LIBS chemical characterization of the JET first wall after its last experimental campaign, with special focus to the divertor zone: first results and next steps

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(ENEA)

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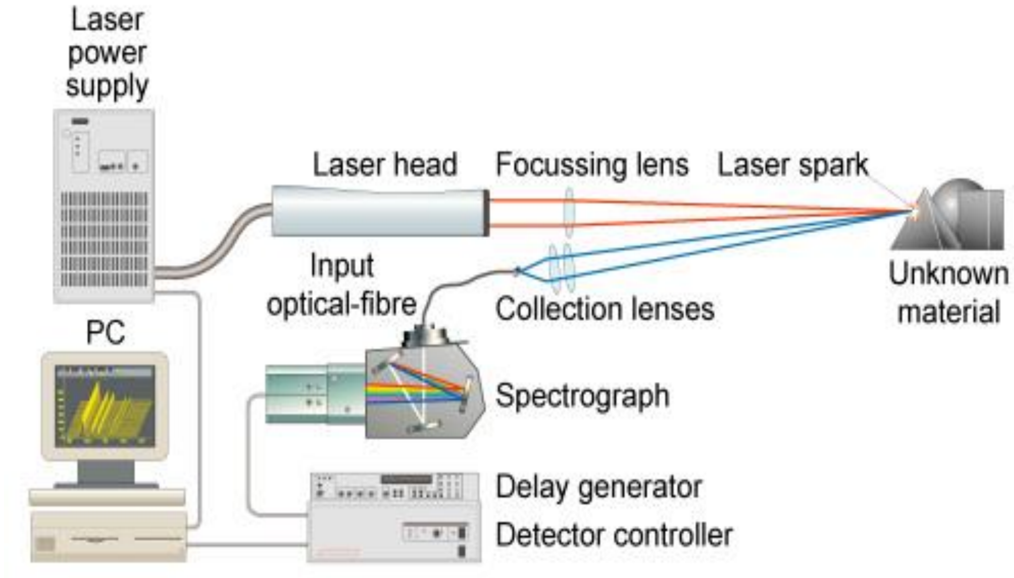
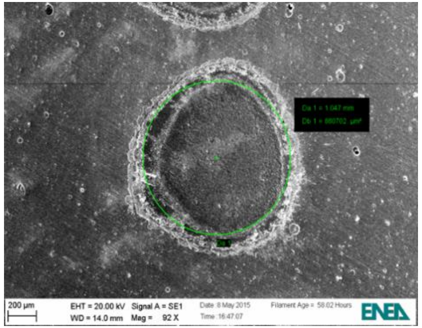
Summary

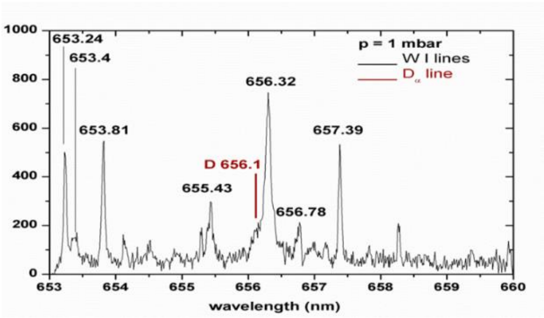
- Brief recap of the Laser-Induced Breakdown spectroscopy technique
- The LIBS device developed for JET
- Depht profiling analysis of different materials inside the JET VV
- Depth profiling analysis of the JET divertor
- (ongoing) quantification of the hydrogen isotopes through the calibration free (CF) technique
- Conclusions

Brief recap of the LIBS technique

LIBS is a rapid technique of chemical analysis using a focused short laser pulse (typical $\tau_{pulse} \leq 10^{-9}$ s) which induces a micro-plasma on the sample surface (e.g. PFCs) that can be spectrally analyzed giving the chemical composition of the sample. Laser and optics can be close to or several meters away from the target.





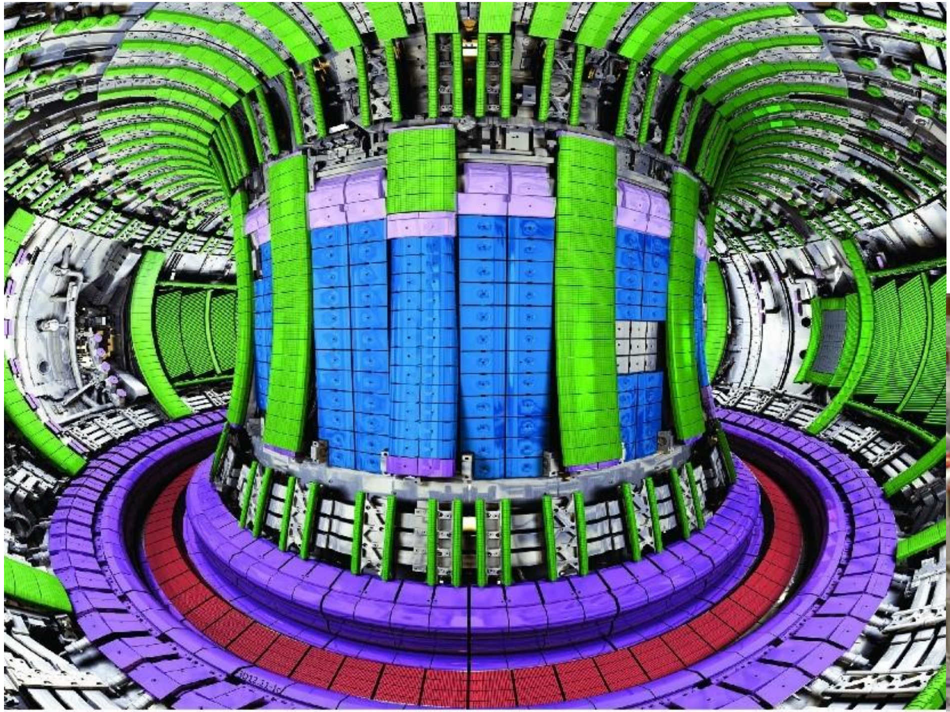


Brief recap of the LIBS technique

LIBS is a rapid technique of chemical analysis using a focused short laser pulse (typical $\tau_{pulse} \leq 10^{-8}$ s) which induces a micro-plasma on the sample surface (e.g. PFCs) that can be spectrally analyzed giving the chemical composition of the sample. Laser and optics can be close to or several meters away from the target.

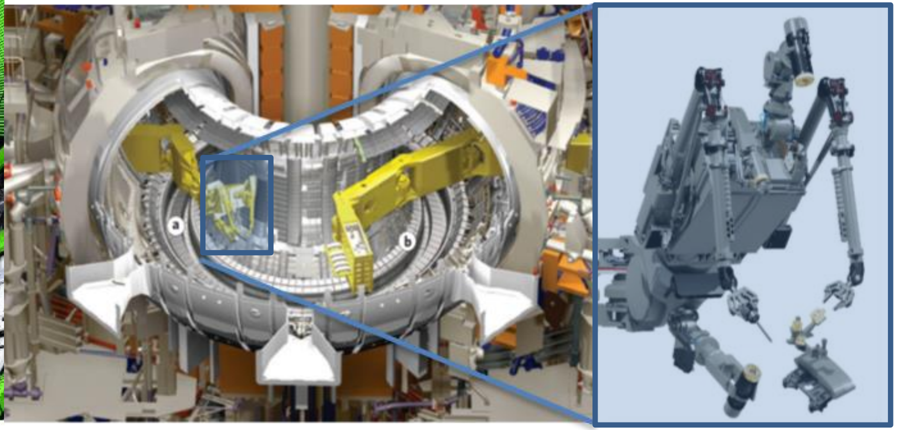
- **All chemical elements can be detected simultaneously even at trace level**
- **Hydrogen isotopes detection**
- **Microdistructivity, only few μg of sample are needed: further analyses with other techniques can be done**
- **No sample preparation is necessary**
- **Depth profiling and stratigraphy capabilities**
- **Remote detection, either from optical ports or through robotic probes**
- **Suitable for hostile environments, hard Rad compatibility**
- **Semi quantitative and quantitative analysis demonstrated**
- **Data acquisition in real time (seconds)**
- **Data analysis can be automatized**

The LIBS device developed for JET



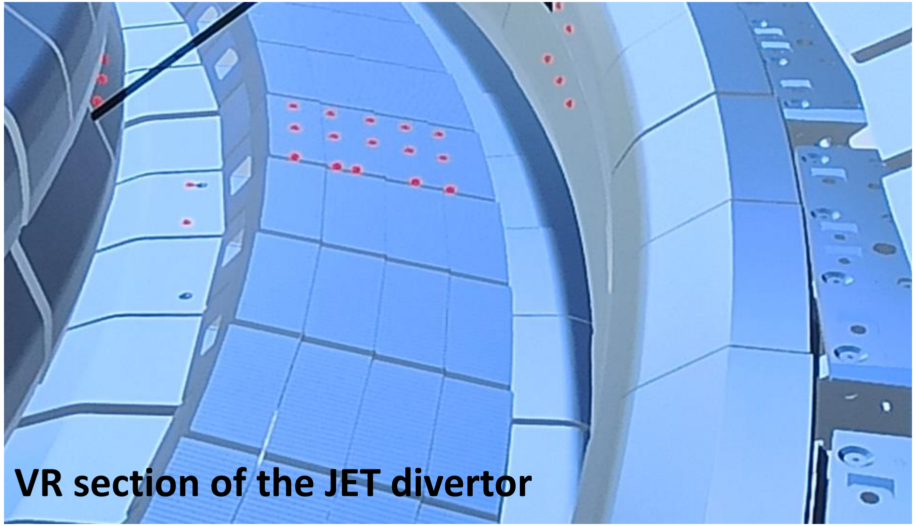
Beryllium | CFC tungsten coated | Inconel tungsten coated
Tungsten | Inconel beryllium coated

JET was the first tokamak capable of carrying out experiments using deuterium-tritium (D-T) fuel and it is equipped with a beryllium first wall (FW), a tungsten divertor, tritium and beryllium handling facilities, and <u>a highly proficient remote-handling system.</u>



The LIBS device developed for JET

The MASCOT telemanipulator robot is a two-armed machine remotely operated from a control room, where a kinematically similar master manipulator is used to control motions, and provide high-fidelity force feedback systems. In addition to a CCTV viewing system, JET uses synthetic views created by a real-time virtual reality (VR) system, constantly updated with position data relating to the robotic systems. MASCOT has generally been used for maintenance operations of the JET first wall such as replacement of worn components of the first wall or of the divertor.



In the case of the LIBS project, MASCOT has been used to deploy inside the JET VV a LIBS tool able to sample the FW and the divertor **with the main task to detect the residual D-T and the eroded and redeposited materials on the whole surface of the VV accessible to the tool**

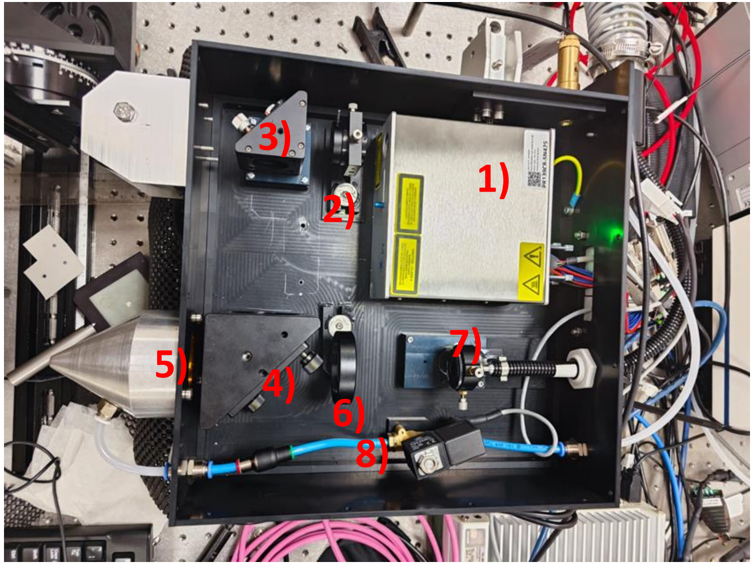
Main requirements of the LIBS tool:

1) **compact system**
2) **weight ≤ 10 kg**
3) **No water cooling tubes for the laser head**

The LIBS device developed for JET

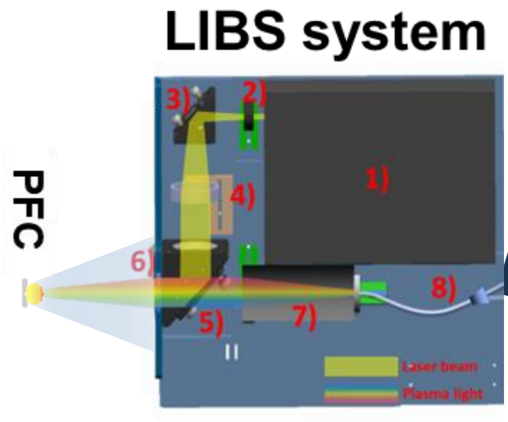
- The LIBS head includes a compact Nd:Yag laser head carried inside the VV together with some optical components.
- A hollow Aluminium cone houses the final focusing lens, to ensure the correct focusing distance between the lens and the JET-PFC.
- Ar gas is fluxed (2l/min) on the target during the LIBS measurements, to reduce the interference of the environmental hydrogen to the LIBS signal and increase the signal-to-background ratio, according to literature data.

