Reporting Meeting PWIE-SPE 2024

Jari Likonen

On behalf of the SP E team and task holders

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SP E focus points in 2024

I: LIBS on a Remote-Handling arm in JET→ SP E.1

II: Comparison of hydrogenic retention quantification by different techniques and fuel removal assessment (ITER housekeeping approach) → SP E.2

III: Post-mortem analysis of PFC and other objects in JET→ SP E.3

SP E resources 2024

Deliverable Owner	Beneficiary	PM	
P. Veis	CU	4	SP E.1
S. Almaviva	ENEA	9	SP E.1
T. Dittmar	FZJ	13	SP E.1-3
E. Grigore/C. Porosnicu	IAP	8	SP E.2-3
P. Gasior	IPPLM	4	SP E.1
E. Fortuna-Zaleśna	IPPLM	2	SP E.3
J. Butikova	ISSP-UL	4	SP E.1
E. Pajuste	ISSP-UL	12	SP E.2-3
N. Catarino	IST	7	SP E.2-3
D. Mergia	NCSRD	2	SP E.2
P. Paris	UT	6	SP E.1
D. Primetzhofer	VR	6	SP E.2-3
J. Likonen	VTT	12	SP E.1-3
Total		89	

Device	Beneficiary	Days
Accelerator	IST	7
Accelerator	VR	3
Accelerator	VTT	2

SP E Tasks 2024

Activity	Deliverable ID(s)	Task Title
SP E.1	D001-D007	Participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS (CU, FZJ, IPP_LM, ISPP_UL, UT, VTT)
SP E.2	D001	Characterization of JET divertor tiles with LID-QMS and TDS (FZJ)
SP E.2	D002	Analysis of samples from JET divertor tiles with TDS and GDOES (IAP)
SP E.2	D003	Analysis of samples from JET divertor tiles with TDS, FC and dissolution method. Completion of simulation of C39 JET baking experiment(ISSP-UL)
SP E.2	D004, D005, D007	Characterization of JET divertor tiles using ion beam analysis (RBS, NRA,HIERDA) (IST, NCSRD, VR)
SP E.2	D006	Characterization of samples from JET divertor tiles using SIMS and TDS (jointly with UKAEA) (VTT)
SP E.3	D001	Characterization of JET plasma facing components with LIBS, LID-QMS, TDS and metallography (FZJ)
SP E.3	D002	Analysis of JET plasma facing components with TDS and GDOES (IAP)
SP E.3	D003	Electron microscopy (SEM, TEM, FIB) and nanoindentation of JET plasma facing components (IPPLM)
SP E.3	D004	Analysis of JET plasma facing components with TDS, FC and dissolution method (ISSP-UL)
SP E.3	D005, D006	Characterization of JET plasma facing and diagnostics components using ion beam analysis RBS, NRA, HIERDA, µbeam NRA (IST, VR)
SP E.3	D007	Characterization of JET plasma facing components using SIMS and TDS (jointly with UKAEA) (VTT)

SP E Milestones 2024

Relevant Work Package Milestones for SP E extracted from WP PWIE PMP 2024

WM98	SP E	Post-mortem erosion, deposition and metallographic analysis of JET tiles and diagnostics components exposed to CX neutrals completed. (ITER)	31.12.2024
WM99	SP E	Comparison of quantitative hydrogenic retention analysis by various post-mortem analysis techniques (FC, LID-QMS, NRA, SIMS, TDS) carried out. (ITER + DEMO)	31.12.2024
WM100	SP E	LIBS experiments at JET using RH and in VTT laboratory executed, and data analysis of CF LIBS started. (ITER)	31.12.2024

SPE program 2024

- LIBS experiment at VTT using the JET LIBS setup (February & March 2024)
- Data analysis of VTT LIBS experiment (on-going)
- LIBS experiment at JET (October)
- Data analysis of JET LIBS experiment
- Completion of tile analysis (e.g. C39 baking studies)
- Analysis of limiter tiles from top and bottom of IWGL and WPL limiters
- Completion of metallography and microstructural studies of Langmuir probes and W lamellae
- Analysis of louvre clip and mirror cassettes
- Removal of in-vessel components (UKAEA)

SPE.1

SP E.1 - LIBS at JET (35PM)

LIBS at JET

General Information

- The aim is to perform in-vessel analysis of PFCs using LIBS on a remote handling arm at JET

Task and questions to be addressed

- PWIE-SP E.1.T-T002-D001-D007

Approach

Experiments at VTT

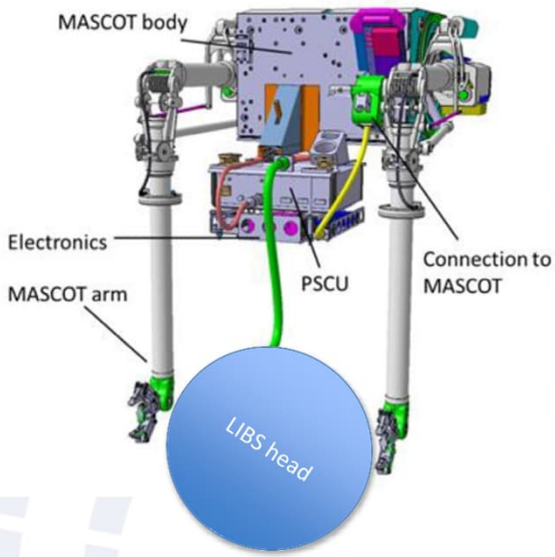
- Commissioning of LIBS system (February 18th – 24th)
- Measurement campaign March 11th – 22nd)

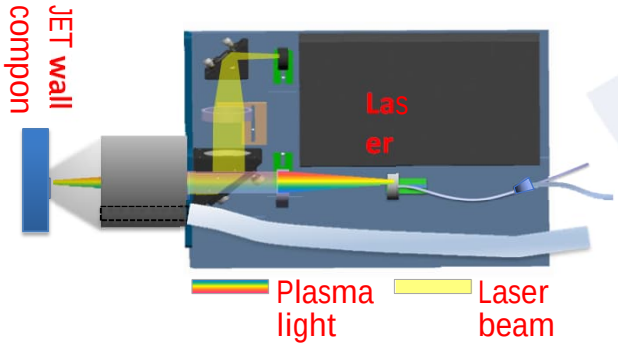
LIBS at JET

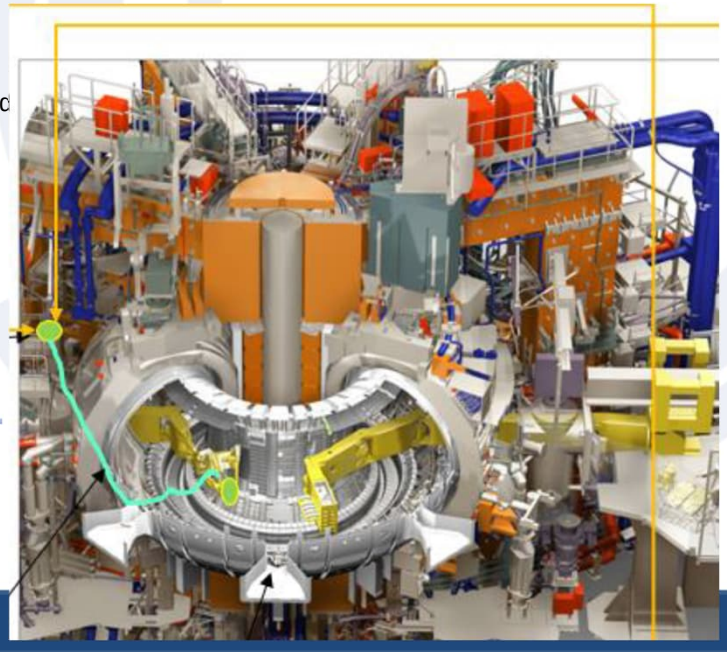
- Commissioning of LIBS system (April 29th – May 10th, June 17th – 21st, August 5th – 23rd September 23rd – October 2nd)
- Experiment dates: October 2nd – 18th

Results

- *LIBS experiment was completed successfully*
- 840 locations were analysed







VTT Measurements: 14IWG1A (2011-2016)

- W lines start to appear around 150 laser pulse
- Be I 457.3 nm line disappears around 300 laser pulse
- Mo I 550.67 nm line intensity start increasing around 700 and disappear around 900 laser shots

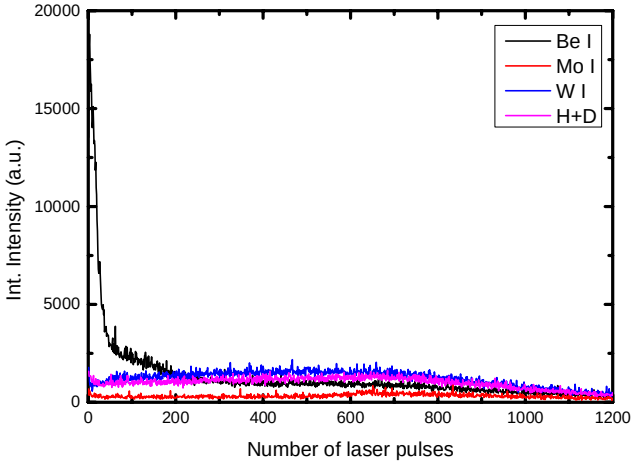
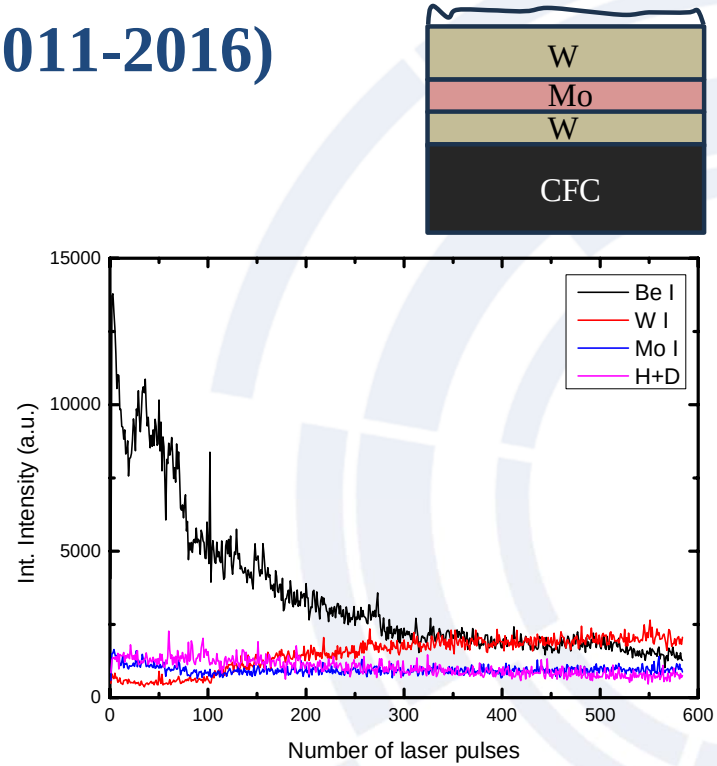


Fig. 1. Depth profile for sample 14IWG1A_3a



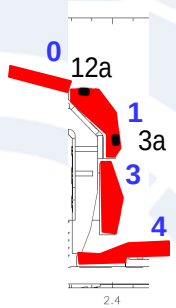


Fig. 2. Depth profile for sample 14IWG1A_12a

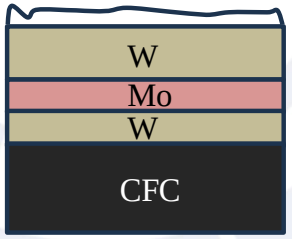
Deliverable: **PWIE-SP E.1.T-T003-D001**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

