of the bending magnet, yielding higher power and particle fluxes at the target.

When the TZM target was replaced by the target of W CPS, partially wetted with Sn, a completely different spectrum was recorded, as expected from the higher vapor pressure and lower sputtering threshold of Sn compared to that of Mo. Two examples of such spectrum are given in figure 10. As seen in fig 10a, several Sn I and Sn II lines are recorded. However, a structured background is also evident from the figure. This structure is an artifact produced by UV damage of the optical fiber but this can corrected using the absolute intensity calibration. Once corrected, spectra like that shown in fig 10b can be reconstructed. Some neutral potassium lines are also present between 765 and 770 nm, these originating from the potassium present in the Macor support that is exposed to the beam when the target is tilted. Again, fitting the spectrum background to a blackbody emitter, a radiative temperature of 4600 K is deduced, significantly higher than the melting point of W (3683 K). Moreover, the presence of Sn I and Sn II emission lines and the absence of emission lines from higher ionization states of Sn point to the presence of low temperature ablation plasma in front of the target. Indeed, the ratios of the Sn I and Sn II line intensities indicate a plasma temperature of 1~ eV at the end of the pulse, lower the estimates from the H line ratios. The protective effect of Sn on the surface is supported by visual inspection of the target after NBI irradiation, shown in Fig 10c. Only the part of the W-CPS fully covered by Sn remains unaltered, while those parts only partially, or not wetted, exhibit clear signs of melting and erosion.

Likewise, post-mortem SEM/EDS measurements corroborated the presence of tin deposits on optical windows of the OLMAT chamber as a result of these processes. Finally, the generation of a cold plasma upon the interaction of the beam with the substrate conveys the emergence of a potential difference between both elements, the so-called floating potential. By electrically isolating the target, this parameter was readily measured with time resolution. Values between -5 and -2 V were recorded, in reasonable agreement with expectations from simple sheath theory for H+ plasmas [16], $V_f = -3kT_e$, where k stands for the Boltzmann constant and T_e is the electron temperature, determined through Sn spectroscopy. Saturation currents up to 400 mA were measured on grounded targets. The observed dependence of the electrical parameters with nominal NBI power could be associated to the presence of ions in the beam, although no systematic study in this line has been done in this work.

4. **Working plan within the EF Roadmap.**

The OLMAT facility aims at testing material candidates for high heat flux areas of future fusion devices under reactor-relevant conditions. Several facilities with the same goal are presently available within the European EuroFusion laboratories [4], and some of the specific capabilities and shortcomings of the new facility are worth outlining.

4a. Materials

Although initially planned for Liquid Metal-based target concepts, solid refractory metals can be also exposed to the NBI in OLMAT, although no beryllium operation is possible at present. Due to the size of the exposed area, multi-sample experiments can also be easily carried out, this number being ultimately limited by the total weight to be carried by the linear manipulator. For a typical probe size of 1 cm [17] more than 10 samples can be accommodated within an area in which more than 60% of the peak power is guaranteed. Either different samples at constant power or a single sample exposed to varying power densities can be simultaneously tested. This is not possible for more complex CPS-LM prototypes, and only one item will be accommodated in each run. So far, only inertially cooled targets have been tested. However, active cooling is foreseen for future operation when required. Due to the pulsed characteristics of exposures, and to preclude potential hazard when using reactive lithium targets, only gas cooling will be considered.

4b. Heat Flux Factor.

The maximum pulse length achieved in the experiments described here is 150 ms; therefore, contrary to other similar facilities [18], no steady state temperature is reached during a single pulse for inertially cooled conditions. Even so, temperatures as high as 700 ºC were seen during a train of pulses at medium power, this eventually forcing the shut down of the beam due to excessive pressure build-up at the OLMAT main chamber. While the isolation valve from the TJ-II vacuum vessel remained closed for experiments in which material from the