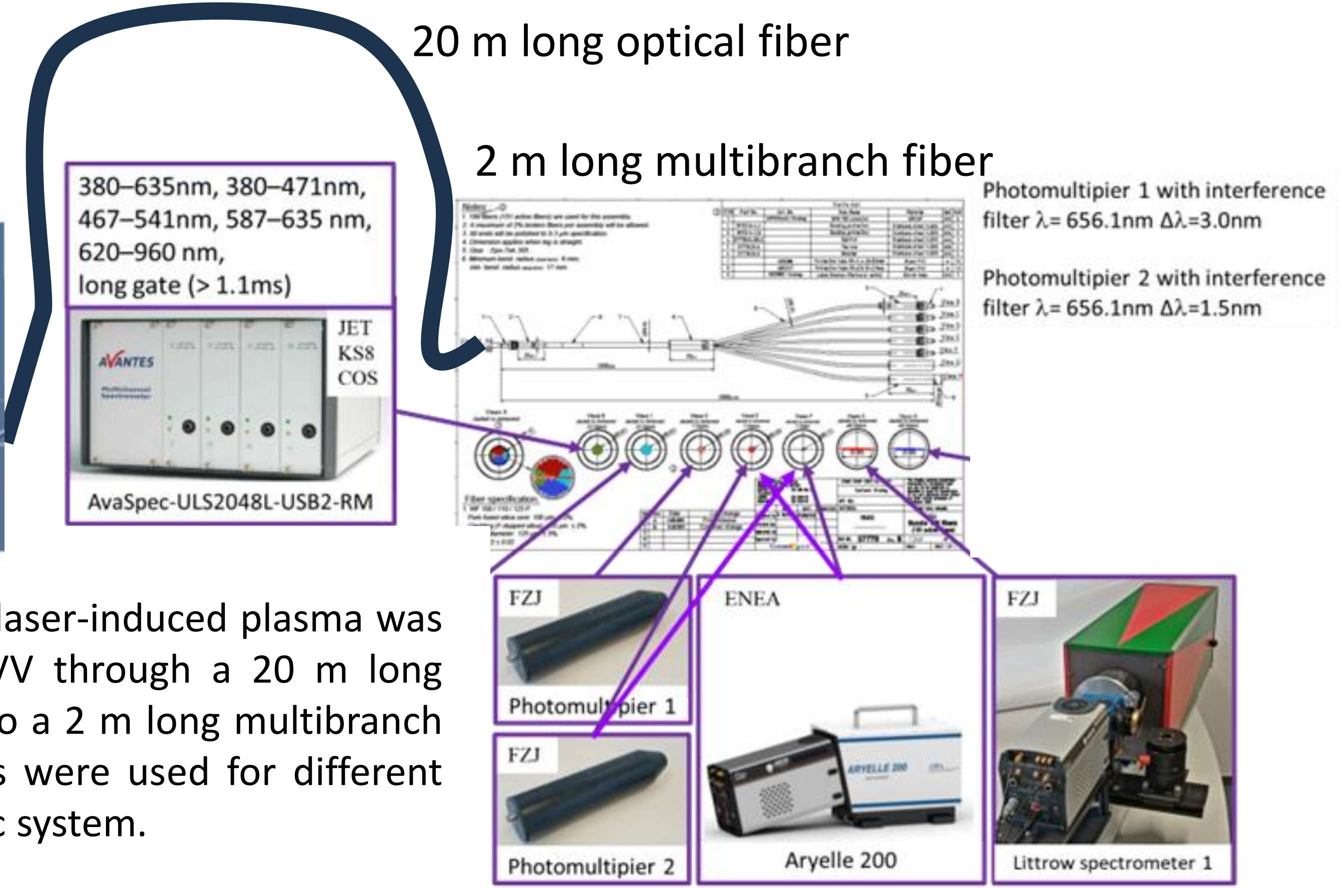
  - The laser power cable, the laser-PC communication cable, the optical fiber and a fluxing tube for Ar gas connected the LIBS head inside the VV with the rest of the system (spectrometers, control PC, electronics, etc) outside the VV.



	Description
1)	Compact Nd:Yag – laser (λ = 1064 nm)
2)	Circular diaphgram
3)	1'' dia. HR-IR 45° mirror (45°)
4)	2'' dia. HR-IR HT-VIS dielectric mirror (45°)
5)	2'' dia. lens (f = 75 mm) inside the cone
6)	2'' dia . Lens (f = 100 mm) collecting the LIBS light on the optical fiber
7)	Optical fiber (20 m)
9)	Ar Gas tube

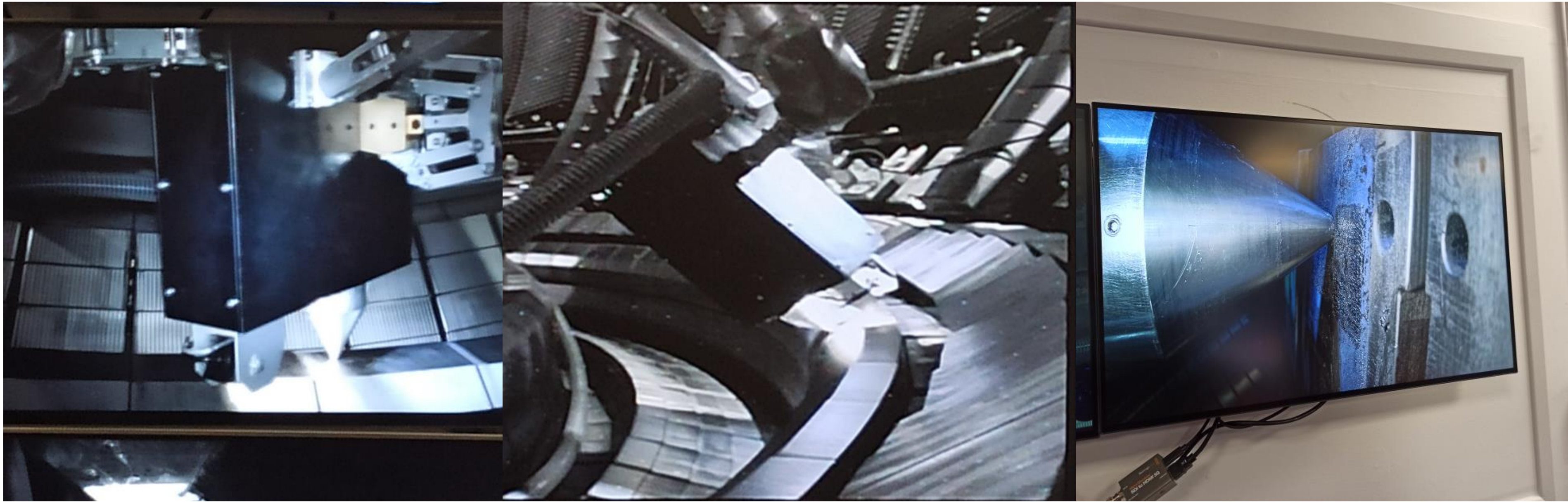
The LIBS device developed for JET



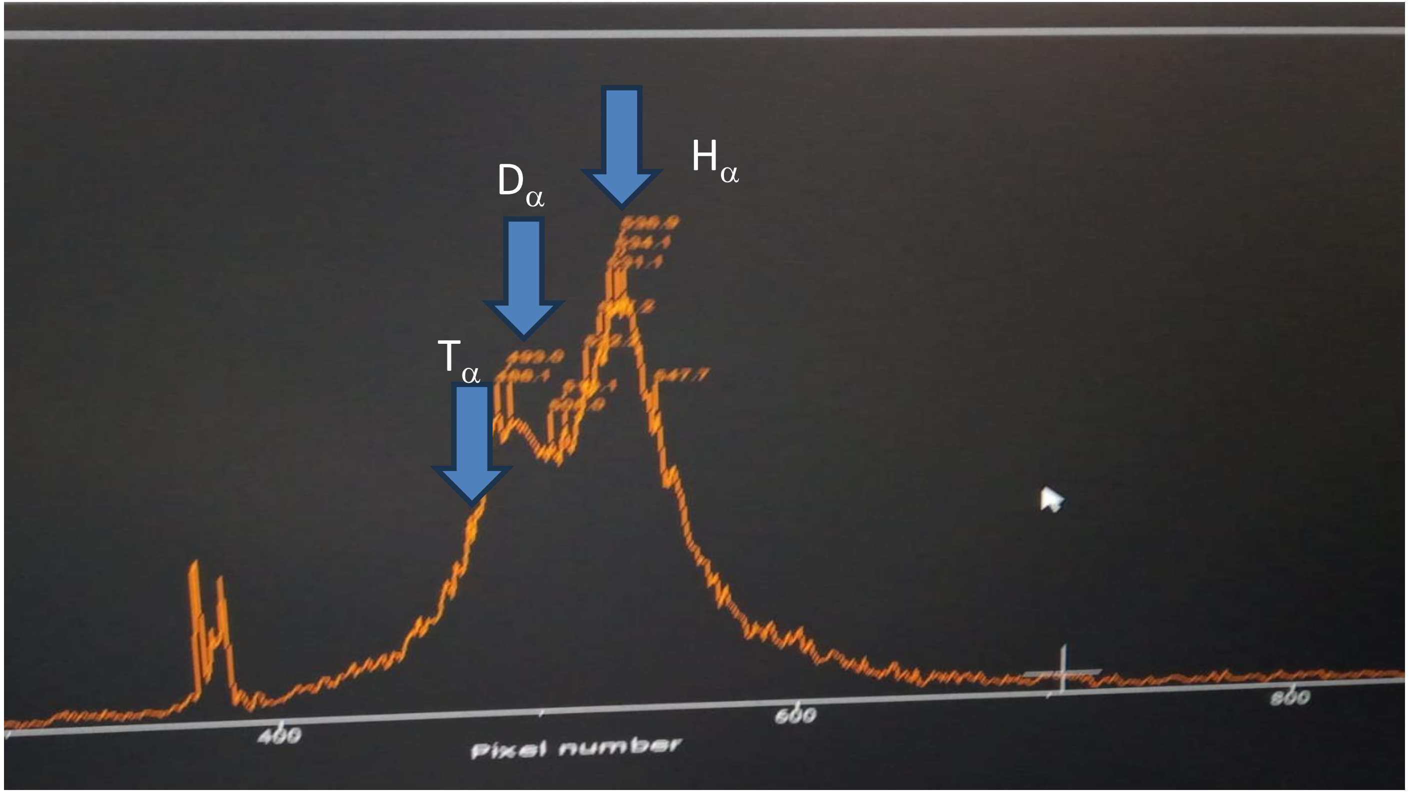


- The LIBS signal from the laser-induced plasma was carried out of the JET VV through a 20 m long optical fiber, connected to a 2 m long multibranch fiber whose terminations were used for different devices and spectroscopic system.

The LIBS device developed for JET



The LIBS device developed for JET



Depth profiling data analysis: procedure

- The depth profiling analysis consists in consecutively ablating the sample on the same points with multiple laser pulses and subsequently analyzing the emitted spectrum of each pulse to gather information about elemental concentration with respect to depth.

- The typical depth resolution for LIBS depth profiling falls between 100 and 500 nm per laser shot

- Given the large number of LIBS spectra acquired during the experimental campaign at JET the depth profiling analysis has been performed through the development of scripts capable of processing the large number of spectra automatically, in a short time.

- For each spectrum the intensity trend of peculiar and characteristic emission lines of the most meaningful chemical elements in the VV (e.g. W, Be, C, Mo, Ni, Cr, T-D-H etc) was monitored and reported as a function of the number of applied laser shots.