Analysis of VTT Measurements

Plasma parameters for **14IWG1A_12a**

Gate delay (ns)	N_e (10^17 cm^-3)	T_e (eV)	Mcwhirter cond.	No of pulses to go through layer
500	1.65	0.74	checked	300±20
1000	0.89	0.67	checked	300±20
1500			NC	300±20

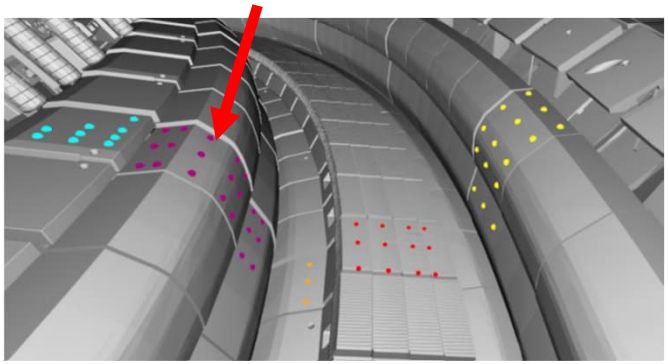
Sample	No of laser pulse	Gate delay (ns)	Gate width (ns)
4D15_686	2-3	1000, 500	1000, 500
4D15_703	5-6	1000, 500	1000, 500
14IWG1A_3a	200	1000, 500	1000, 500
14IWG1A_12a	300	1000, 500	1000, 500

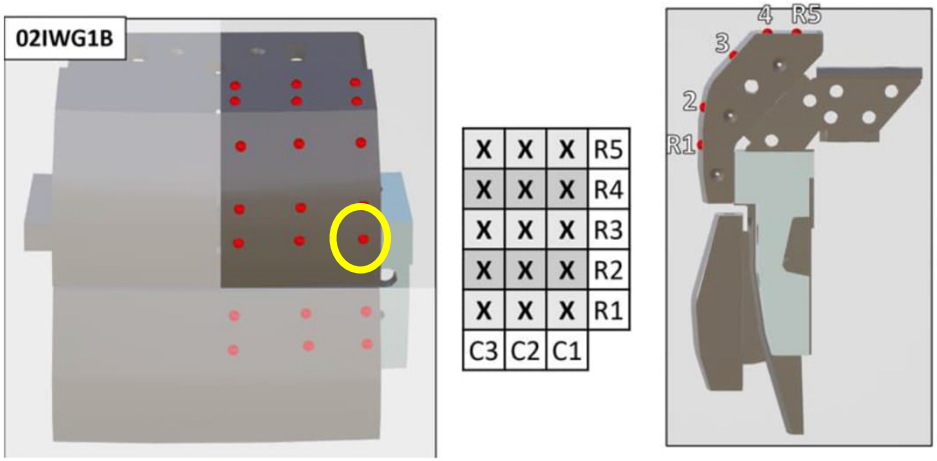


JET LIBS Campaign 2024: 2IWG1B_R3C1

Pulse-353 in the campaign

2IW G1B





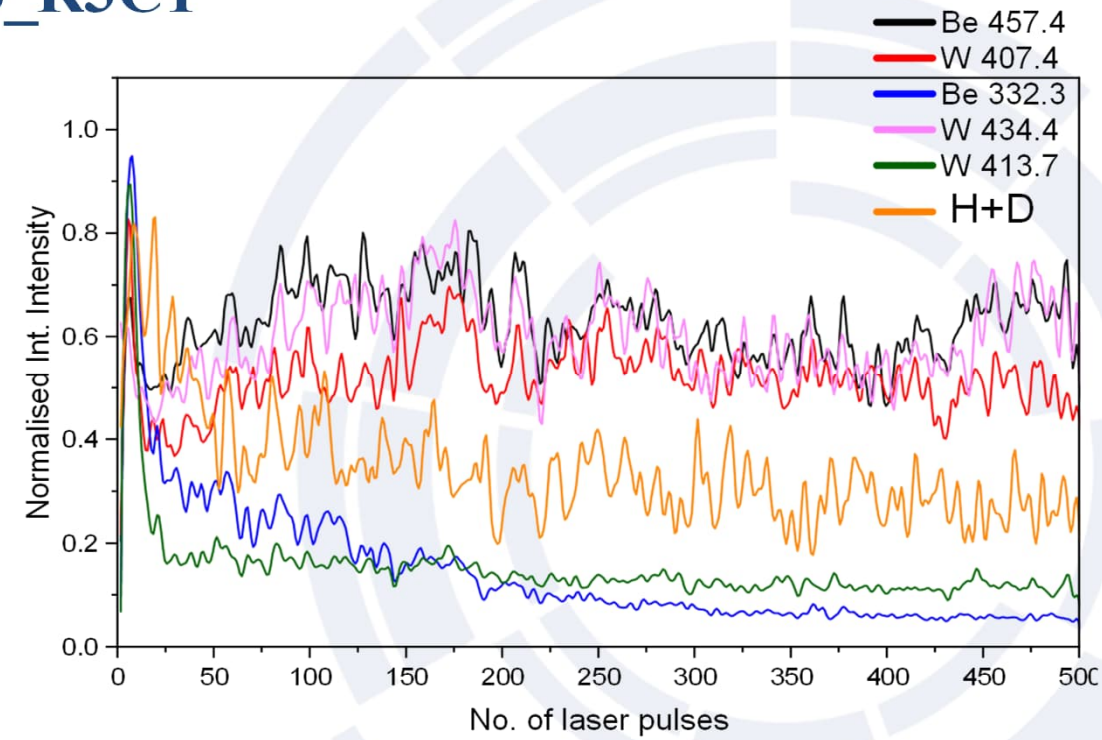
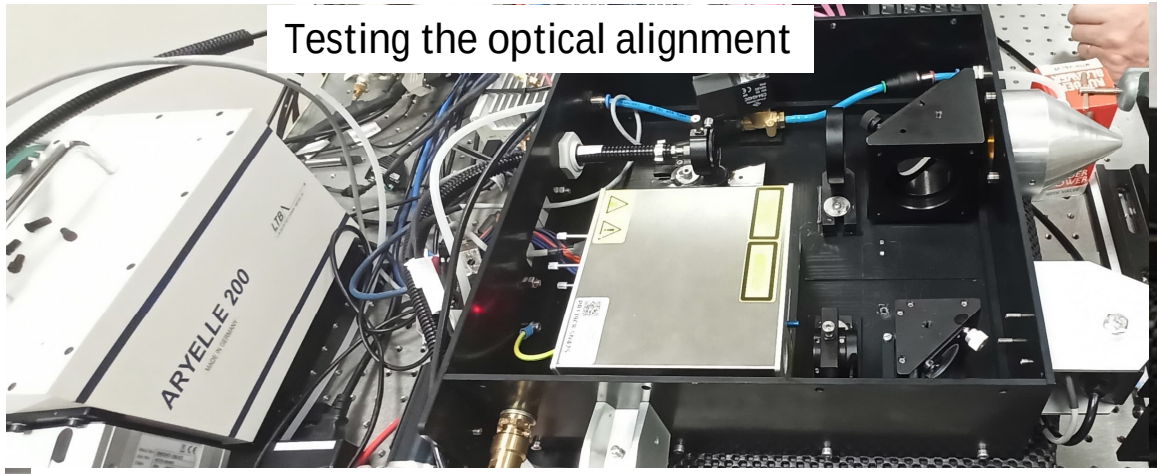


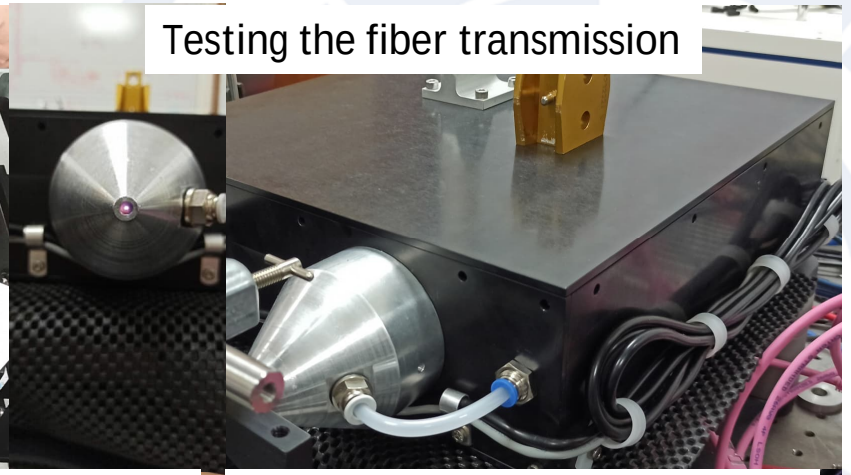
Fig. 2. Depth profile for 0IWG1B_R3C1

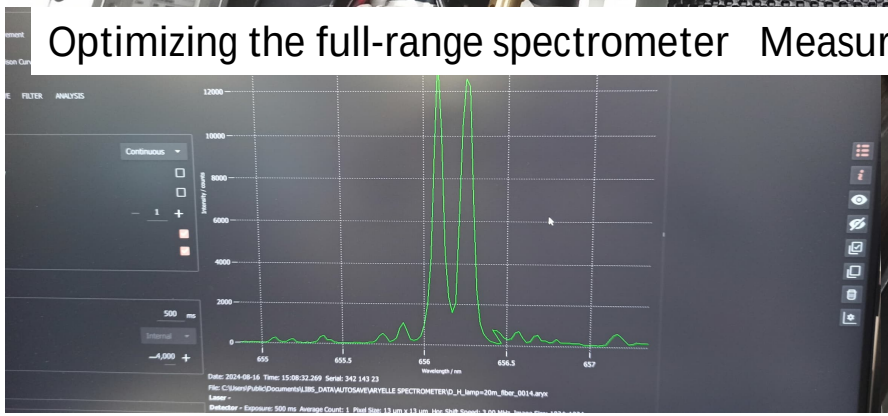
The Be is observed in the co-deposited layer upto the laser shot number ~25

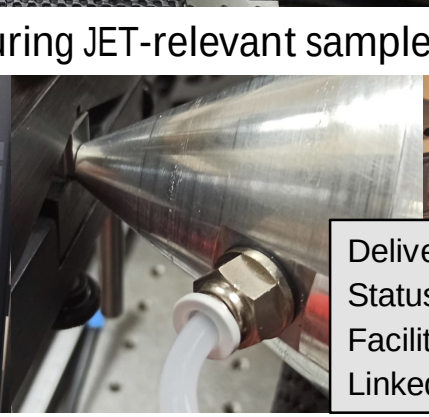
PWIE-SP E.E1.T-T003-D002 (ENEA participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS)

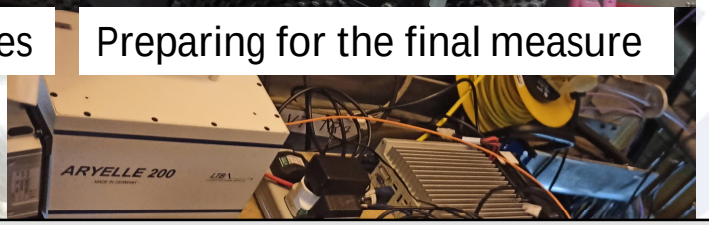
- ENEA's participation in the PWIE-SP E.E1.T-T003-D002 task concerned the development of the LIBS system for JET at VTT in the experimental campaigns of February and March and, subsequently, at UKAEA in those of May, June and August. During these campaigns the compact LIBS device to be mounted on JET's RH was optimized, in particular the optical alignment and the 20 m optical fibre transmission was tested, the acquisition parameters of the Aryelle full range spectrometer have been optimised and tests were carried out on several JET-relevant samples before using the system in the final configuration.