target could be dragged by the beam into the
TJ-II chamber, this was not the case for refractory metals. Furthermore, thermal isolation between the target and the valve can be drastically improved by inserting radiation shields coupled to the fore mentioned valve, as experimentally verified. Back heating of the target up to 700ºC has been already produced, thus enlarging the range of temperatures of exposure.
Based on dedicated experiments with varying pulse lengths and powers [19], it has been suggested that the heat flux factor, rather than the pulse duration or peak power values on their own, is the relevant parameter behind the thermal damage threshold of the material. This factor is defined as: FHF= Q.√t ($MW/m^2.s^{1/2}$). For tungsten, values of this parameters of ~12 were found for a low number of heat pulses (<100), while this factor drops to less than 6 whenever pre-damaged samples or high numbers of pulses (>1000) were explored [20]. Sample structure, composition and temperature are responsible for the scattering of the reported values found in the literature for this parameter. For OLMAT pulses of 60 MW/m2 and 100 ms duration, FHF = 19 $MW/m^2.s^{1/2}$, so testing of tungsten at conditions leading to crack formation upon repetitive pulse exposure is possible even for a low (<100) number of pulses. Present estimates are that series of 1000 pulses per day at intermediate powers could be produced under demand in devoted campaigns. However, a full test of the facility and its reliability under these demanding conditions is still to be performed and the implementation of active target cooling may become mandatory for this mode of operation.

.

4c) Plasma Wall Interaction studies

One of the unique capabilities of OLMAT as a HHF facility is the possibility to address plasma wall interaction studies through the spectroscopic characterization of the local plasma at the target surface. Note that, while this type of studies is common in linear plasma devices [21], it is not in electron or ion beam-based facilities. Thus for example, the erosion mechanism of the target material can be investigated as a function of beam power and sample temperature through the monitoring of the spectrum of the resulting plasma, once its microscopic parameters are characterized. Furthermore, issues related to the recycling of H atoms on the target can be addressed through emission spectroscopy and mass spectrometry. The description of this kind of studies in OLMAT will be the subject of a future publication.

4d) Laser irradiation.

One of the ongoing upgrades of the OLMAT facility is the incorporation of a high power fiber laser with pulse length between 0.2 and 10 ms and the possibility of CW operation. With a repetition rate of 2 kHz, the laser may provide a fast way to check for thermal fatigue effects for high numbers of heat pulses, as it has been previously used [22]. For a nominal CW power of 0.9 kW and a test area of 5x5 mm2, a peak power of 3.6 GW/m2 can be obtained for 1 ms pulses (FHF = 114) if full power absorption is assumed. In CW operation (900 W), the same focusing will yield 36 MW/m2 or 18 MW/m2 in a 10x5 mm2 spot, thus resembling the strike point area of a reactor divertor. NBI and laser pulses will be used in an alternate or simultaneous way depending on experimental goals.

5. Conclusions

A new facility dedicated to testing armor materials under relevant heat fluxes for a future reactor divertor has been installed and commissioned at CIEMAT. Thermal parameters beyond those specified for slow transients in a reactor were achieved. TZM samples were exposed to heat loads up to ~ 60 MW/m^2 in 100ms pulses (FHF = 19 $MW/m^2.s^{1/2}$ and to trains of 100 pulses (100 ms duration) at 30 MW/m^2 (FHF = 9.5 $MW/m^2.s^{1/2}$) without any sign of deterioration. However, a clear melting of the SS supporting ring was observed in a single shot, as expected for the peak temperatures calculated with a simple slab model. Preliminary trial results on a CPS target of Sn and a W capillary mesh stress the need of a good wetting and the associated thermal contact for successful operation of liquid metals under the extreme heat loads foreseen in a fusion reactor. Qualitative and quantitative spectroscopic characterizations of the resultant plasma plume were also undertaken.

The OLMAT facility is now ready to provide new data on the behavior of divertor target materials under the highly demanding conditions of fusion reactor plasmas.

Acknowledgements

This work was partially financed by the Spanish 'Ministry of Science and Innovation' under projects ENE2014-58918-R, RTI2018-096967-B-I00 and PID2020-116599RB-I00.

This work has been carried out within the framework of the Eurofusion Consortium and has received funding from the Euratom research and training program 2014–2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The authors are indebted to Dr Macarena Liniers and Dr Angel Perea for their contribution to the thermal model calculations and discussion.

References.