The procedure has been developed to perform multiple depht profiling analyses of the acquired spectra looking at intense and free of interference emission lines of the elements.

```
tic;
clear
d=dir(
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    if

    er
end
delete
figure
x_axis
plot(x
legend
xlabel
ylabel
figure
x_axis
semilc
legend
xlabel
ylabel
fclose
toc;
elapse
```

```
%tungsten lines
indices = find( x > 400.75 & x <= 401.05);
% figure(2)
% plot(file_appoggio(min(indices):max(indices),1),file_appoggio(min(indices):max(indices),2))
% title("W 400.87 nm");
% hold on
W_I_400_87nm(ind_PCA,1) = sum(y(min(indices): max(indices)));
indices = find( x > 407.05 & x <= 407.25);
figure(3)
plot(file_appoggio(min(indices):max(indices),1),file_appoggio(min(indices):max(indices),2))
title("W 407.06 nm");
hold on
W_I_407_06nm(ind_PCA,1) = sum(y(min(indices): max(indices)));

%Chromium lines
indices = find( x > 425.4 & x <= 425.6);
% figure(4)
% plot(file_appoggio(min(indices):max(indices),1),file_appoggio(min(indices):max(indices),2))
% title("Cr 425.44 nm");
% hold on
Cr_I_425_44nm(ind_PCA,1) = sum(y(min(indices): max(indices)));
indices = find( x > 428.87 & x <= 429.07);
Cr_I_428_97nm(ind_PCA,1) = sum(y(min(indices): max(indices)));

%Beryllium lines
indices = find( x > 332.05 & x <= 332.35);
Be_I_332_13nm(ind_PCA,1) = sum(y(min(indices): max(indices)));
figure(4)
plot(file_appoggio(min(indices):max(indices),1),file_appoggio(min(indices):max(indices),2))
title("Be 332.13 nm");
hold on
indices = find( x > 457.25 & x <= 457.5);
Be_I_457_27nm(ind_PCA,1) = sum(y(min(indices): max(indices)));
figure(5)
plot(file_appoggio(min(indices):max(indices),1),file_appoggio(min(indices):max(indices),2))
```

'look' for W lines at 400.87 nm and 407.06 nm

txt' files in the folder

'look' for Cr lines at 425.44 nm and 428.97 nm

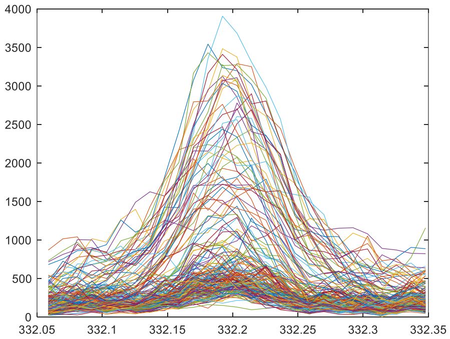
```
6nm), 'To'
lo I 557.0
H_656nm,'
lo I 557.0
```

'look' for 'Be' lines at 332.13 nm and 457.27 nm

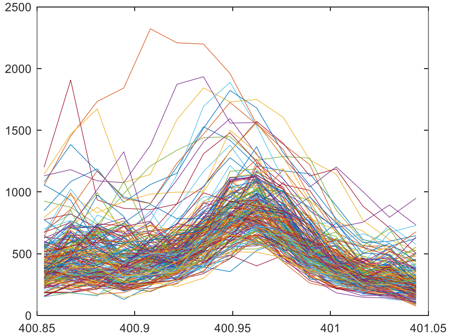
▪ Depth profiling data analysis: procedure

A list of the emission lines considered for each element is shown below. The rationale for choosing these lines is that they should be intense and as free from spectral interference as possible.

Atiom/Ion	Wavelength (nm)	Motivation
Be I	332.12	Be deposits on the divertor area
Be I	457.27	
W I	400.87	W substrate and redeposited material from erosion
W I	407.44	
T_α-D_α-H_α	656-656.3	Unburned (or implanted) fuel
Mo I	550.65	Mo interlayer (if present)
Mo I	553.3	
Mo I	557.04	
Cr I	425.43	Inconel structural material
Cr I	428.97	
Ni I	341.47	Inconel structural material
Ni I	345.85	
Ni I	346.16	
He I	587.58	Reaction product

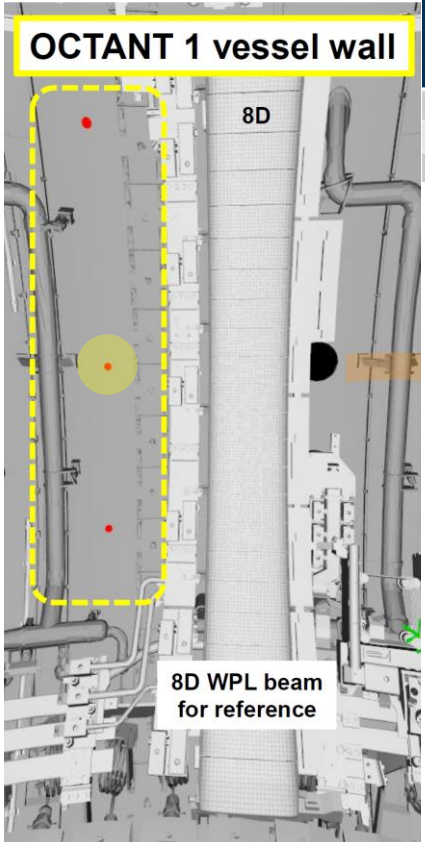


Ex 1: Point of analysis 775_14ONG8A_R2C2 Be I line at 332.12 nm



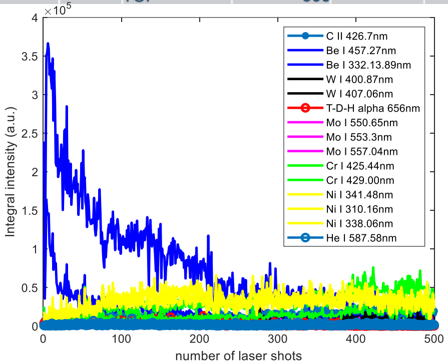
Ex 2: Point of analysis 775_14ONG8A_R2C2 W I line at 400.87 nm

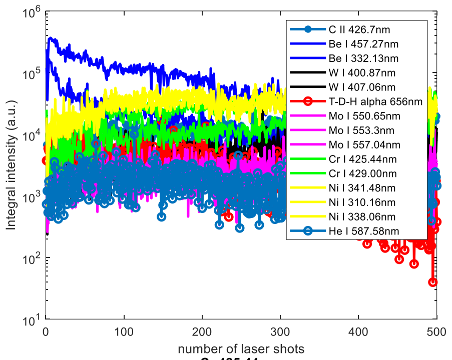
Depht profiling of point 357 - Oct1_VW - MIDDLE – (Inconel_reference)

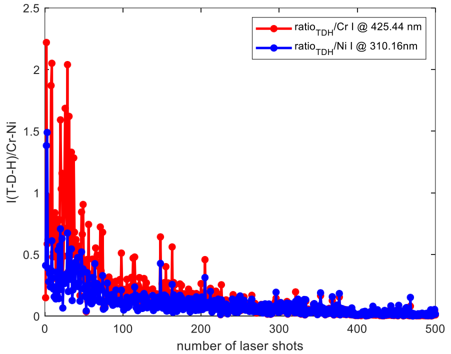


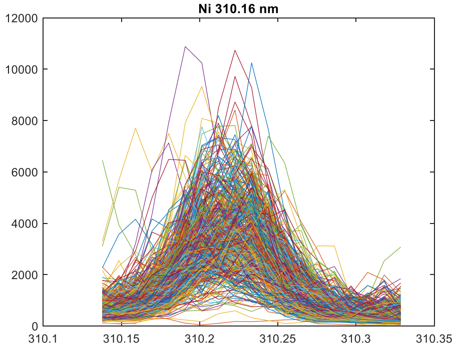
LIBS pulse no. #	Tile/ Loc.	Coords.	Tentative no. of laser shots	Actual no of laser shots	Comments
	VW OCT1	BOTTOM	500		
		MIDDLE	500	**500**	
		TOP	500		

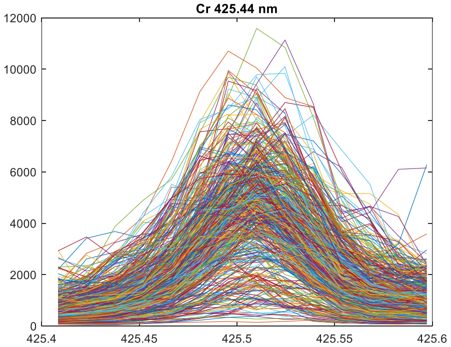
No residual signal from W and Be

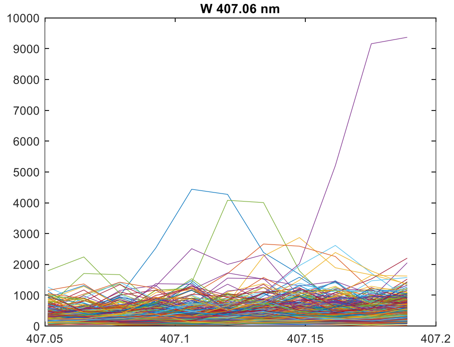








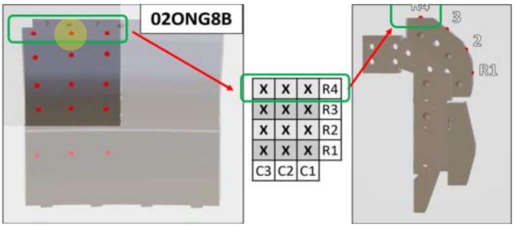


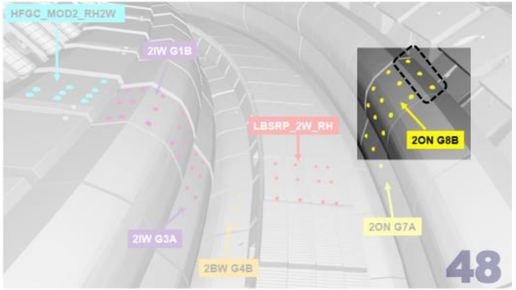


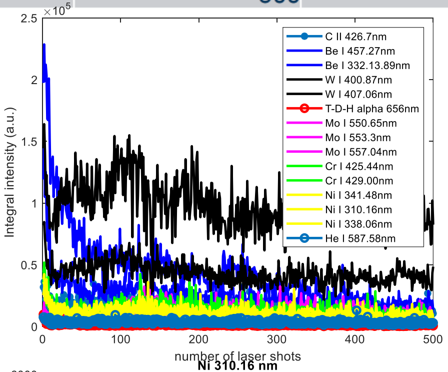
Depht profiling of point 360 - 02ONG8B - R4 C2 (W_reference)

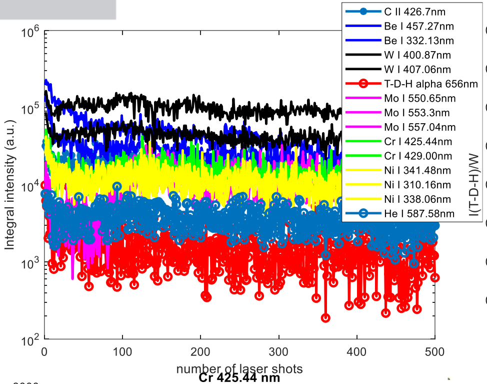
LIBS pulse no. #	Tile/location	Coordinates	Tentative no. of laser shots	Actual no of laser shots
	2ON G8B	R4C1	500	
		R4C2	500	500
		R4C3	500	