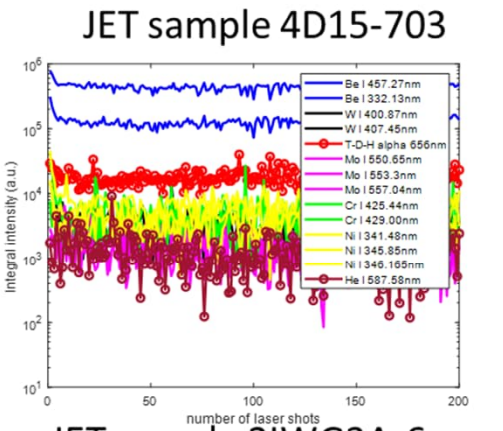


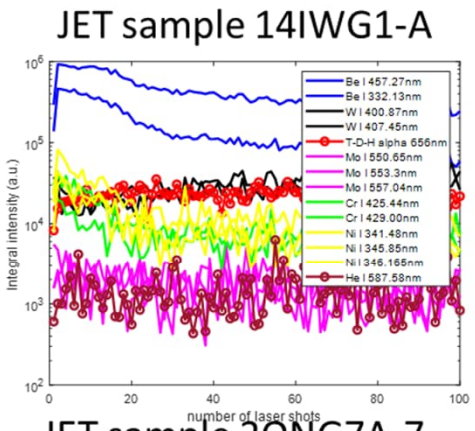


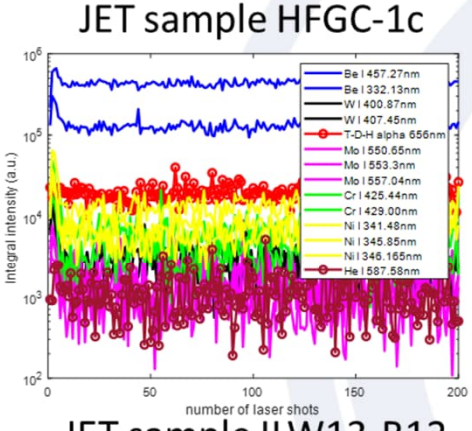


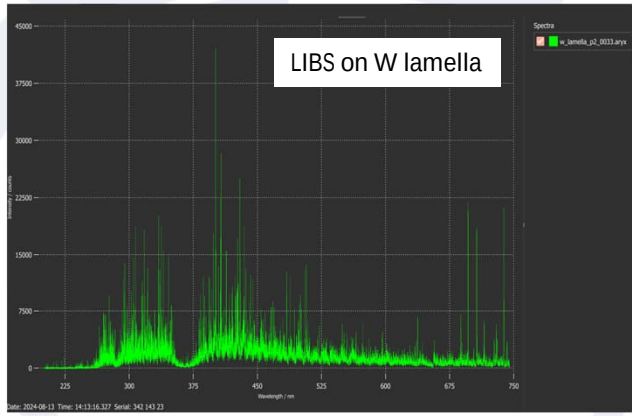
Deliverable: **PWIE-SP E.1.T-T003-D002**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

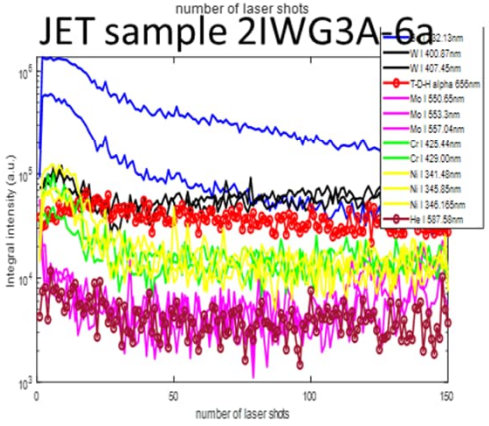
- Regarding the analysis of the LIBS spectral data obtained during the experimental campaigns, ENEA has developed some computer tools based on MATLAB™ platform that allow to quickly visualize the intensity trend of significant spectral lines of each chemical element of interest (D-H-T, W, Be. Cr, Ni. Mo etc) in a sequence of hundreds (or thousands) of spectra. ENEA is also developing further tools to estimate the concentration of these elements based on the CF LIBS procedure.

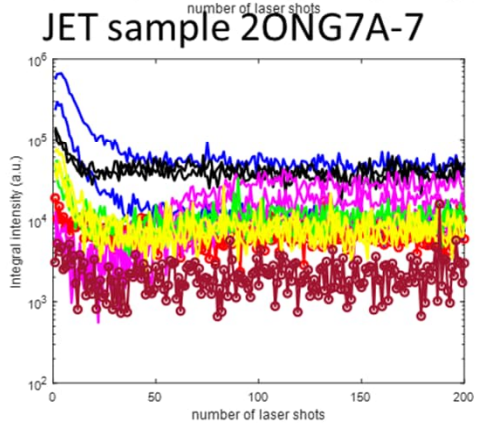


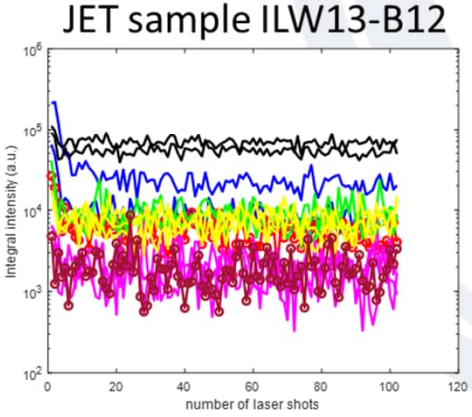


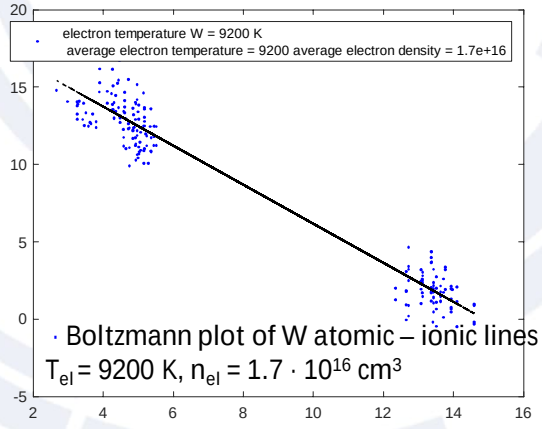








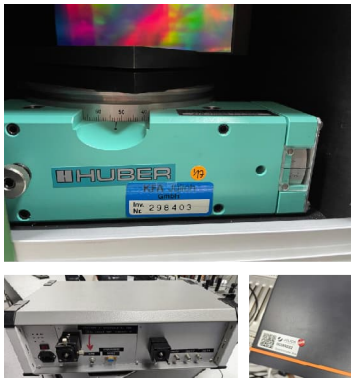


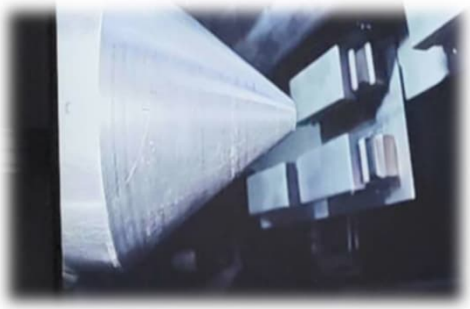


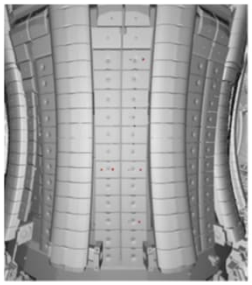
JET-LIBS project

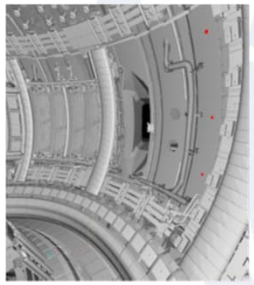
JET-LIBS tips :

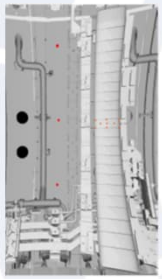
a) High resolution and photon flux Littrow spectrometer, high sensitivity PMT detector for fuel retention. Overview wide range Avantes spectrometer for deposition analysis
b) Total more than 800 laser analysed positions, which gives global overview of fuel retention and material erosion and deposition.
c) Dedicated analysed area for comparison between LID-QMS and LIBS
d) Wavelength and absolute light flux calibration has been done, and H/D peaks can be separated clearly

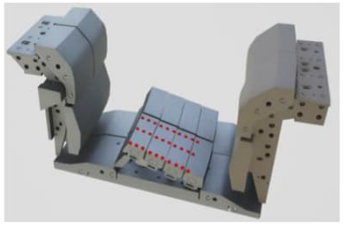


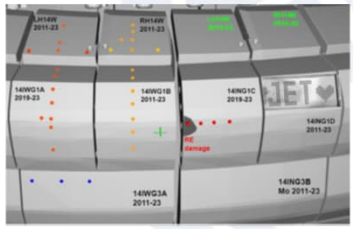


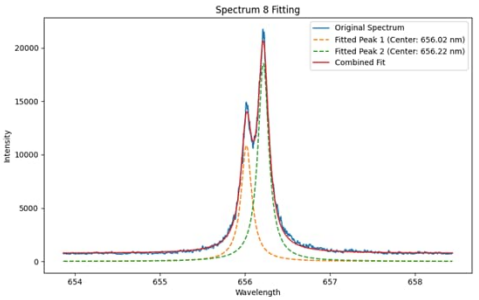












Deliverable: **PWIE-SP E.1.T-T003-D003**
Status: ***completed/ongoing***
Facilities: **JET**
Linked WP or TSVV: **if applicable**

LID-QMS of JET samples in FZJ

Status: All planned measurements for EUROfusion task done. Evaluation ongoing.

Possible problems for upcoming data analysis:
1. No significant T peak(only D and H separated peaks can be observed), possible reasons are, T and D are so closed to each, and the amount of retained T is much lower than D.
2. A good strategy for data analyzing is significant (what do we want to know and how can we extract them from the huge amount of data)
3. Which additional post-mortem analysis for improving the performance will be necessary?

Some advice:
Make sure every screw is tightened, better even glued !!!