1] https://www.euro-fusion.org/eurofusion/roadmap/
2] R. Wenninger. et al. Nucl. Fusion 55 (2015) 063003
3] M Wirth et al. Nucl. Fusion 55 (2015) 123017
4] Ch. Linsmeier et al. Nucl. Fusion 57 (2017) 092012
5] Pitts R.A. et al. A full tungsten divertor for ITER: physics issues and design status J. Nucl. Mater. 438 (2013) S48–56
6] R. E. Nygren and F. L. Tabarés, Nuclear Mater. Energy 9 (2016) 6
7] D Alegre et al. "Design and testing of advanced liquid metal targets for DEMO divertor: The OLMAT project" J. Fus. Energy 39 (2020) 411–420
8] C. Fuentes et al. Fus. Eng. Design 82 (2007) 926
9] M. Liniers et al. Fus. Eng. Design 123 (2017) 259
10] W. Eckstein and H. Verbeek in Nucl. Fusion (1984) Special issue on Data Compendium for Plasma-Surface Interactions, p.12
11] http://qedfusion.org/LIB/PROPS/PANOS/matintro.html
12] H.S. Carslaw and J.C. Jaeger, "Conduction of Heat in Solids", Oxford Sci. Pub. 2nd ed.,pg. 101
13. X. Kang et al. Jpn. J. Appl. Phys. 33 (1994) L1041
14] A. Hassanein et al. J. Nucl. Mater. 390–391 (2009) 777
15] W. Lochte-Holtgreven, "Plasma Diagnostics", American Vacuum Society Classics, AIP, New York (1995)
16] P. C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, IOP Publishing, London 2000
17] G. Pintsuk et al. Phys. Scr. T167 (2016) 014056
18] Greuner H., Böswirth B., Boscary J. and McNeely P, J. Nucl. Mater. 367–70 (2007)1444
19] J. Linke et al. J. Nucl. Mater. 367–370 (2007) 1422
20] M. Wirtz et al. Nuclear Mat Energy 12 (2017) 148
21] G.J. van Rooij et al. Appl. Phys. Lett. 90 (2007) 121501
22] M. Wirtz et al. J. Nucl. Mater. 438 (2013) S833

Table I. Summary of experimental results.

Case	1	2	3	4	5	6	7	8	9	10	11
NBI par.											
W (kW)	**160**	**200**	**250**	**280**	**330**	**355**	**400**	**450**	**500**	**626**	**706**
V (kV)	20.5	23	23	25	25	28.6	31	31	32	31	32
I (A)	24	28	28	31	31	42	45	50	56	50	56
Ions?	no	no	yes	no	yes	no	no	no	no	yes	yes
Rate (K/ms)	0.28	0.40	0.52	0.76	0.92	1.08	1.14	1.41	1.48	1.99	2.24
Q ($\mathbf{MWm^{-2}}$)											
Coupling*No	5.6	8.0	10.4	15.2	18.4	21.6	22.8	28.2	29.6	40.0	44.8
Full	9.0	12.8	16.6	24.3	29.4	34.5	36.5	45.1	47.3	63.7	71.6
Avg.	**7.3**	**10.4**	**13.5**	**19.7**	**23.9**	**28.0**	**29.6**	**36.6**	**38.4**	**51.8**	**58.2**
Ptcle. Flux** (10^{22} $m^{-2}.s^{-1}$)	0.34	0.43	0.55	0.75	0.92	0.96	0.92	1.13	1.15	1.60	1.74

*See text.

** Assuming average Q

Figure Captions.

Figure 1. a) Sketch of the OLMAT facility (top view). B)3D CAD drawing of the main components.

Figure 2. A) Sketch of the CPS target: a) supporting SS plate with holes for the thermocouples, b) holding TZM ring (SS for the TZM target), c) machined TZM plate (target) d) isolating ceramics e) heating wire f) thermocouples. Not shown is the Sn wetted W mesh on top of the TZM target. Total diameter = 100 mm. TZM target thickness = 7 mm. B) TZM target before exposure C) CPS target partially wetted by Sn before irradiation showing the wetted area and the 2 W wires inserted to prevent bulging of the mesh.

Figure 3. Single shot temperature increment at the target as a function of pulse length for two values of NBI power.

Figure 4. Power density at the target as a function of nominally injected NBI power. See text for the evaluation of the error bars.

Figure 5.Profile of temperature increment vs. radial location at the target.

Figure 6. a) Time traces of the pyrometer signal at different pulse durations and constant NBI nominal power of 625 kW. b) Fitting of the data to a simple slab model.

Figure 7. a) Survey spectrum of the local plume in a TZM target. B) Detail of the Hα spectral region showing the different NBI energy components.

Figure 8. a) Emission spectrum showing the blackbody contribution. b) Photograph of the TZM target after extensive exposure to the NBI. Note the melting of the SS holding ring.

Figure 9. Radial profiles of Hα emission in front of the target w and w/o activation of the bending magnet. Target located at x=0.

Figure 10. a) Emission Spectrum of a CPS Sn target showing a structured blackbody background. b) The same spectrum corrected for the uneven transmission of the optical fiber using a calibrated light source. A blackbody temperature of 4600 K is deduced from the background. c) The CPS target after irradiation by the NBI at high power. Note the melting of the W mesh in non-wetted areas and the non-perturbed remaining Sn at the right side.