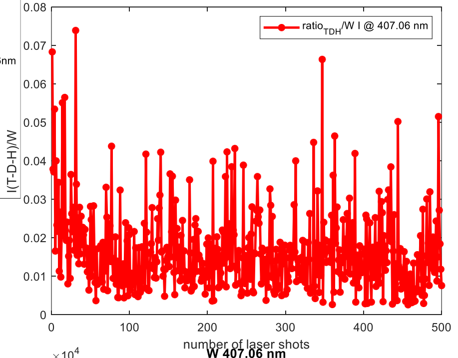
No residual signal from Ni, Cr and Be

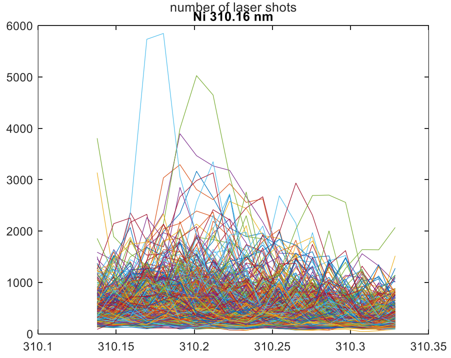


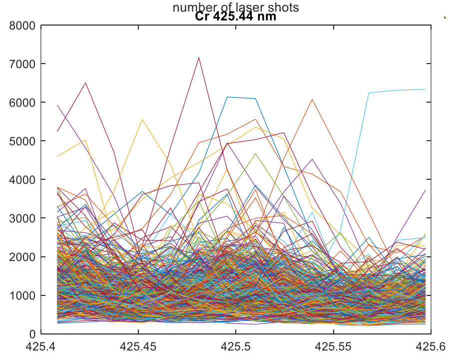


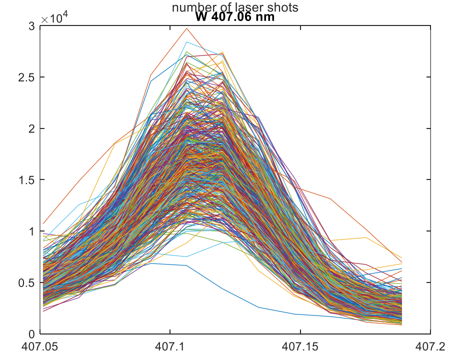




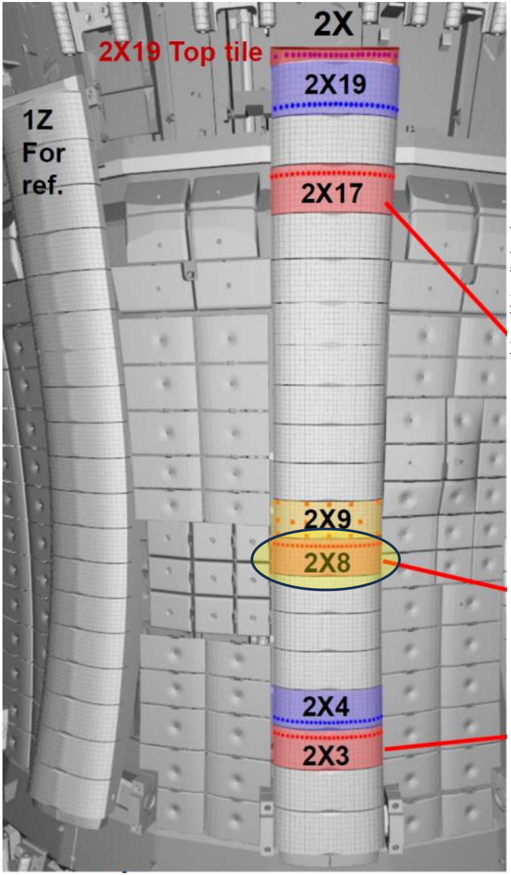


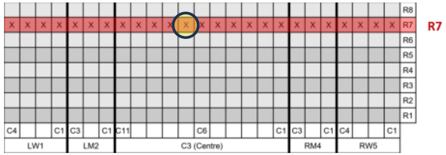


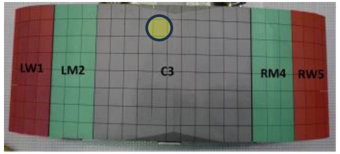




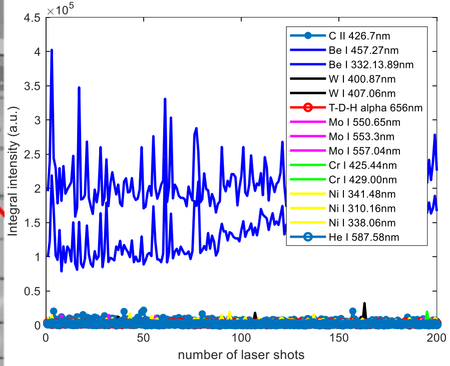
Depht profiling of point 492 - 2X08 - R7 C3-C7 (Be reference)

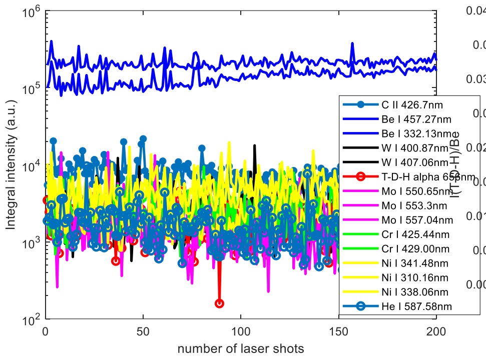


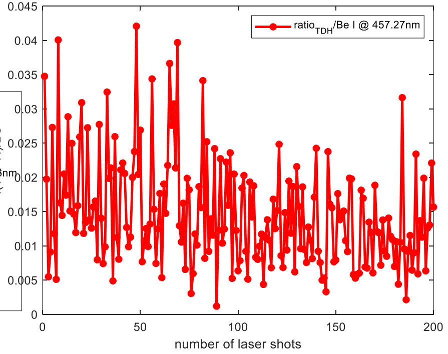


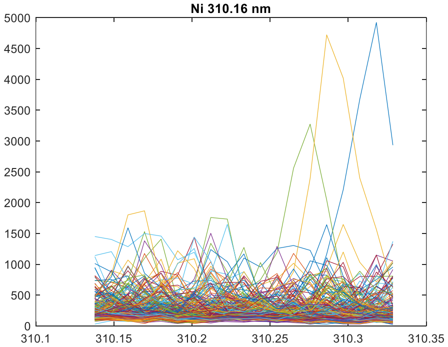


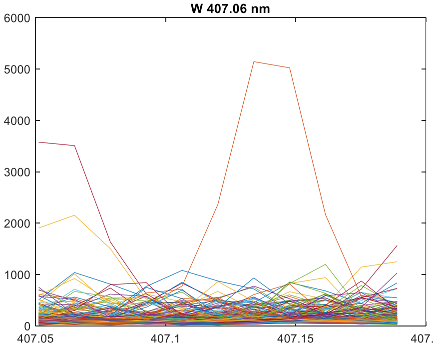
No residual signal from Ni and W

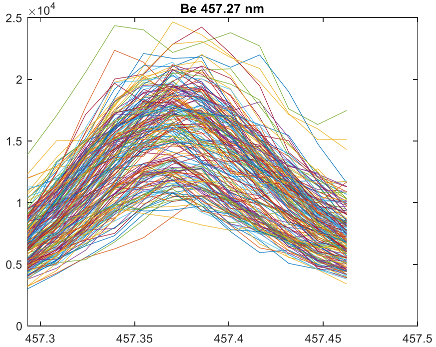






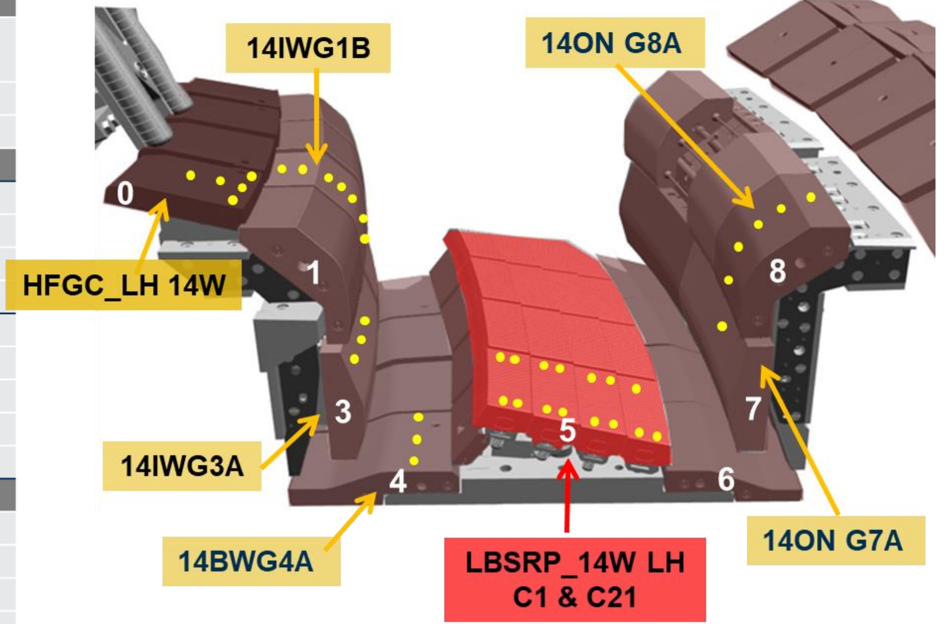






Depht profiling data analysis: divertor cross section

Tile			Initial Pulse no.	Additional pulse no.(relatively same location)
HFGC (LH 14W)			59 – 63	777 – 780
Tile 1 (14IW G1B)			808; 12 – 15; 73 – 74	786 (a repeat of 74)
Tile 3 (14IW G3A)			809 – 811	Same as above
Tile 4 (14BW G4C)A			75 – 77	787 – 788
Tile 5 LBSRP_14 WLH	C1	Stack A	20	765
		Stack B	23	766
		Stack C	26	768
		Stack D	29	769
	C21	Stack A	40	770
		Stack B	43	771
		Stack B (C12)	34	
		Stack C	46	773
		Stack D	49	-
Tile 6			NO LIBS on T6	NO LIBS on T6
Tile 7 (14ON G7A)			805	-
Tile 8 (14ON G8A)			802; 54; 57	775 (between 54 and 57)
Tile 8 (2ON G8B)			360 & 368	No repeated pulses
Top of tile 8 (14ON G8A)			51	-



▪ Depth profiling data analysis for the divertor: procedure

the operating scheme of the procedure already illustrated **has been implemented as follows**

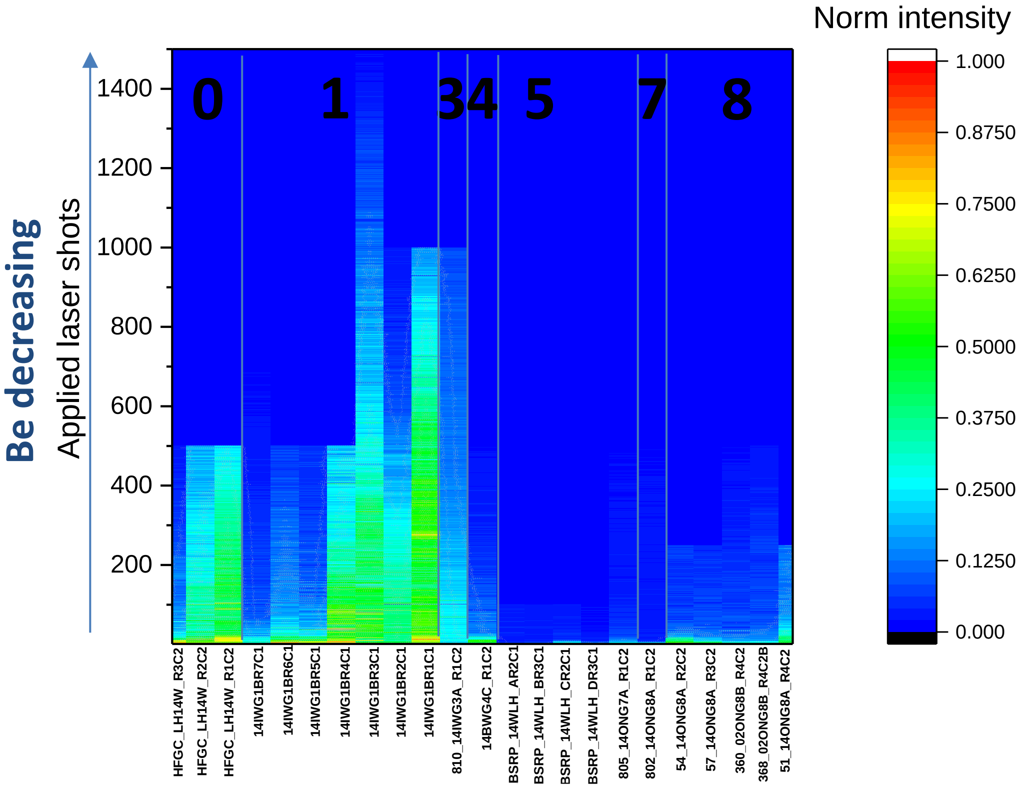
Steps illustrated

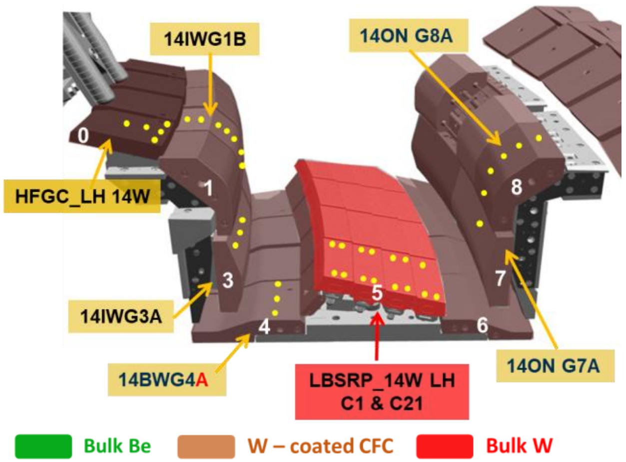
1. Read Aryelle txt file (sequentially)
2. Look for representative emission lines of peculiar chemical elements
3. Compute the integral intensities (IIs.) of the emission lines
4. Store and save the IIs. of the lines
5. Display the IIs. as a function of the laser shots

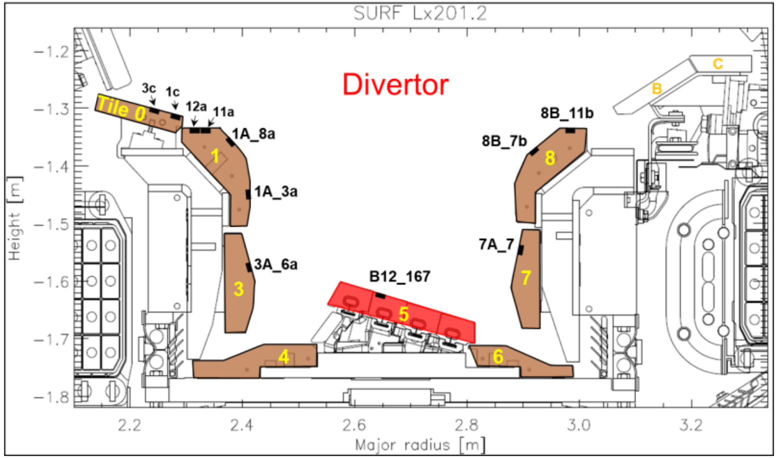
Additional steps

1. Compute the average intensity of more lines of the analyte (when available) for representative points of the divertor
2. Normalize [0,1] the average intensity
3. Perform a surface map of the normalized intensity