Deliverable: **PWIE-SP E.1.T-T003-D003**
Status: ***completed/ongoing***
Facilities: **JET**
Linked WP or TSVV: **if applicable**

IPPLM contribution - LIBS at JET

General Information

- Participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS

Task and questions to be addressed

- General: Adaptation of remote handling for LIBS operation at JET to prove it can be applied in the next-step devices.
- IPPLM specific: Implementation of machine learning and digital signal processing algorithms to facilitate data analysis

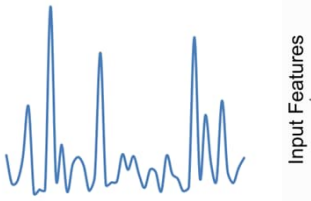
Approach

- Application of digital data filtering for preliminary data engineering
- Application of DNN-based autoenconer for dimensionality reduction and denoising (DNN=Deep Neural Networks)
- Application of DNN and CNN for data analysis (CNN=Convolutional Neural Networks)

Results (for data obtained at the VTT campaign)

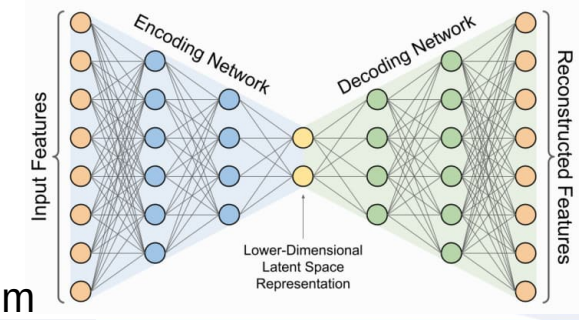
- Experimental data obtained during the Be campaign at VTT are noisy and samples are relatively often rejected by anomaly detection algorithms; however, they significantly benefit from preprocessing.
- Filtering may be based on previously developed SimulatedLIBS and is efficient in reduction of data volume
- Autoencoders are very useful in dimensionality reduction with keeping quantitative information on the plasma constituents even though the line intensities are not perfectly restored
- Autoencoders effectively remove noise and random interference
- Further works are ongoing on CNN based autoencoders

Deliverable: **PWIE-SP E.E1.T-T003-D004**
Status: ***ongoing***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**



Input spectrum

Autoencoder



Output spectrum

SPE.1: LIBS at JET (ISPP_UL)

- Participation in VTT campaign
  - Optimal Montfort Laser M-Nano laser parameters have been determined:
    - Pulse energy: 10 mJ @ 110 mA
    - Pulse repetition rate: 2 Hz
    - Delay time: 500 ns to 1500 ns, optimal: 1000 ns
  - Spectral lines for the indentification of the elements of interest have been selected; strongly self-absorbed lines have been excluded
  - Contents of co-deposited layers and ablation rate have been identified
  - The criterion for when to stop the ablation has been determined: the layer has been ablated when 50 % of maximum intensity for the rise of the signal of next element has been reached

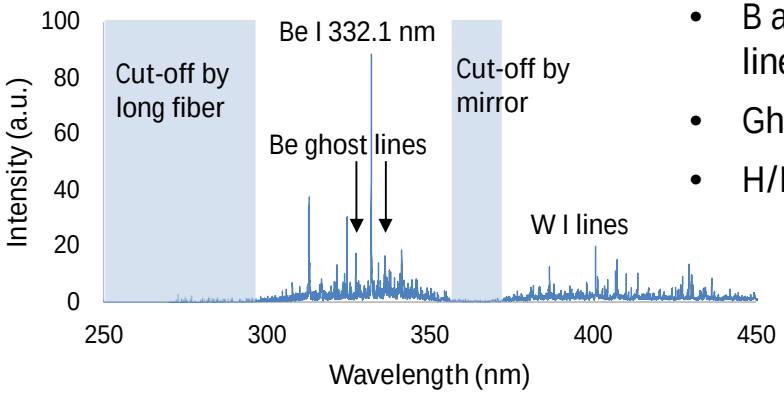
- Participation in JET campaign (only preparatory phase due to delays at UKAEA)

Deliverable: **PWIE-SP E.1.T-T003-D005**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

SP E.1 Preparation for JET remote handling LIBS campaign in VTT (UT)

LIBS in atm. pressure Ar, 20 m fiber for signal collection and Echelle type Aryelle spectrometer for wide spectral range

LIBS spectrum (2ONG7A-7)

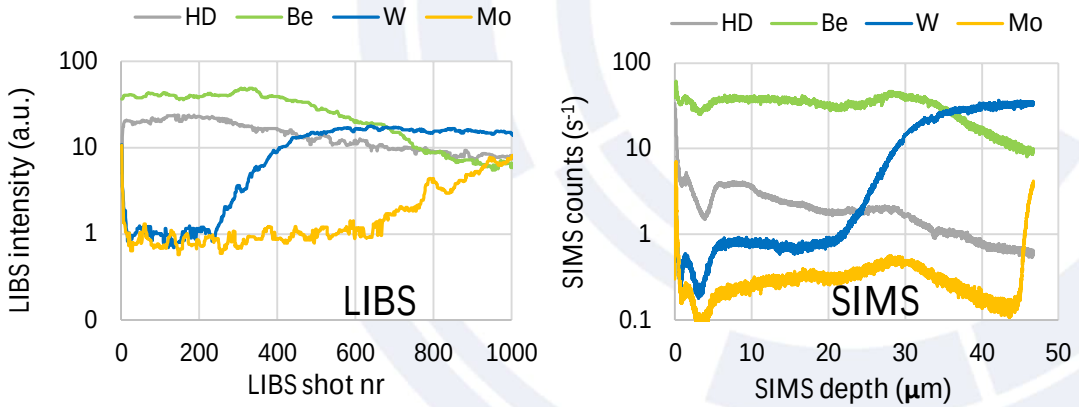


- Be, W, Mo, Fe, Ni, Cu, Cr, Ar, H, D were present in the spectra
- Samples were from different positions on limiters (2XR11, 4D15) and divertor (HFGC, 14IWG1A, 2IWG3A, b12_167, 2ONG7A, 2ONG8B).
- Deposit layers distinguishable in LIBS depth profiles and confirmed by SIMS

Limitations for remote handling application

- B and C are not detectable because strong lines near 250 nm absorbed in long fibre and lines between 300-500 nm are too weak due to low LIBS plume temperature
- Ghost lines present due to Echelle type spectrometer
- H/D/T line intensities were near the detection limit and overlapping

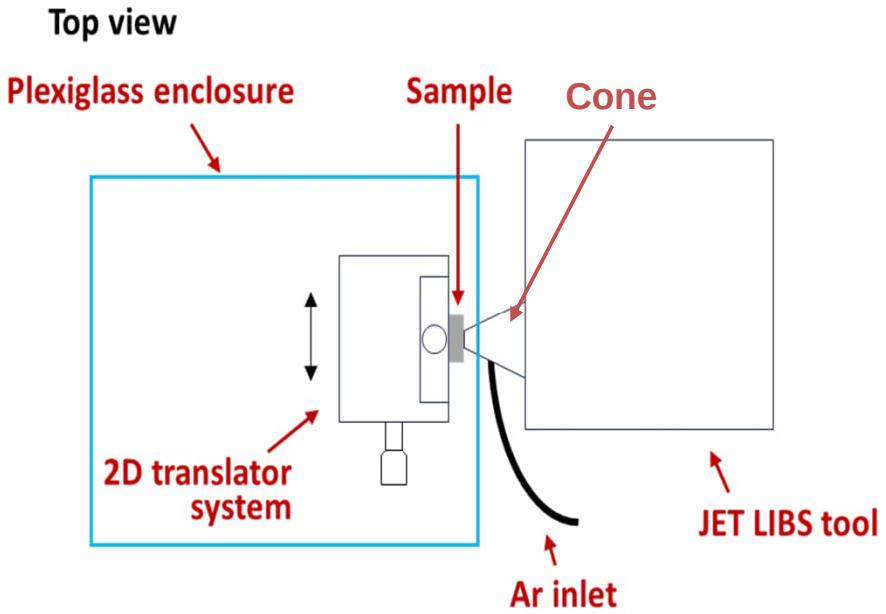
LIBS and SIMS depth profiles of 14IWG1A 11a

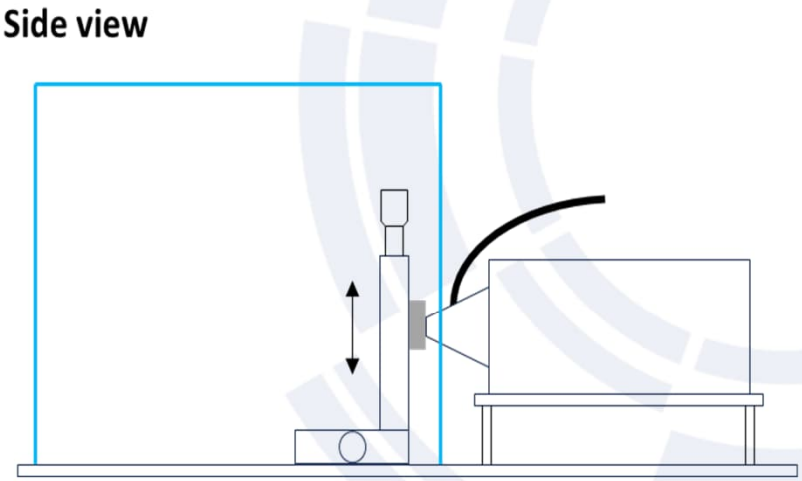


Deliverable: **PWIE-SP E.1.T-T003-D006**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

LIBS experiment at VTT

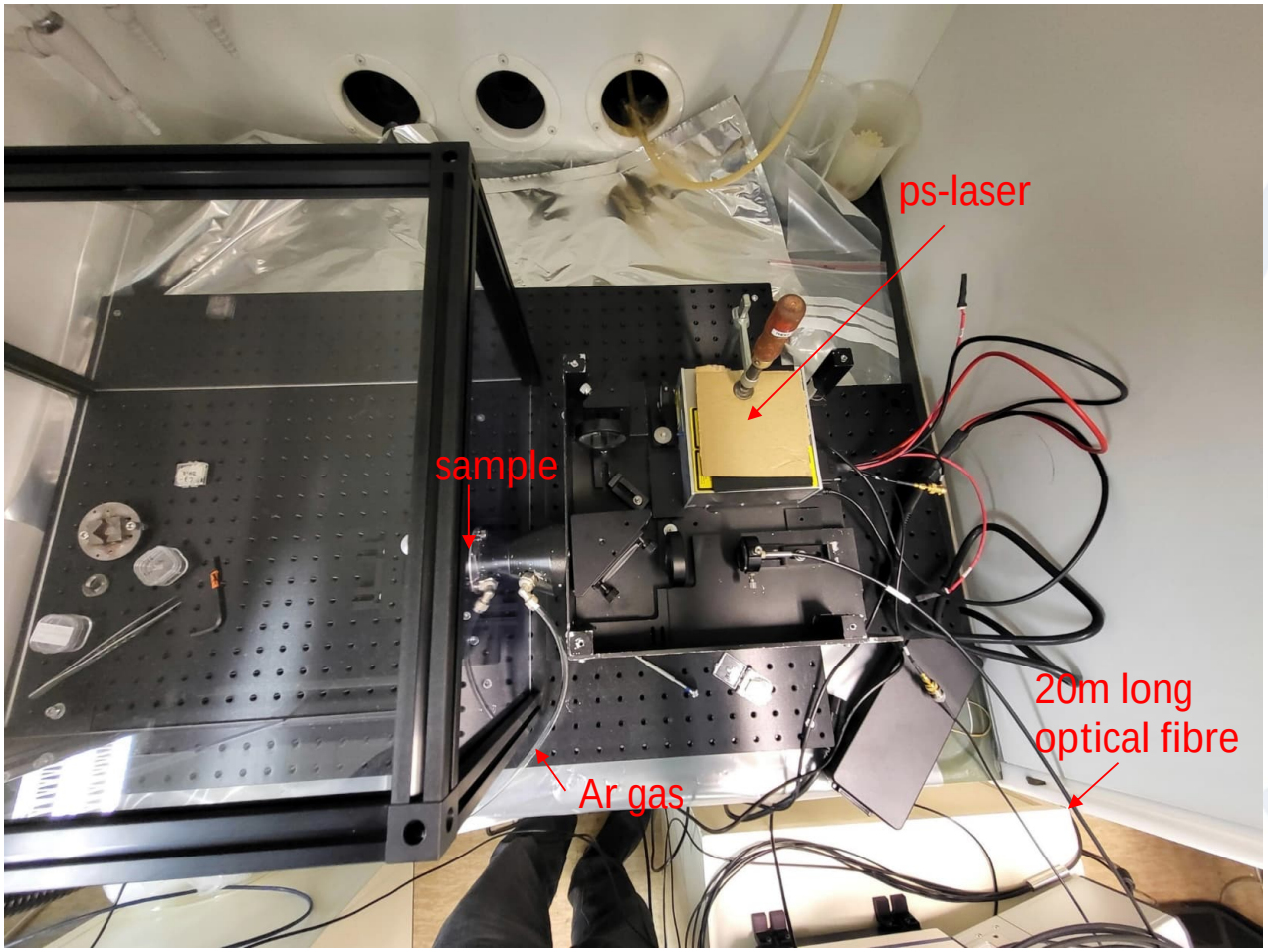
- LIBS system at VTT recently upgraded to allow investigations in conditions similar to JET
  - ✓ Samples placed in a plexiglass enclosure inside a fume cupboard for Be safety
  - ✓ Cone of the JET LIBS tool brought in contact with the sample surface through a hole in the enclosure
  - ✓ Sample mounted on a 2D translator system allowing accurate positioning of the laser spot in horizontal and vertical directions
  - ✓ Several JET samples analysed (2XR11_623, 2XR11_641, 2XR11_668, 4D15_686, 4D15_703, HFGC_1c, 14IWG1A_12a, 14IWG1A_8a, 14IWG1A_3a, 2IWG3A_6a, 2ONG7A_7, 2ONG8B_11b, W lamella B12_167)