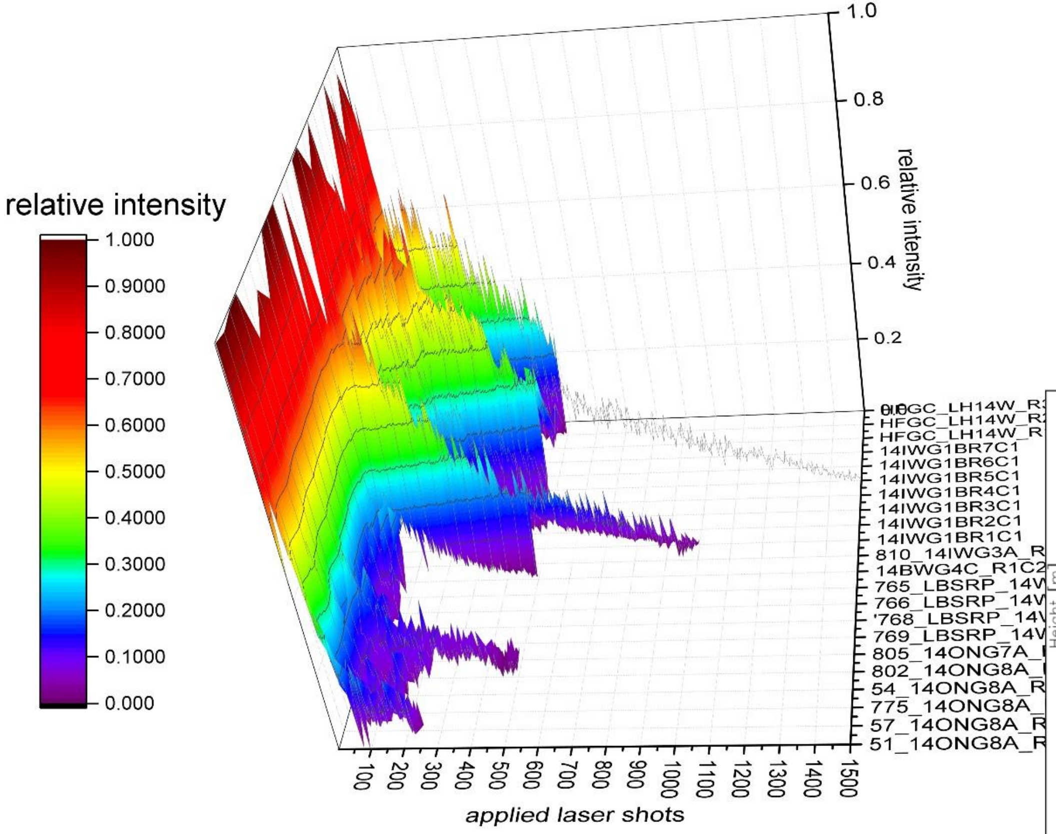
■ Results: **Be profile** on the divertor (normalized to the **max intensity**)

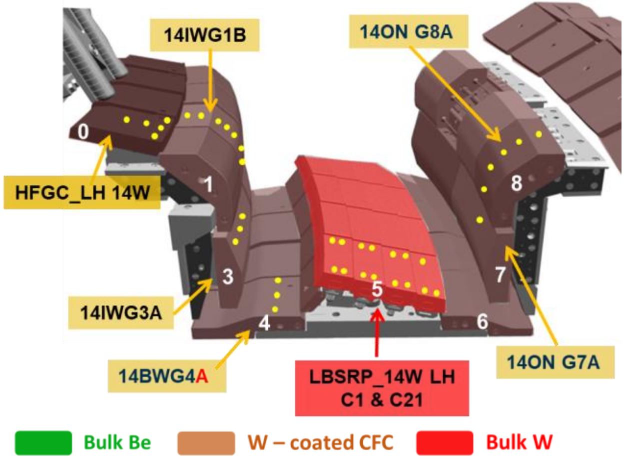


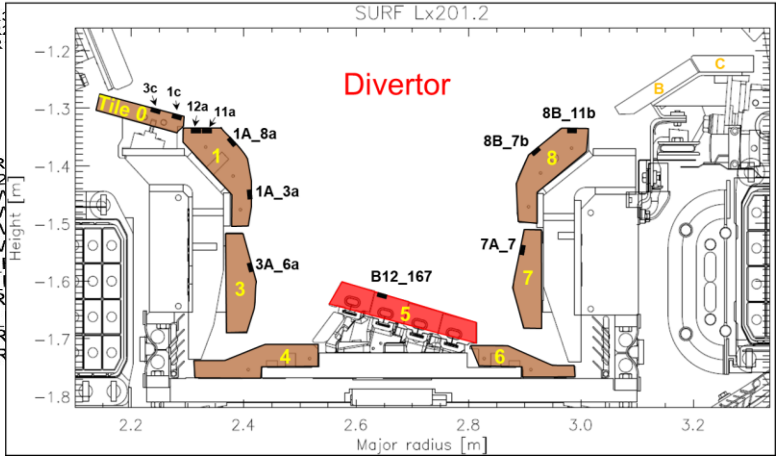




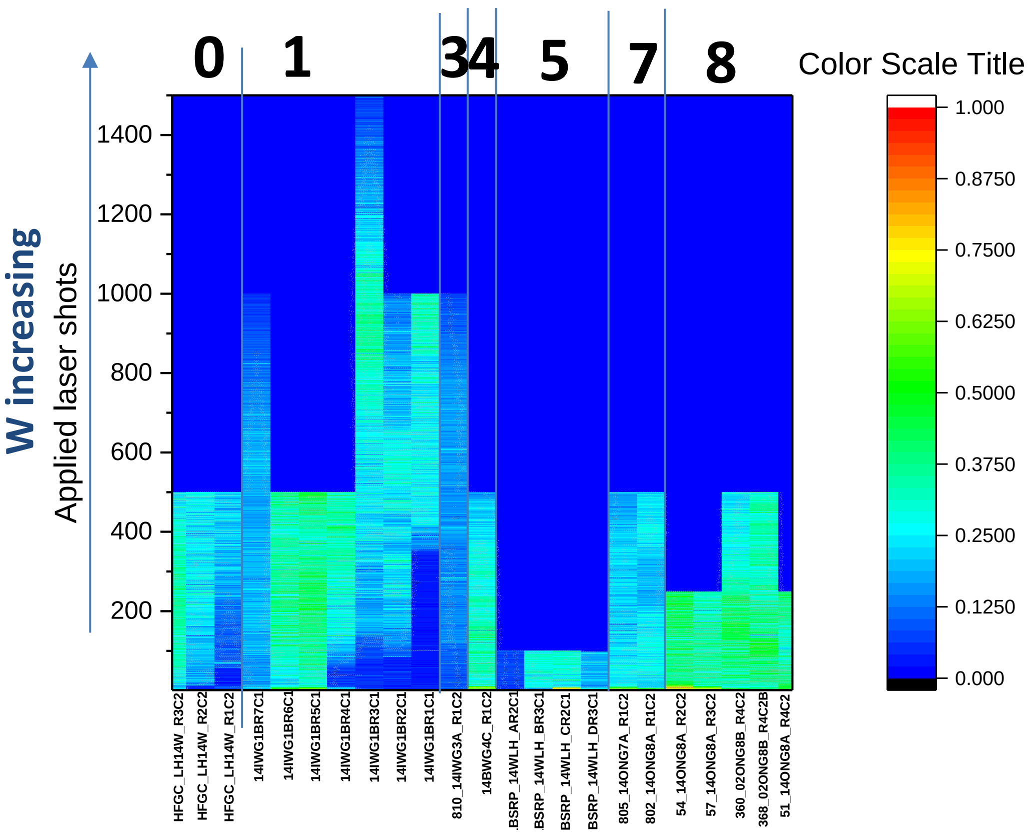
- Results: **Be profile** on the divertor

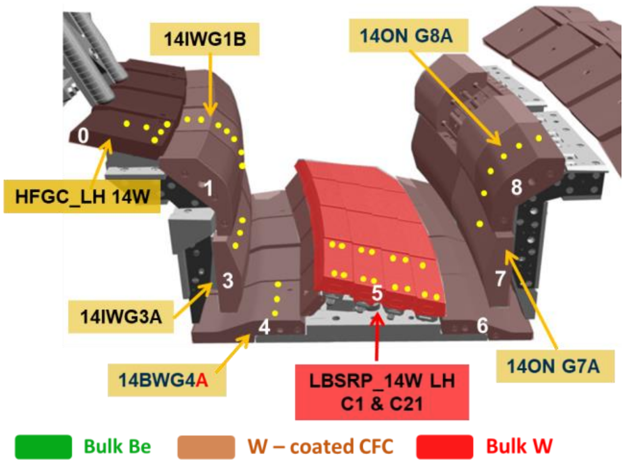


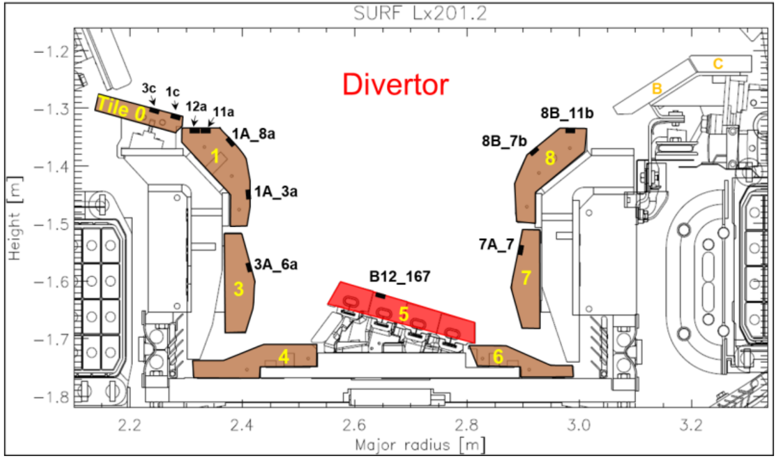




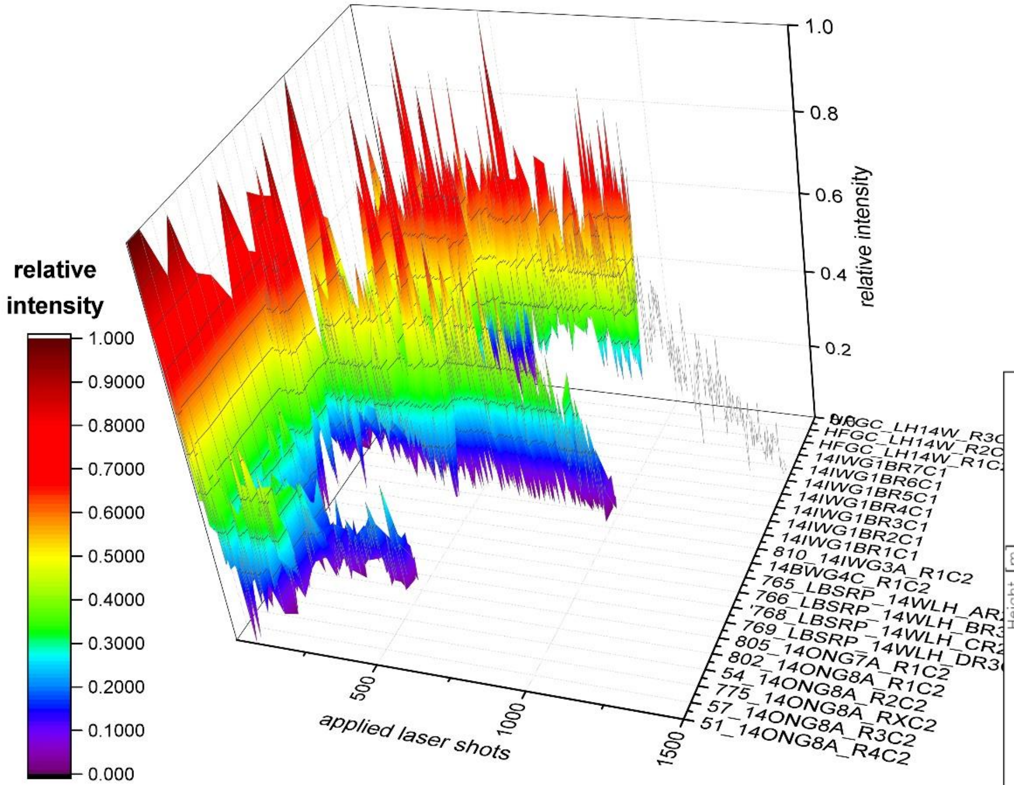
▪ Results: **W profile** on the divertor (normalized to the **max intensity**)

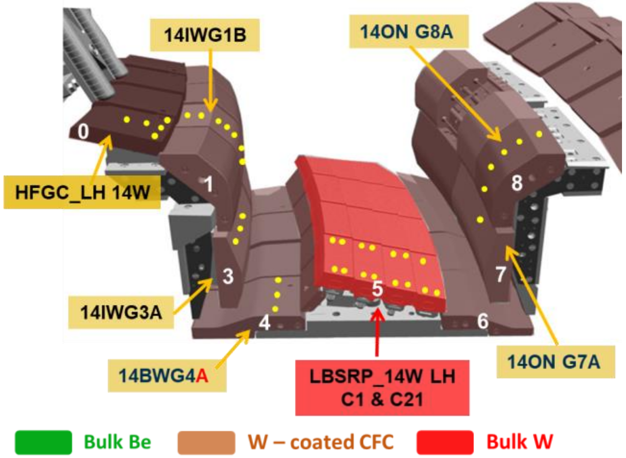


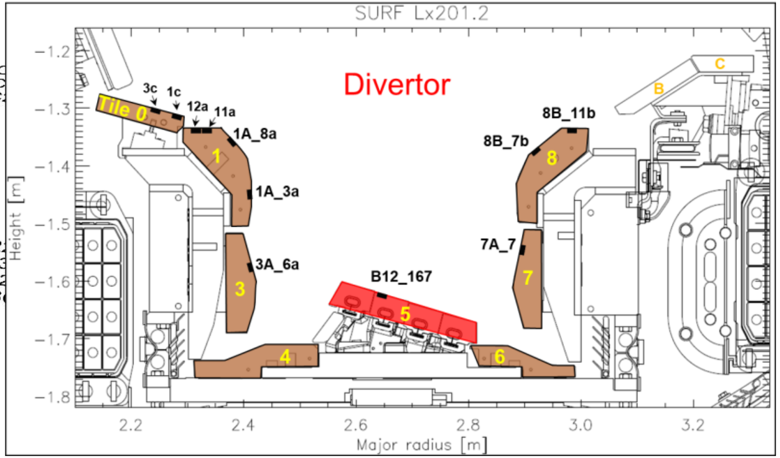




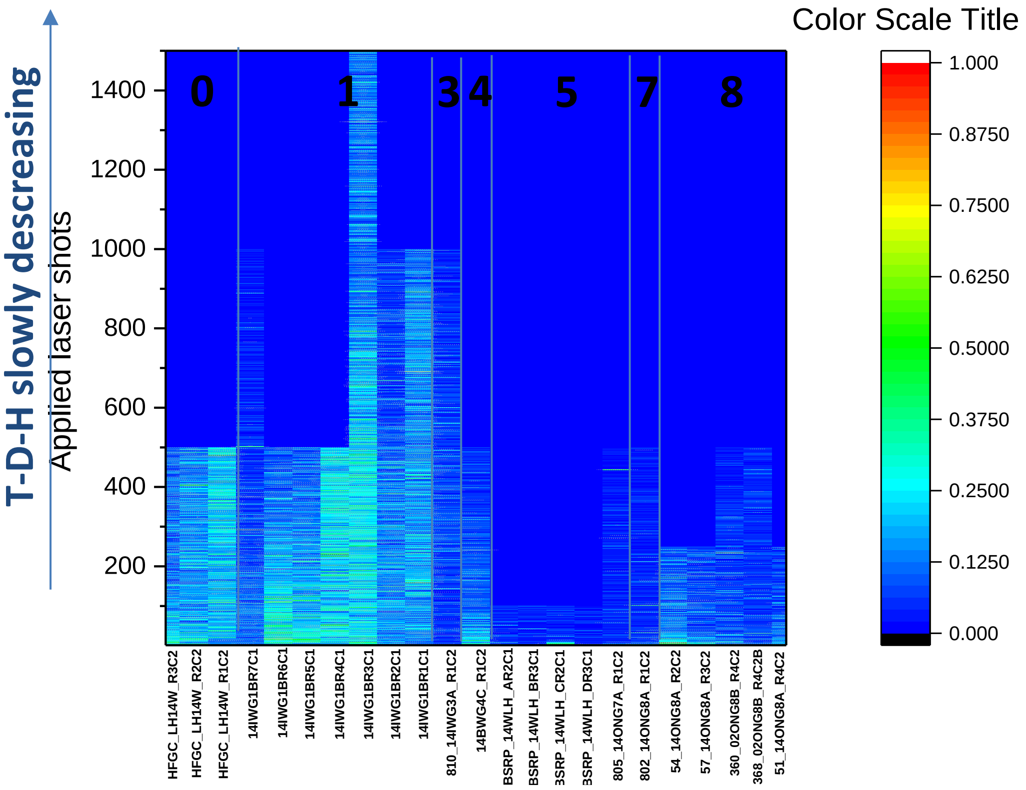
▪ Results: **W profile** on the divertor

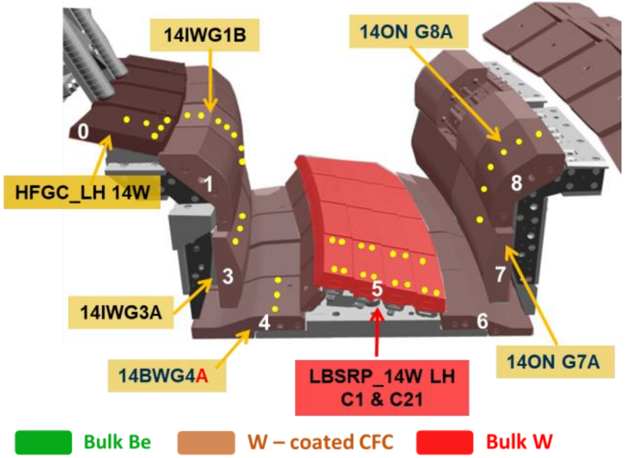


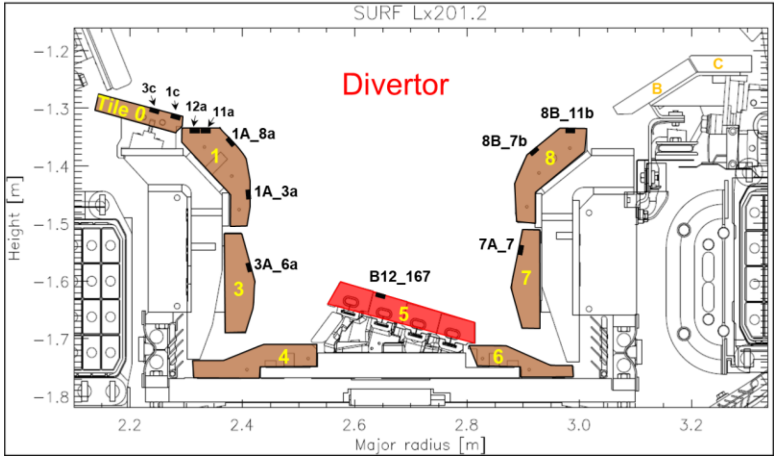




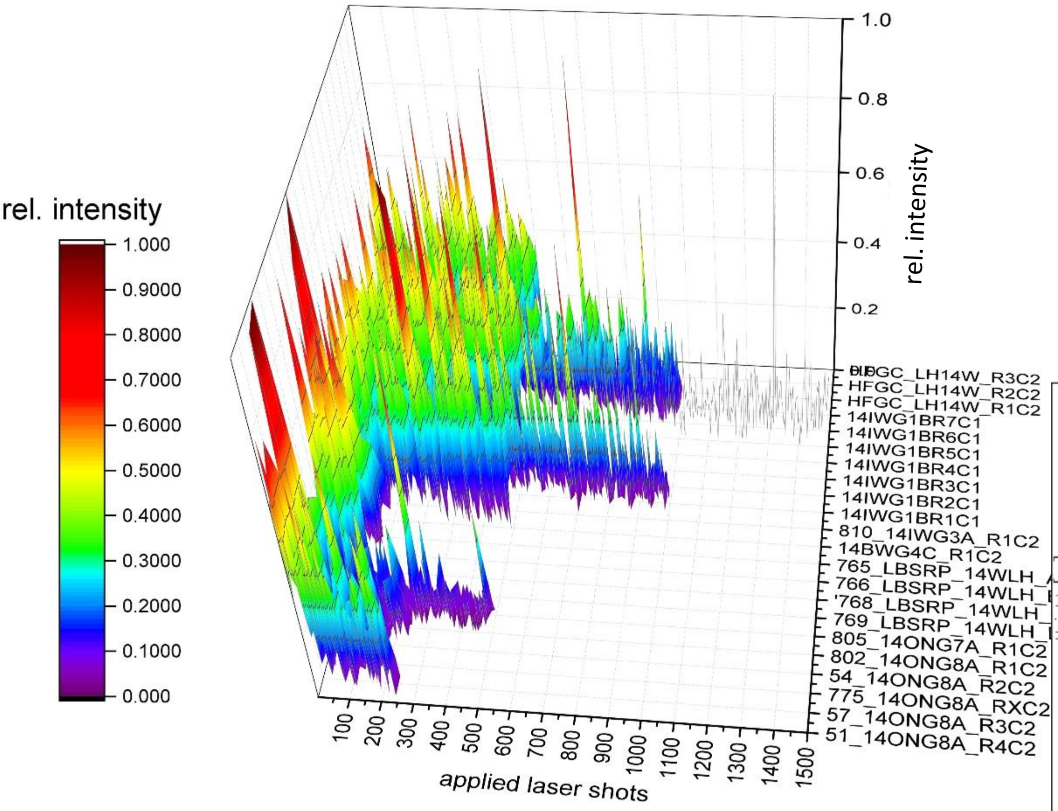
- Results: **T-D-H profile** on the divertor (normalized to the **max intensity**)

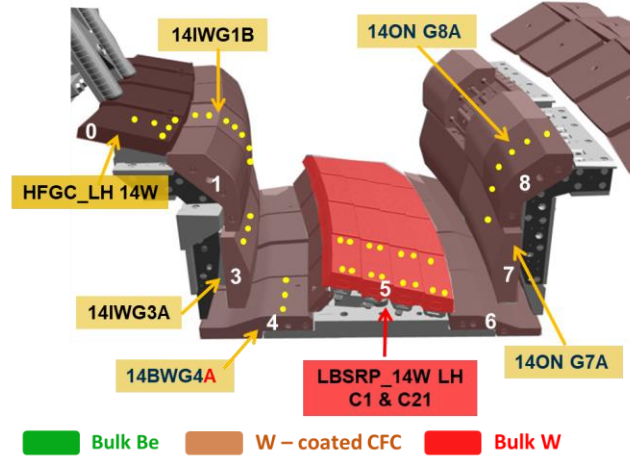


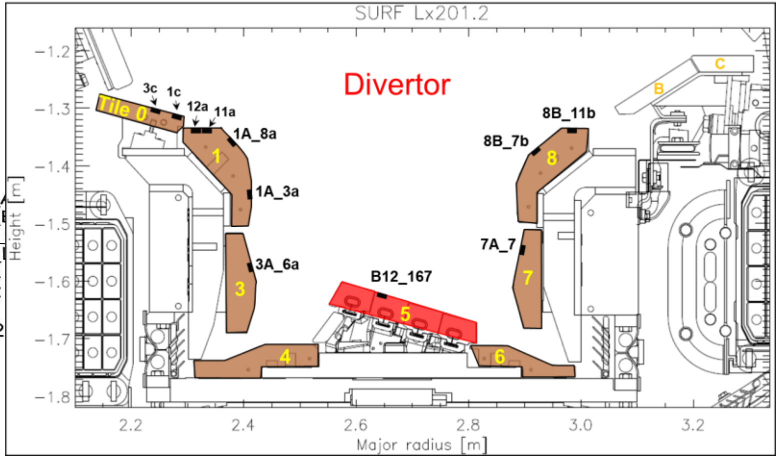




▪ Results: **T-D-H profile** on the divertor (normalized point by point)