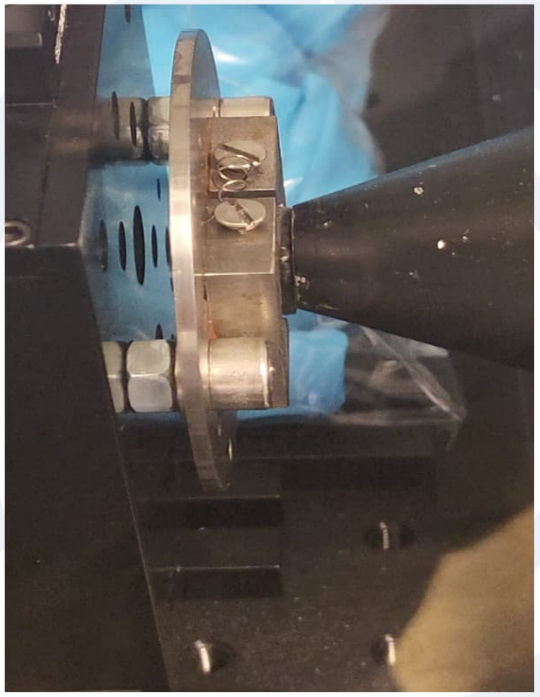




Deliverable: **PWIE-SP E.1.T-T003-D007**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

LIBS system at VTT, new setup



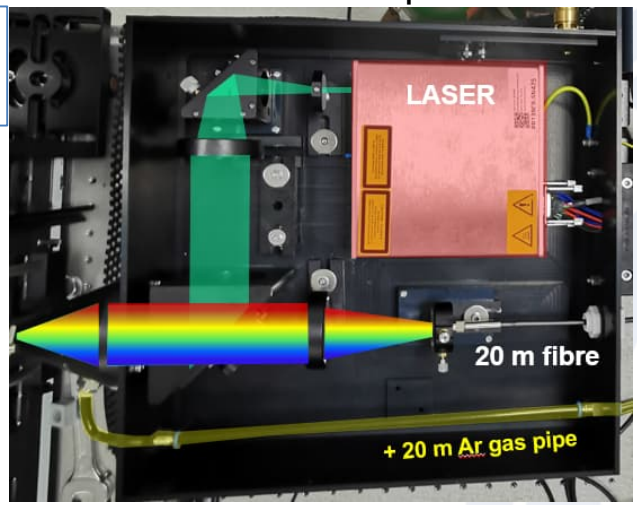


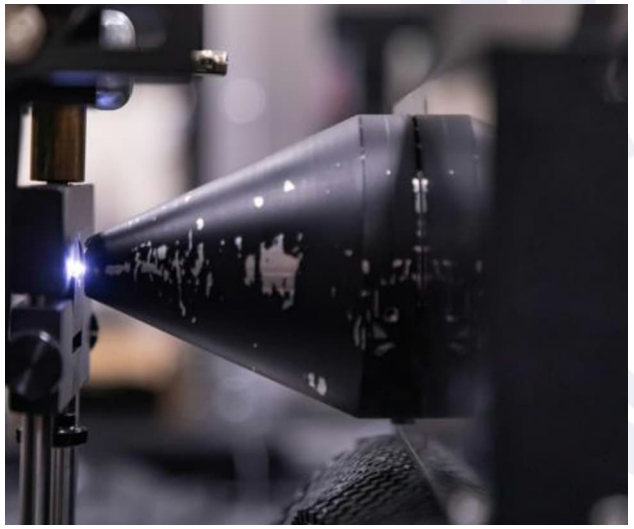
SPE.E1 Participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS (UKAEA)

1. LIBS tool lab commissioning @ JET (made three times)

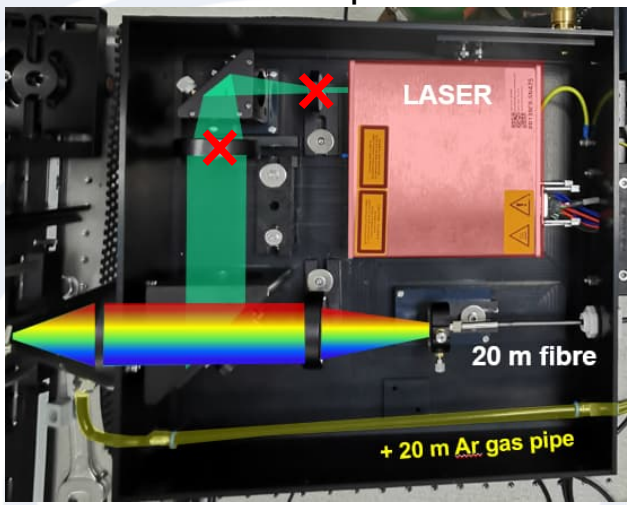
- ✓ Installation of optics and laser into new LIBS tool
- ✓ Optics alignment for laser path
- ✓ Optics alignment for light collection
- ✓ Connections between instruments and industrial PC & separate laptop
- ✓ Instruments calibrations using dedicated calibration lamps (H/D & halogen lamps):
  - ➢ Results were similar or even better than the ones obtained in previous lab conditions (@ VTT)
- ✓ Triggering master – LASER – good triggering of subsequent devices using delay generator:
  - ➢ Aryelle Spectrometer & Camera;
  - ➢ Littrow Spectrometer & Camera;
  - ➢ PMTs
- ✓ Data collection testing:
  - ➢ Aryelle & camera – via Sphi nXt software;
  - ➢ Littrow & camera;
  - ➢ PMT – via pico-oscilloscope
  - ➢ LASER data
- ✓ Ar gas flow tests;
- ✓ Industrial PC full connections test

Initial beam set-up & cone





Final beam set-up & cone

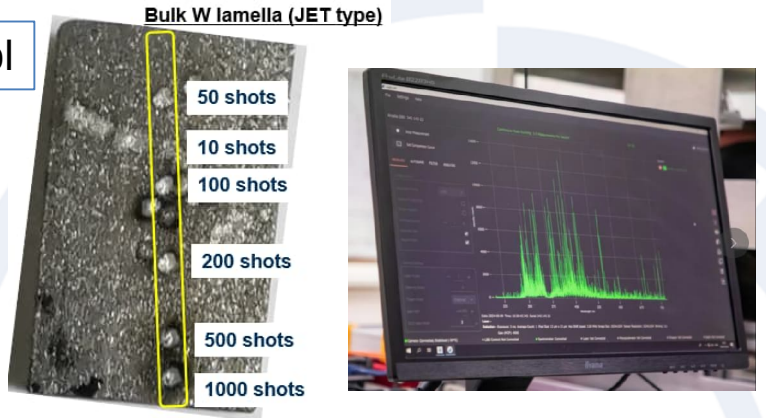


SPE.E1 Participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS (UKAEA)

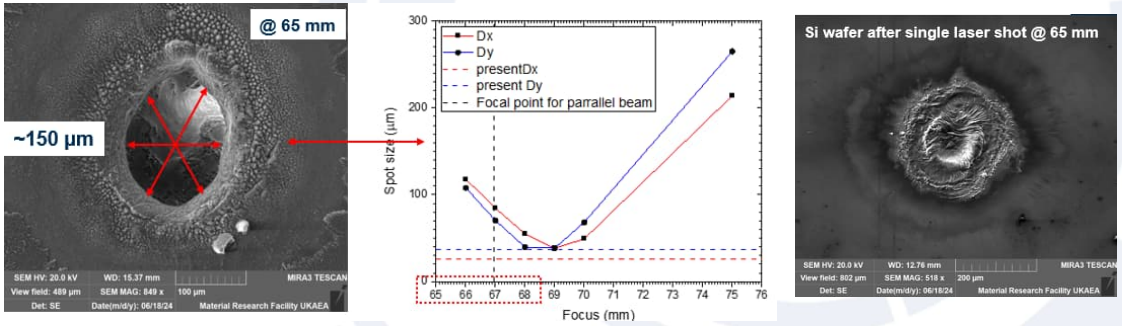
1. LIBS tool lab commissioning @ JET – Performed tests before releasing the tool

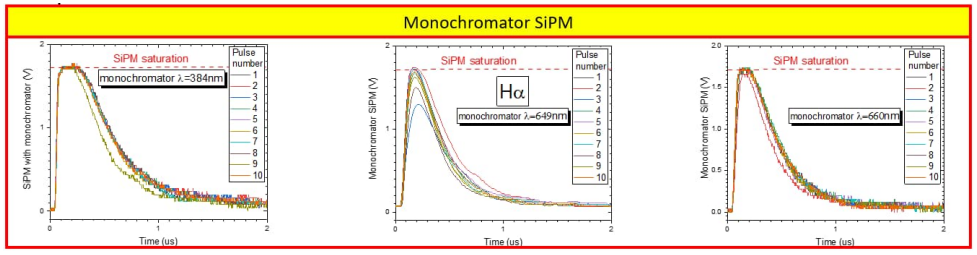
Measurements performed on (results being processed by the LIBS team):

- **Bulk W lamella (JET type):**
  1. **Evaluation of ablation rate**
  2. **Crater formation evaluation (to confirm proper laser alignment &focus)**
  3. W spectroscopic line assessments via Arielle Spectrometer;
- **Bulk W sample (FZJ):**
  1. **Evaluation of ablation rate;**
  2. **Crater formation evaluation**;
- **W-CFC samples (WEST) with H-D inclusions (very little D)**
  1. W spectroscopic line assessments via Arielle Spectrometer;
  2. H/D assessment via Littrow spectrometer;
  3. H/D assessment via PMTs