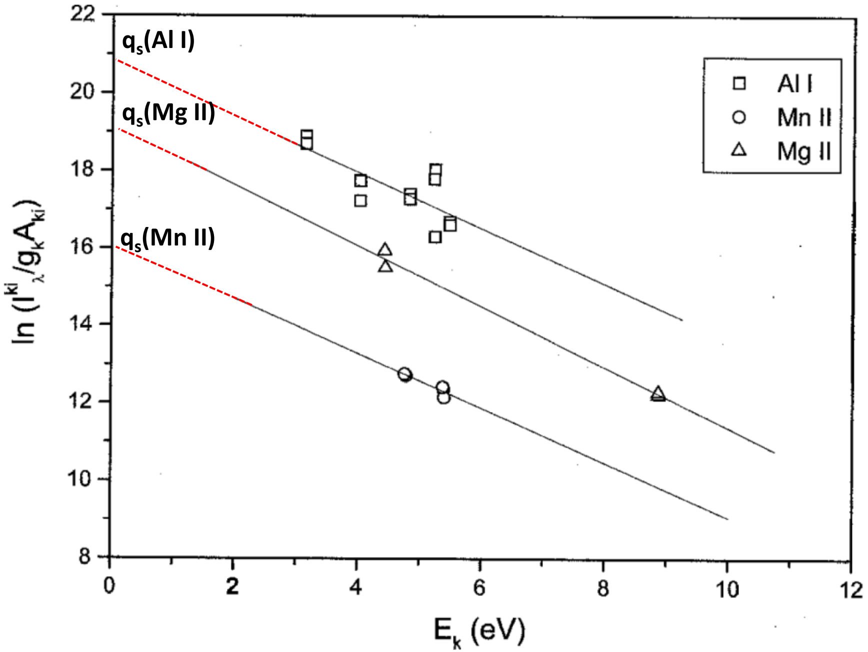
Calibration free analysis: procedure

The CF procedure (Appl. Spec. 53(8), (1999), 960-964) aims to quantitatively estimate the chemical elements detected in the LIBS plasma. CF will be applied to estimate the concentration of T+D+H (the latter being present as residual impurity in the spectrum) respect to W (bulk material of the divertor PFCs) and respect to Be (bulk material of the first wall and major eroded material on the divertor PFCs).
CF is based on the experimental intensities of the emission lines.
Indeed, if the LIBS plasma can be considered in local thermodinamic equilibrium (LTE) these intensities can be expressed as follows:

$$I_\lambda^{ki} = C_s A_{ki} \frac{g_k e^{-(E_k/k_B^T)}}{U_s(Te)}$$

where, $I_\lambda^{ki} =$ exp. intensity of the k→i transition, $C_s =$ concentration of the species, A_{ki} = transition probability for the given line, g_k is the k level degeneracy, E_k the upper energy level of the transition, k_B^T = Boltzmann constant, $U_s(T)$ is the partition function for the emitting species at the plasma temperature T_e.
The emission lines of each species can be plotted as points in a graph (**Boltzmann plot, BP**) and their linear fits give an intercept, q_s which is related to the relative concentration of the species through the following equation:

$$C_s = \frac{U_s(T_e)}{F} e^{q_s}$$



(Appl. Spec. 53(8), (1999), 960-964)

the operating scheme of the procedure is illustrated below:

1. Read Aryelle txt file (one by one)
2. Rescale the experimental emission intensities taking into account the response of the whole spectroscopic system
3. Consider the three W I emission lines 426.94 nm, 429.46 nm, and 430.21 nm and compute n_e
4. Make the extended Boltzmann Plot (BP) for W I and W II and compute $T_{e.}$
5. Make the BP for W + (H+D+T) and, from the intercepts, compute the [H+D+T]/[W] concentration ratio
6. Include other elements: Be as dust in the divertor region and as bulk material in the first wall…

▪ Calibration free analysis procedure: evaluate the electron temperature T_e

To apply the CF procedure it is necessary to consider the atomic and ionic emission lines of each element under analysis, complete of their spectroscopic parameters and the partition function of the emitting species at the plasma temperature; this was done for W I, W II, Be I, Be II, H(D,T), the data being retrieved from the NIST website (https://www.nist.gov/pml/atomic-spectra-database). Below **(left)** an example of the data for W I and **(right)** the partition functions of W I and H at typical temperatures of the LIBS plasmas.

Observed Wavelength Air (nm)	A_{ki} (10^8 s^{-1})	Acc.	E_i (eV)		E_k (eV)	g_i - g_k
400.1380	5.6e-03	B	1.507891	-	4.605562	9 - 9
400.87506	1.63e-01	B	0.365913	-	3.457880	7 - 9
401.9227	6.7e-03	B	0.412313	-	3.496218	5 - 3
402.8786	2.48e-02	B	1.181329	-	4.257920	1 - 3
403.5356	2.90e-02	B	1.916797	-	4.988377	7 - 9
403.6855	1.49e-01	B	2.387469	-	5.457908	9 - 7
404.3894	1.42e-01	C	2.387137	-	5.452232	5 - 5
404.5594	2.88e-02	B	0.365913	-	3.429715	7 - 5
404.7938	5.0e-04	C	0.207090	-	3.269126	3 - 5
405.3932	4.9e-02	B	1.856810	-	4.914315	5 - 3
405.523	1.79e-03	C	1.655011	-	4.711538	7 - 9
406.0705	5.9e-02	B	2.458319	-	5.510728	7 - 7
406.4791	1.59e-01	B	2.387469	-	5.436811	9 - 7
406.9950	3.60e-02	B	0.598844	-	3.644317	7 - 5
407.0608	5.7e-03	B	0.207090	-	3.252077	3 - 5
407.1928	3.29e-02	B	1.916797	-	4.960794	7 - 5
407.4358	1.0e-01	B	0.365913	-	3.408091	7 - 7
408.8330	4.13e-03	C	0.412313	-	3.444095	5 - 3
410.2702	4.9e-02	B	0.771099	-	3.792260	9 - 7
410.2942	4.2e-04	C	0.598844	-	3.619823	7 - 5

NIST data

W.txt

File Modifica Visualizza

wv (Å)	E_k(eV)	g_k	E_i(eV)	g_i	A_{ki} ($10^8 s^{-1}$)
4001.380	4.6056	9	1.5079	9	0.0056
4008.751	3.4579	9	0.3659	7	0.1630
4019.227	3.4962	3	0.4123	5	0.0067
4028.786	4.2579	3	1.1813	1	0.0248
4035.356	4.9884	9	1.9168	7	0.0290
4036.855	5.4579	7	2.3875	9	0.1490
4043.894	5.4522	5	2.3871	5	0.1420
4045.594	3.4297	5	0.3659	7	0.0288
4047.938	3.2691	5	0.2071	3	0.0005
4053.932	4.9143	3	1.8568	5	0.0490
4055.230	4.7115	9	1.6550	7	0.0018
4060.705	5.5107	7	2.4583	7	0.0590
4064.791	5.4368	7	2.3875	9	0.1590
4069.950	3.6443	5	0.5988	7	0.0360
4070.608	3.2521	5	0.2071	3	0.0057
4071.928	4.9608	5	1.9168	7	0.0329
4074.358	3.4081	7	0.3659	7	0.1000
4088.330	3.4441	3	0.4123	5	0.0041
4102.702	3.7923	7	0.7711	9	0.0490
4102.942	3.6198	5	0.5988	7	0.0004

W_I_UT.txt — H_I_UT.txt

File Modifica Visualizza — File Modifica Visualizza

T (K)	U(T)	T (K)	U(T)
6962.715003702	21.92	6962.715003702	2
7542.941254010	24.46	7542.941254010	2
8123.167504319	29.44	8123.167504319	2
8703.393754627	33.91	8703.393754627	2
9283.620004936	38.9	9283.620004936	2
9863.846255244	44.43	9863.846255244	2.01
10444.07250555	50.51	10444.07250555	2.01
11024.29875586	57.17	11024.29875586	2.03
11604.52500617	64.4	11604.52500617	2.06
12184.75125647	72.21	12184.75125647	2.11
12764.97750678	80.61	12764.97750678	2.19
13345.20375709	89.58	13345.20375709	2.33
13925.43000740	99.12	13925.43000740	2.54
14505.65625771	109.22	14505.65625771	2.85
15085.88250802	119.86	15085.88250802	3.3
15666.10875832	131.03	15666.10875832	3.91
16246.33500863	142.7	16246.33500863	4.73
16826.56125894	154.85	16826.56125894	5.81
17406.78750925	167.47	17406.78750925	7.21
17987.01375956	180.53	17987.01375956	8.97
18567.24000987	194	18567.24000987	11.17
19147.46626018	207.86	19147.46626018	13.85
19727.69251048	222.09	19727.69251048	17.1

Calibration free analysis & Matlab procedure: compute n_e

To make the BP of each chemical species more reliable to obtain it is a common procedure to make the extended BP, where atoms and ions are displayed together in the same BP, once the coordinates of the ions are modified as follows:

$$E_{k-ions} = E_{k\to i} + E_{ionization}$$

$$\ln\left(\frac{I_{k\to i}}{g_k\, A_{k\to i}}\right)_{ions} = \ln\left(\frac{I_{k\to i}}{g_k\, A_{k\to i}}\right) - ln\left[2\left(\frac{mk}{2\pi\hbar^2}\right)^{\frac{3}{2}}\frac{T^{\frac{3}{2}}}{n_e}\right]$$

therefore, the electron density, n_e is the needed parameter to include ions in the BP of the species.

Through the knowledge of n_e it is also possible to have the relative concentration of atoms and ions of the same chemical species through the **Saha-Boltzmann equation**:

$$\frac{C_{ions}}{C_{atoms}} = \frac{2U_{ions}(T_e)}{n_e U_{atoms}(T_e)}\left(\frac{mk_BT}{2\pi\hbar^2}\right) e^{-\frac{E_{ion}}{k_BT}}$$

(E_{ion} = ionization energy, m = electron mass)

necessary to correctly quantify the concentrations of the chemical species

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Spectrochimica Acta Part B 62 (2007) 378–385

SPECTROCHIMICA ACTA PART B

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Multi-element Saha–Boltzmann and Boltzmann plots in laser-induced plasmas

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$$\ln\left(\frac{\varepsilon^z\lambda}{Ag_j}\right)^* = \ln\left(\frac{\varepsilon^z\lambda}{Ag_j}\right) - B^z(T,N_e) \qquad (2)$$

where

$$B^z(T,N_e) = z\ln\left[2\left(\frac{mk}{2\pi\hbar^2}\right)^{3/2}\frac{T^{3/2}}{N_e}\right] \qquad (3)$$

and

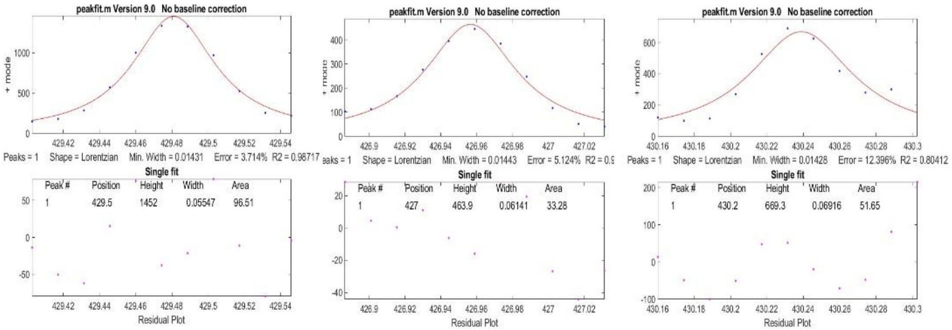
$$E_j^{z^*} = E_j^z + \sum_{k=0}^{z-1}(E_\infty^k - \Delta E_\infty^k) \qquad (4)$$

***Spectrochim. Acta B 62 (2007) 378–385**

The electron density was computed according to the following formula:

$$n_e = \frac{\Delta\lambda_{FWHM}}{w^0_{FWHM}}(10^{23}m^{-3})$$

where $\Delta\lambda_{FWHM}$ is the experimental line broadening (reduced by the instrumental broadening which was estimated through the emission lines of the low pressure Hg lamp)



and w^0_{FWHM} is the Stark parameter of the three W I lines at 426.9, 429.4, 430.2 nm from the Nishijima and Doerner publication (J. Phys. D: Appl. Phys. 48 (2015) 325201 (6pp)):

Table 1. Summary of W I Stark FWHM.

λ (nm)	T_e (eV)	n_e (10^{23} m^{-3})	w_{FWHM} (nm)	w^0_{FWHM} at 10^{23} m^{-3} (nm)
426.9	0.73–0.99	0.12–0.41	0.00940–0.0248	0.0634 ± 0.0022
429.4	0.73–1.0	0.12–0.41	0.00727–0.0226	0.0513 ± 0.0022
430.2	0.83–0.99	0.19–0.41	0.00537–0.0157	0.0330 ± 0.0026

IOP Publishing — Journal of Physics D: Applied Physics

J. Phys. D: Appl. Phys. **48** (2015) 325201 (6pp) — doi:10.1088/0022-3727/48/32/325201

Stark width measurements and Boltzmann plots of W I in nanosecond laser-induced plasmas

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CrossMark

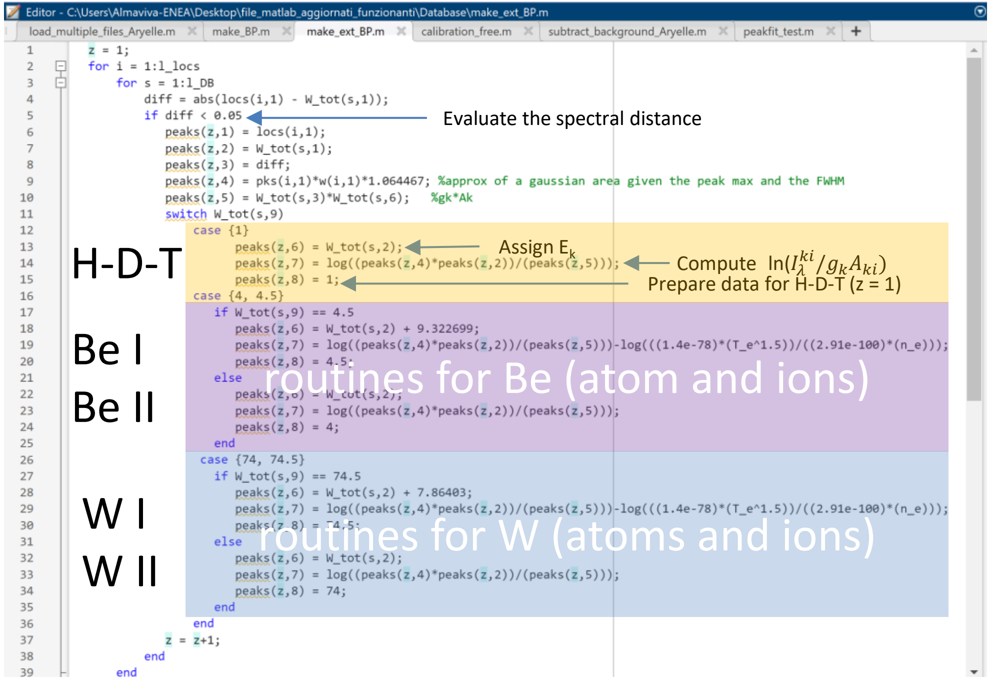
Abstract

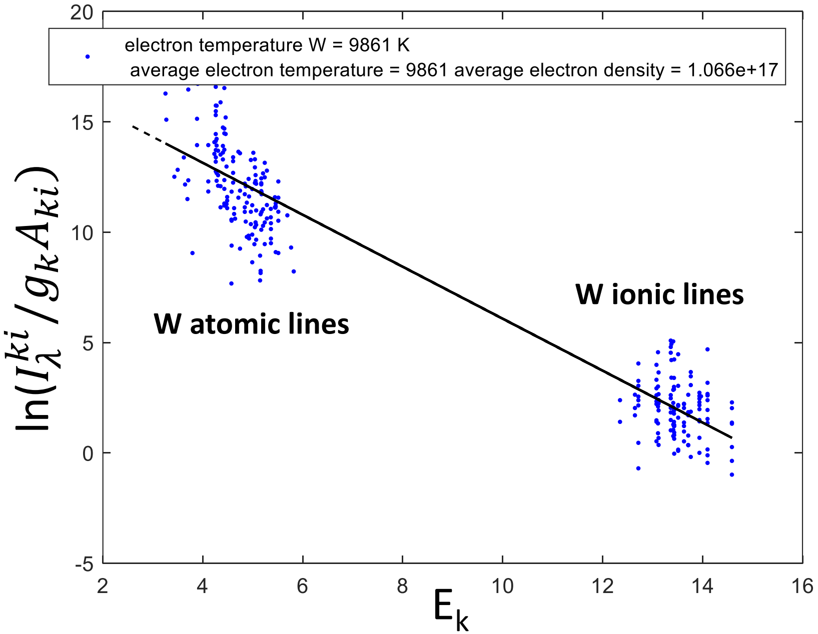
We report the first measurements of Stark broadening widths of W I lines (426.9 nm, 429.4 nm, and 430.2 nm) as a function of electron density, n_e. The electron density is obtained from Stark broadening of a C II line at 426.7 nm in nanosecond laser-induced tungsten carbide plasmas. A linear relation between the W I Stark widths and n_e is confirmed. The electron temperature, T_e, is evaluated from Boltzmann plots of W I transitions with an oscillator strength $f_{ik} < 1.0 \times 10^{-2}$, since systematically lower population densities are observed for W I transitions with $f_{ik} \geqslant 1.0 \times 10^{-2}$, indicating that absorption occurs. This is consistent with an overestimated n_e derived from Stark broadening of the 429.4 nm line ($f_{ik} = 2.45 \times 10^{-2}$) at a high ambient gas pressure.

Keywords: W I Stark width, W I Boltzmann plot, laser-induced plasma

(Some figures may appear in colour only in the online journal)

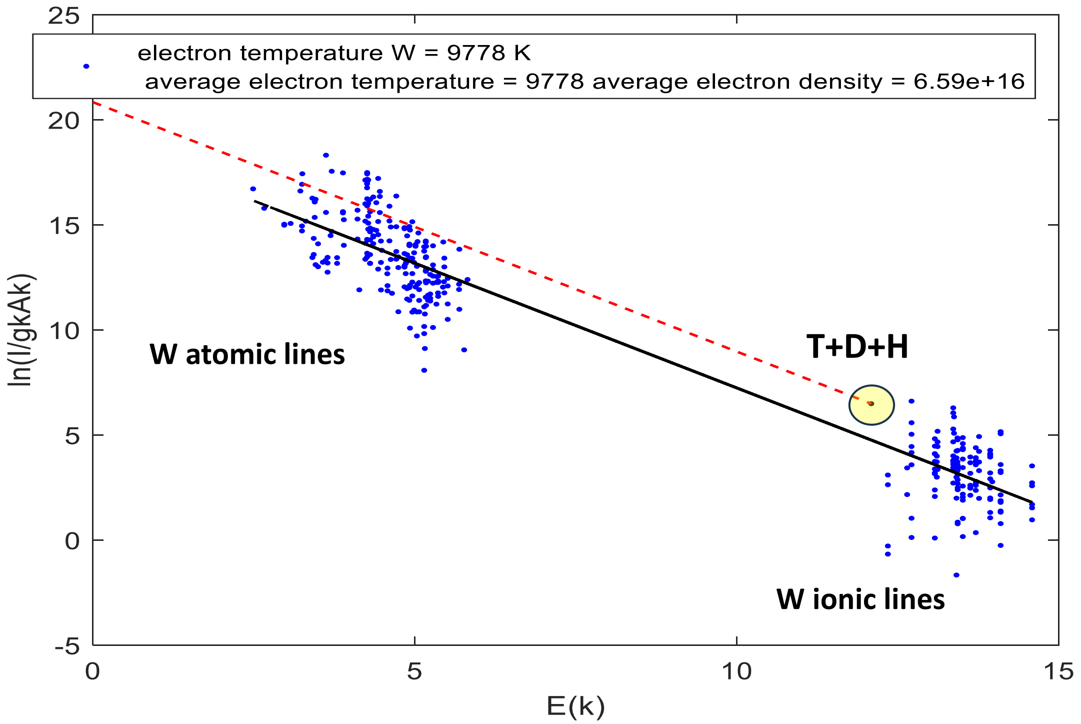
Searching in the database accessible by the procedure, the experimental spectrum is compared with the theoretical one and if the spectral distance between experimental and theoretical lines is below a certain threshold (typically 50 pm) the lines are identifed. Using these lines the extended BP for W (and, in the next steps, for Be) can be setup.





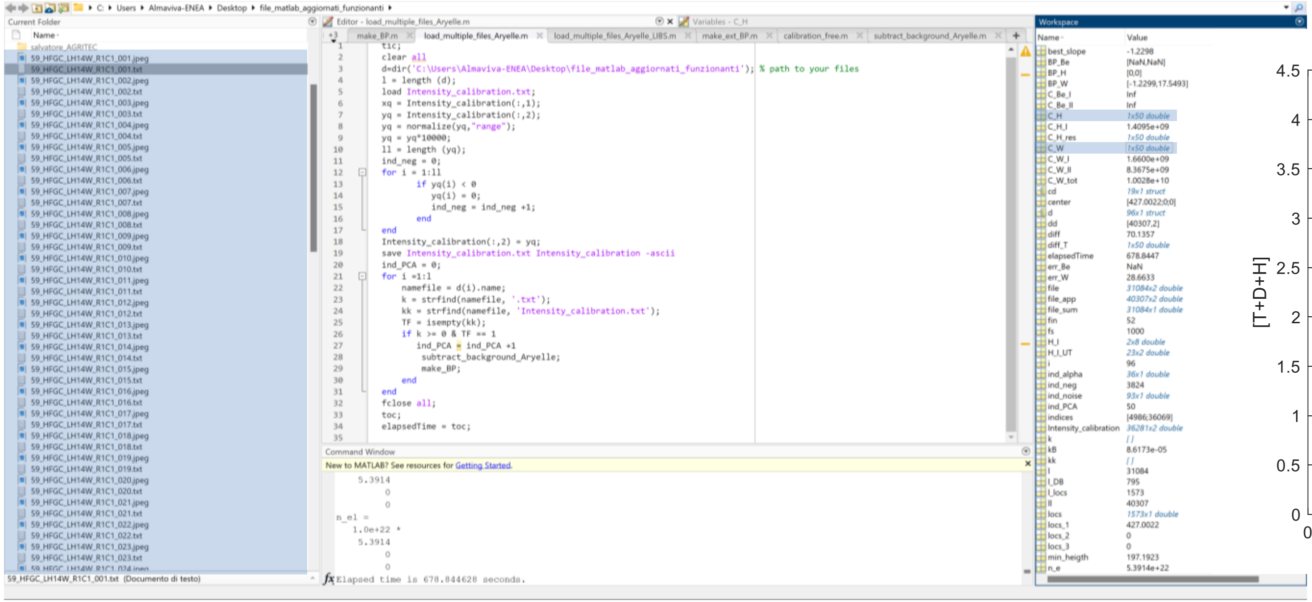
Calibration free analysis & Matlab procedure: evaluate [T+D+H]/[W]

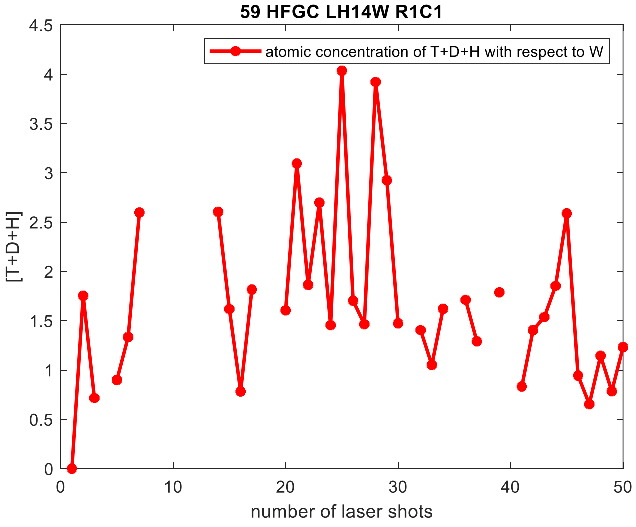
Once the Extended BP for W is setup, the sum of the spectral signal of the Balmer alpha emission T_α, D_α, H_α is included in the BP because the Aryelle spectrometer cannot spectrally resolve the three emission lines but consider the T+D+H signal as a single spectral emission. By applying CF the relative concentration [T+D+H]/[W] is obtained and rescaled in percentage.



With these procedures the following information on the PFCs of the divertor can be obtained:

1) **Atomic concentration (%) of T+D+H with respect to W (bulk material)**
2) **(ongoing) Atomic concentration (%) of T+D+H with respect to Be (redeposited material)**
3) **In-depth atomic concentration (%) of T+D+H with respect to W (bulk material) and Be (ongoing)**
4) **Electron temperature and electron density of the LIBS plasma**
5) **Estimated processing time per spectrum ≈ 15 sec per spectrum**





Conclusions

- Depht profiling of points:
  - 357 - Oct1_VW - MIDDLE – (**<u>Inconel reference spectrum</u>**)
  - 492 - 2X08 - R7 C3-C7 (**<u>Be_reference spectrum</u>**)
  - 20 - 2X08 - R7 C3-C7 (**<u>W reference spectrum</u>**)
- Depth profiling of the plasma facing components (PFCs) of the divertor profile for Be, W, T-D-H
  1. Be superficial contamination of the divertor section **<u>mainly on tile 0 and 1</u>**
  2. The thickness of the Be layer is estimated to be 10 – 50 μm
  3. T-D-H contamination of the divertor section **<u>mainly on tile 0 and 1</u>**
  4. The max contamination of material eroded from the first wall is in the first shots
- CF analysis for the quantification of the residual (T-D-H) content in the PFCs:
  - Pros:
    1. the procedure to estimate the relative concentration of T-D-H for W and Be based PFCs over a large (huge) number of spectra is developed and requires a few tenths of seconds for each spectrum
  - Cons:
    1. To be reliable the CF analysis need a precise procedure to rescale the intensities of the experimental LIBS spectra (ongoing)

Partnership

UK Atomic Energy Authority

JÜLICH Forschungszentrum

Thank you for your attention !

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