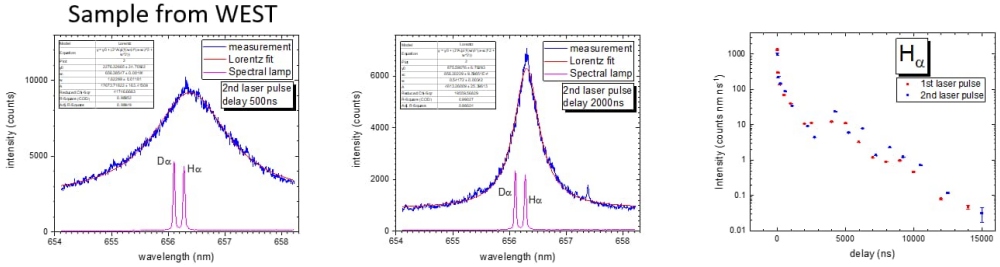


Si LIBS ablations for crater evaluation function of focusing lens position



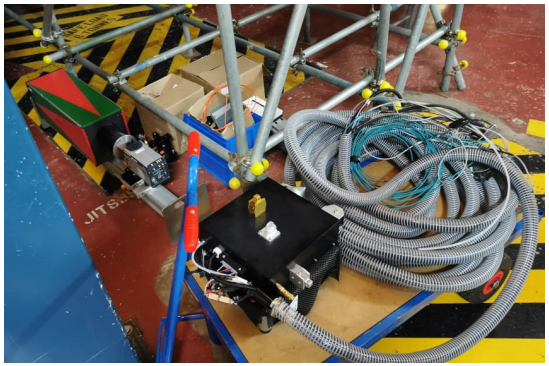


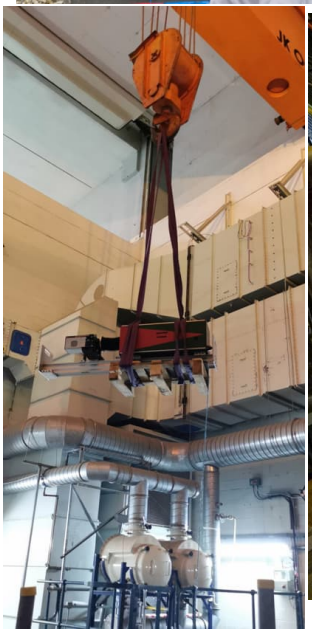
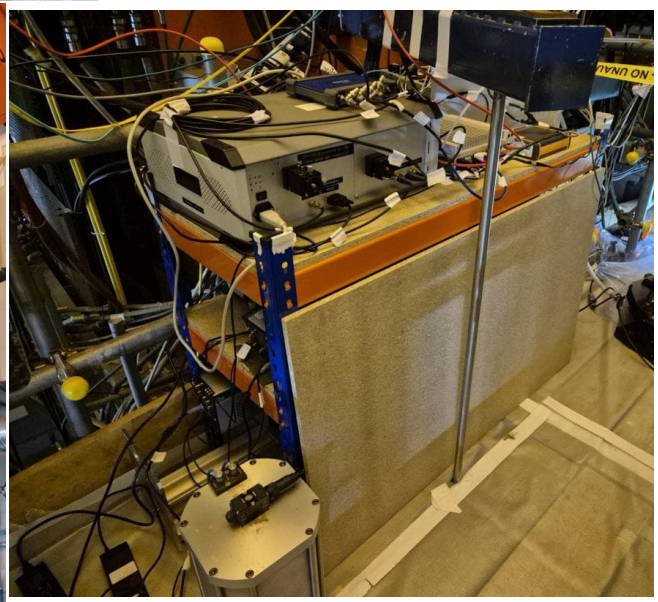
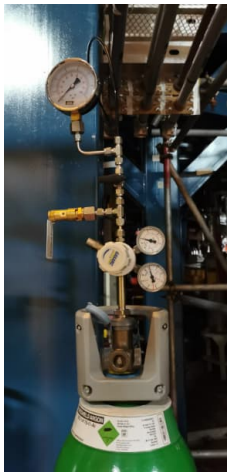
Sample from WEST



SPE.E1 Participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS (UKAEA)

2. LIBS equipment move set-up and final calibrations into J1T

3. Final calibrations into J1T

- ✓ Industrial PC remote connection <u>from RH control room (CR);</u>
- ✓ Instrumentation communication (spectrometers, cameras, oscilloscope, laser unit) with industrial PC;
- ✓ Aryelle signal intensity check with Hg and D lamp directly connected and via fibre splitter;
- ✓ Littrow signal intensity check with D lamp via fibre splitter;
- ✓ H-D lamp calibration at tip of the cone (LIBS tool at ground level) for both Aryelle and Littrow;
- ✓ Compact “sphere” and W lamp (FZJ) calibration at the tip of cone;
- ✓ Large 5W integrating sphere(UKAEA) calibration at the tip of the cone;
- ✓ Solenoid ON/OFF tests, LED light ON/OFF;
- ✓ Dry run LIBS pulses - laser trigger (using 0 pulse energy and closed shutter) to check instrumentation triggering (1 shot, 10 shots, 50 shots, 100 shots x 2) and data saving in the dedicated folders.

SPE.E1 Participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS (UKAEA)

4. LIBS campaign @ JET

LIBS campaign

LIBS project completed ☑

1st day of LIBS campaign: 2nd of Oct 2024

Table showing progress over first 6 shifts of LIBS campaign

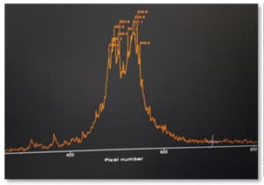
Objective/Task	Pulses/Sessions goals	Status	Pulse #
IWP & inserts	Be and W coating thickness	😐	1-6
Divertor: Module 14, including HFGC, RE damage on Tile 1, and W-LBSRP (Tile 5)	Fuel retention and deposition	☺	7-77
OPL 4D	Fuel retention and depostion in beryllium limiter	☺	73-337
Oct 5 vacuum vessel	Fuel retention and depostion on outer vaccum vessel wall	☺	338-440
IWGL 7X (Be) & 7Z (W-CFC)	Fuel retention and depostion in vicinity of KS8 spots	☺	341-346
Divertor: Module 2	Fuel retention and deposition	☺	347….

6 Official - Sensitive - Commercial

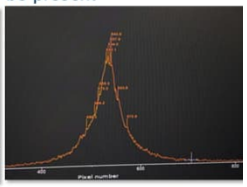
Main scientific results achieved:

- ❑ Large amount of data collected; Aryelle; Littrow (Hydrogen isotopes), Avantes, PMTs
- ❑ H & D peaks clearly visible on Littrow.
- ❑ Ablation of Be and W monitored by Aryelle and Avantes spectrometers
- ❑ Repeated D, HD, Hg lamp measurements for spectrometer wavelength calibration

Tile 1
shot #3/1000
Low T could also be present

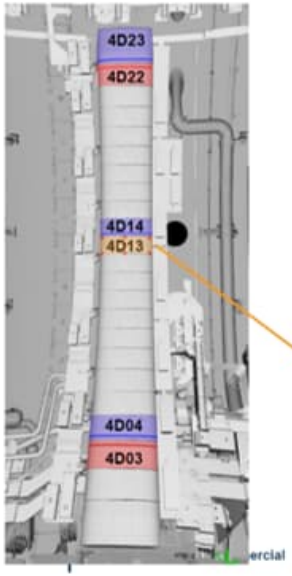


Tile 1
shot #18/1000
Low D could also be present

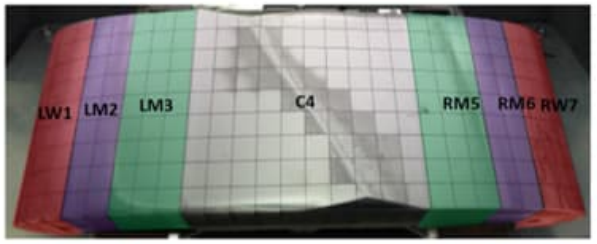


Example of LIBS locations executed in JET

WOPL – wide outer poloidal limiters

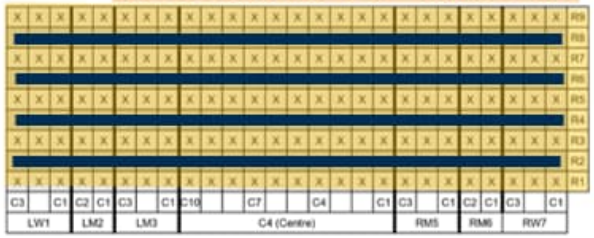


WPL tile layout (each WPL is made of 7 individual tile blocks)

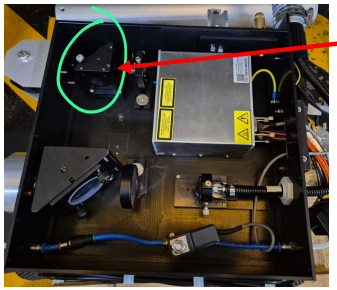


LW1 – Left wing
LM2 – Left inter
LM3 – Left inter
C4 – centre 4
RM5 – Right int
RM6 – Right int
RW7 – Right wi

LIBS locations for 4D13 – full tile scan



Overcoming an unexpected situation during LIBS campaign

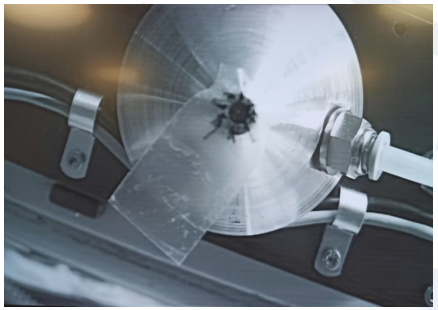


1st mirror fell from its' location

- ❑ Mirror repositioned; optic unit levelled;
- ❑ Approvals and MS for performing laser alignments shots in TCTF while operators inside TCTF;

Performed tests to overcome the problem

- ❑ Laser focus checked at tip of the cone using burn paper ✓
- ❑ Concentricity between lamp beam and laser spot completed ✓
- ❑ Tool redeployed for late shift ✓



SPE.E1 Participation in the LIBS experiment at VTT and at JET using RH, and in the data analysis of CF LIBS (UKAEA)

4. LIBS campaign @ JET : 2nd to 18th of Oct 2024

Total shifts: 20 shifts (including one Sunday)
One shift = 9.25 working hours

Objective/Task	Pulses/Sessions goals	Status	Pulse #	Dates
All planned locations sampled	Be and W coating thickness Fuel retention and deposition	☺	1-742	2-3, 7-8, 11-12, 14-15 October
Littrow delay settings optimisation	Improve H-D line resolution with laser pulses in high fuel retention areas (divertor HFGC & Tile 1)	☺	744-758	16-17 October
Repeated locations with new Littrow settings	Divertor - W-CFC, Tile 5 - W, IWP – Be & W, OPL - Be	☺	759-800	17 October
Divertor “risky pulses” (potential for damage to fibre due to space availability)	Fuel retention and deposition in divertor	☺	801-829	17 October
Littrow 1st order settings	Wider spectral range for comparison with Aryelle spectrometer	☺		18 October
Final D, D-H, Ne light calibration from J1T	Wavelength calibration check	☺		18 October
Fuel retention and deposition with Littrow 1st order settings	Tile 5 – W & Tile 4 – W-CFC	☺	830-840	18 October

SPE.2

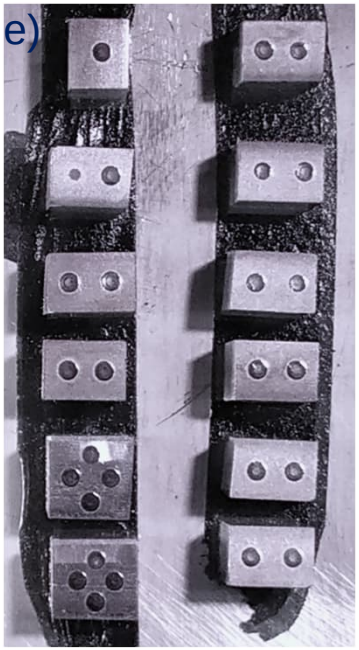
SP E.2 - Comparison of hydrogenic retention quantification by different techniques and fuel removal assessment (26PM)

LID-QMS of JET samples in FZJ

JET samples measured by LID-QMS in FZJ with ∅3 mm laser spot:

a) Tile 0 ILW3 (HFGC14N LH remaining part after coring + core 3b)
b) Tile 1 ILW3 (14IN G1C remaining part after coring + core 11a)
c) Tile 0 ILW1+2+3 (HFGC 14NRH remaining part after coring)
d) Tile 1 ILW1+2+3 (14IWG1A remaining parts after coring)
e) W lamella cuts on top surface (154, 155, 161, 162, 168, 169, 175, 176, 182, 183, 189, 190) measured with ∅2 mm laser spot.

Side surfaces have visible deposition: would be interesting to measure



LID-QMS of JET samples in FZJ

Status: All measurements for EUROfusion tasks done. Evaluation ongoing.

<u>optional:</u>

JET samples in FZJ for LID-QMS but not in EUROfusion tasks:

- Be limiter 2XR10 from ILW3 for poloidal D profile
- IWC 4/2 (2011-2016) 19, 32

FREDIS will go out of operation and moved ~10 m inside the HML lab:
December 2024 – maybe October 2025 (??? end date uncertain)
due to construction works for the new hot cells in HML in FZJ which will be just next to FREDIS

Deliverable: **PWIE-SP E.2.T-T002-D001**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

SPE.2 Analysis of samples from JET divertor tiles by GDOES (IAP)

General Information

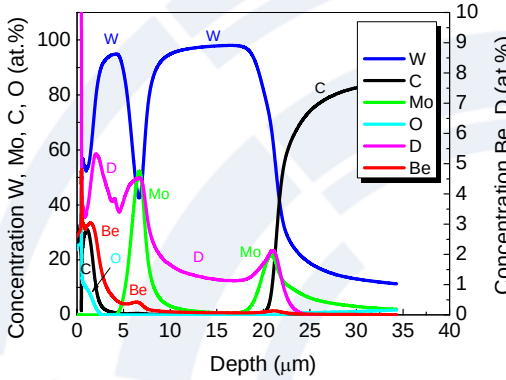
- Determine erosion, deposition, and fuel retention profiles on samples cored from JET divertor tiles

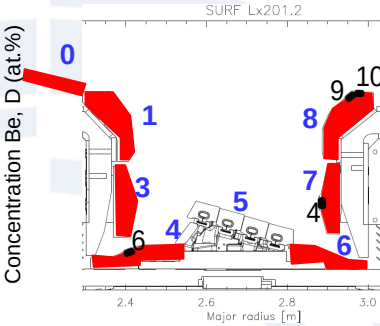
Approach

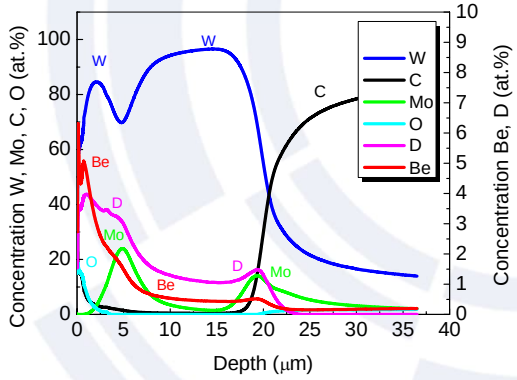
- 16 samples cored from outer divertor tiles: 14BNG4D, 2BNG6C, 2ONG7A and 2ONG8B, exposed in the ILW2 + ILW3 campaigns were analyzed

Results

- Tile 4: No significant amounts of Be have been detected on the four samples cored from this tile
- Tile 7 and Tile 8: at relatively high concentrations of Be (> about 4 at%) D follows Be profile whereas at lower Be concentrations D seems to be retained in the defects of the W/Mo coating structure. Migration of D from both sides of the Mo marker layer for long time exposure to plasma occurs.







GDOES depth profiles for samples cored from (a) Tile 4, 4BNG4D-6d, (b) Tile 7, 2ONG7A-4d

Deliverable: **PWIE-SP E.2.T-T002-D002**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

University of Latvia, Faculty of Science and Technology, Institute of Chemical Physics

General Information

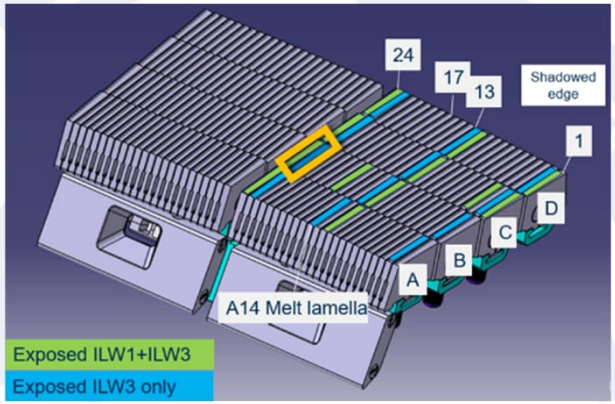
- Fuel (tritium) retention analysis in JET samples

Task and questions to be addressed

- Completion of fuel retention studies using FC, TDS (simulation of C39 baking cycle) and SEM
- Samples from W lamellae

Approach

- W lamellae samples have been analyzed by the means of electrochemical etching, thermal desorption spectrometry (TDS) and full combustion. Additionally, SEM and FT- IR analysis performed of the plasma facing surfaces.



Positions of lamellas in the tile

Tungsten samples for analysis in UoL
Samples received:
186 – B23 (ILW3)
187 – B23 (ILW3)
193 – B24 (ILW1+3)
194 – B24 (ILW1+3)

Results - fuel retention, baking

Manuscript prepared:

Investigating Tritium Retention in Tungsten-Molybdenum Composite Plasma-Facing Wall Components at the Joint European Torus (JET)

Authors: A.S. Teimane, E. Pajuste, L. Avotina, A. Lescinskis, A. Vitins, A. E. Goldmane, M. Sondars, R.J. Zabolockis , J. Likonen, A. Widdowson and JET Contributors,

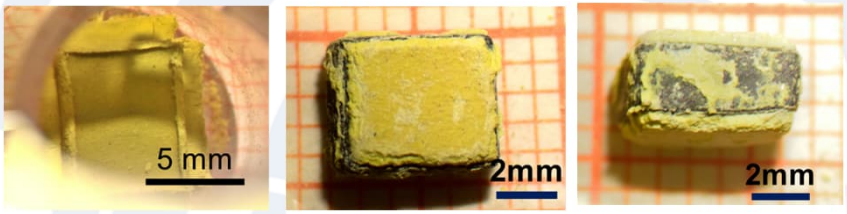
Deliverable: **PWIE-SP E.2.T-T002-D003**
Status: ***ongoing***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

University of Latvia, Faculty of Science and Technology, Institute of Chemical Physics

Results - W lamellae

- Measured tritium concentration varies depending on the method.
- Highest tritium amount measured by electrochemical etching which might indicate that thermal treatment is not suffucient for tritium removal, full removal of the tritium containing layer is required.

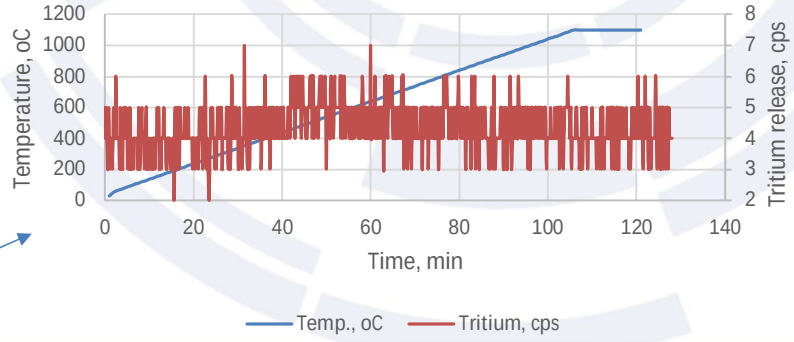
Sample	Measured T concentration, kBq/cm^2	Method applied
186 (B23, ILW3)	0.17	Full combustion, 850^{o}C, 15 h Moistured air flow, oxidation of W, Tritium collected in water bubblers and measured by LSC
187 (B23, ILW3)	16.97	Electrochemical etching of the surface, tritium measurement in the purge gas and collecting in water bubbler after the detector. Most of tritium measured in the etching liquid after the experiment by LSC
193 (B24, ILW1+3)	0.03	Thermal desorption in the Ar purge gas up to 1100oC, tritium measurement in the purge gas and collecting in water bubbler after the detector



Tungsten sample after 8 h full combustion experiment, only an oxide layer. For a full combustion considerably more time is needed.
For the next combustion cycle (5 cycles in total) oxide layer mechanically removed to test if it does not work as a tritium barrier.

Deliverable: **PWIE-SP E.2.T-T002-D003**
Status: ***ongoing***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

During thermal desorption experiment tritium in gas phase under detection limit, only measured in the water bubbler after the detector.



SPE.2 Characterization of JET divertor tiles using ion beam analysis (RBS, NRA), IST

General Information

- Characterization of remaining JET divertor tiles using ion beam analysis (RBS, NRA)

Approach

- IBA analyses completed
- NDF analysis to be completed by 12/2024

W lamellae:

D01(ILW1+3), D02(ILW3), C01(ILW1+3)

Deliverable: **PWIE-SP E.2.T-T002-D004**
Status: ***ongoing***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

SPE.2: Samples, methodology & summary results overview (NCSRD)

JET Tokamak Divertor

Exp. Campaign	Tile	Sample	S-coordinate
2013-16	14BN G4D	3b	868
		5b	824
		7b	779
		9b	735
	2BN G6C	5a	1405
		7a	1447
	2ON G7A	2	1668
		4	1716
		6	1764
	2ON G8B	2b	1865
		4b	1919
		6b	1973
		8b	2027
		10b	2053

Methodology

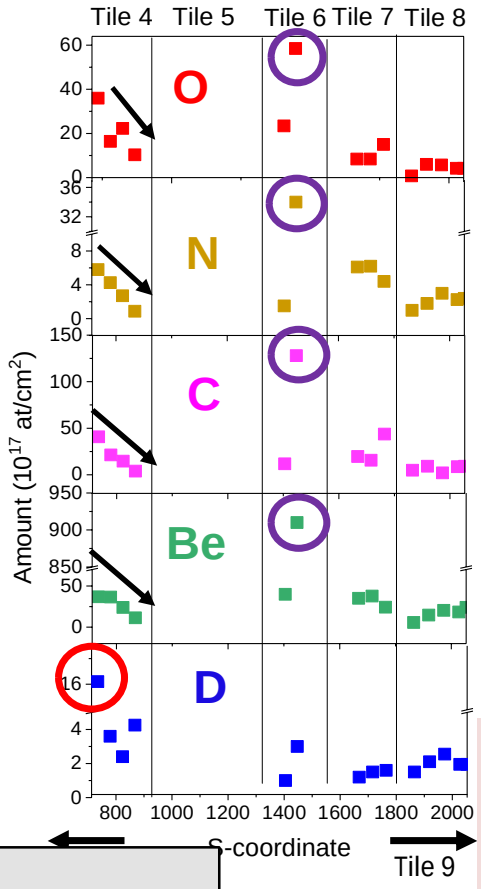
Surface

- d NRA (1.6 MeV)
- SEM & EDS (5 keV & 30 keV)

Cross Section

- SEM & EDS (5 keV & 30 keV)

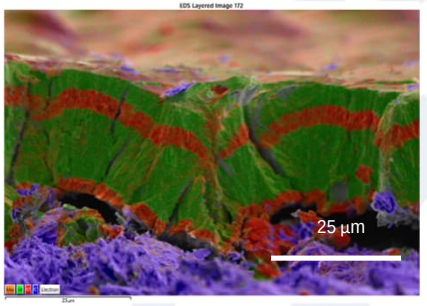
Surface: elemental amount



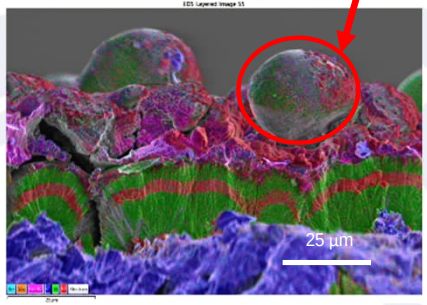
Cross section: elemental mapping

W droplets

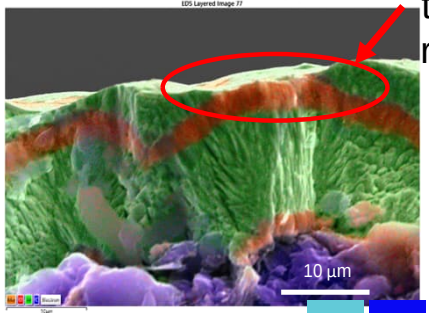
Tile 4 5b (824 mm)



Tile 6 7a (1447 mm)

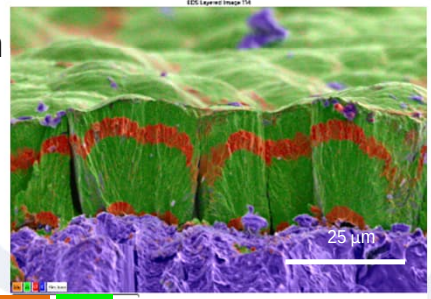


Tile 7 2 (1668 mm)



W top layer thickness reduction

Tile 8 8b (2027 mm)



Be C O Fe Mo W

Tile 4: Highest D retention at S = 735 mm
Deposition decreases from tile 3 to tile 5
Tile 6: The highest deposition at S= 1447 mm
Tile 7: Erosion ≤ 8 µm at S = 1668 mm
Tile 8: Low deposition, no variation along S coordinate. No erosion.

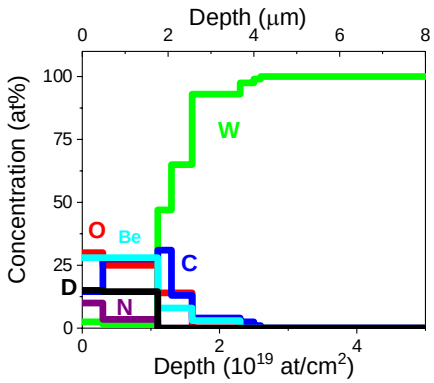
Deliverable: **PWIE-SP E.2.T-T002-D007**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

SPE.2: Tiles 4 & 6: Surface and cross section mapping & depth profiles (NCSRD)

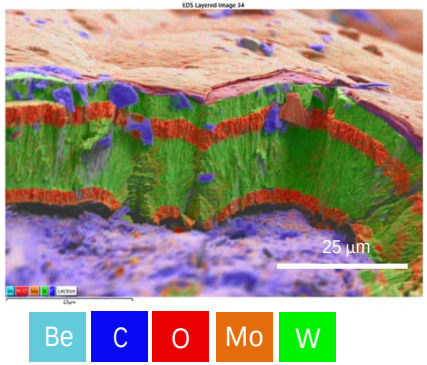
Tile 4

Sample 9b (S=735 mm, near Tile 3)

Surface: depth profile

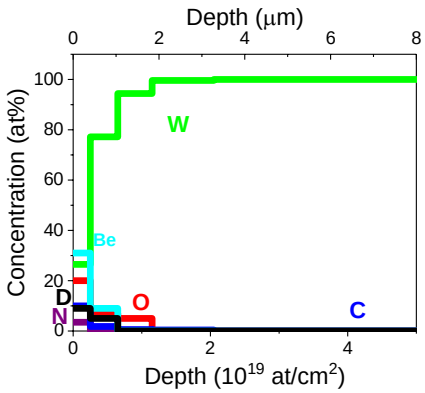


Cross Section: mapping

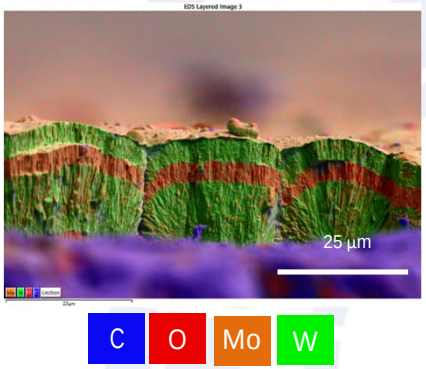


Sample 3b (S=868 mm, near Tile 5)

Surface: depth profile



Cross section: Mapping

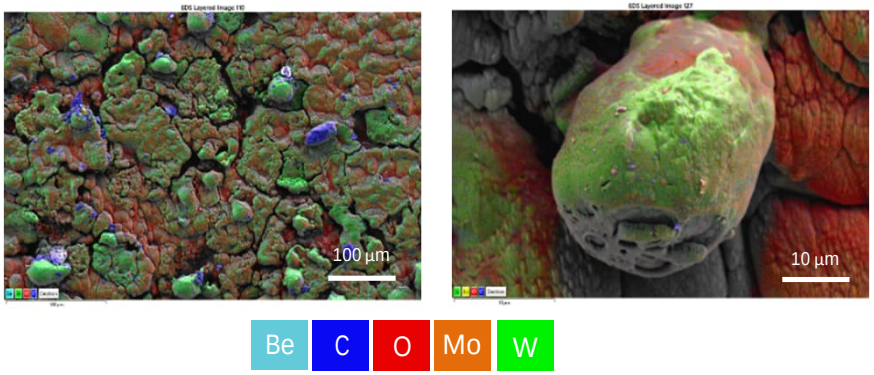


- No erosion
- Thin layer deposition of Be, C, N, O

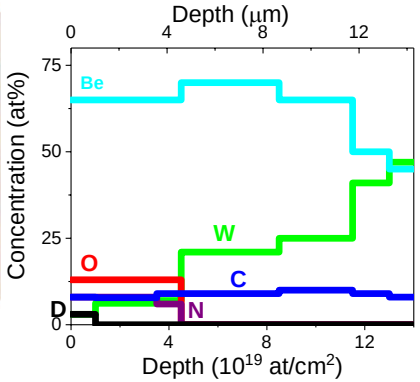
Tile 6

Sample 7a (S=1447 mm, highest deposition)

Surface: mapping

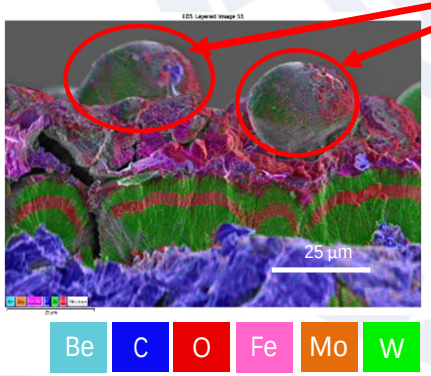


Surface: depth profile



Cross section: mapping

W droplets



- Thick Be-W co-deposits
- Highest elemental deposition

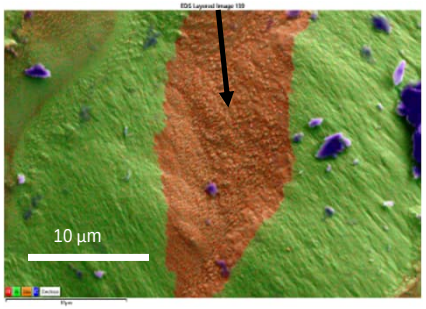
SPE.2: Tiles 7 & 8: Surface and Cross Section Mapping & Depth Profile (NCSRD)

Tile 7

Sample 2 (S=1668 mm, eroded sample)

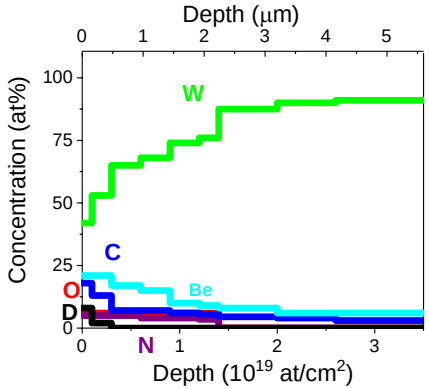
Surface: mapping

Mo interlayer

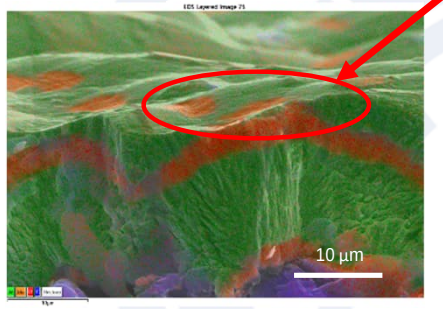


C O Mo W

Surface: depth profile



Cross section: mapping



C O Mo W

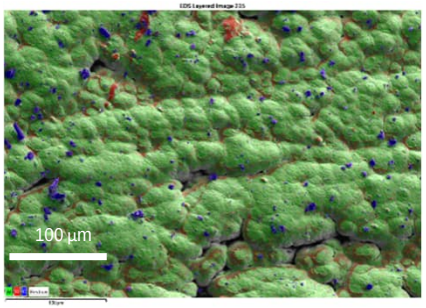
W top layer thickness reduction

- Erosion ≤ 8 μm

Tile 8

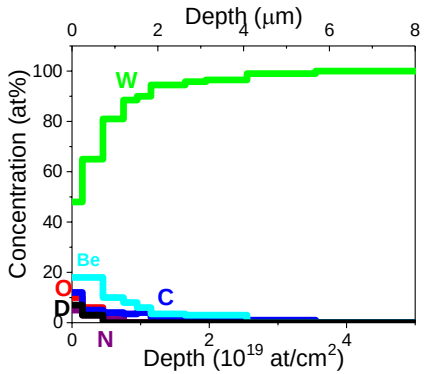
Sample 8b (S=2027 mm)

Surface: mapping

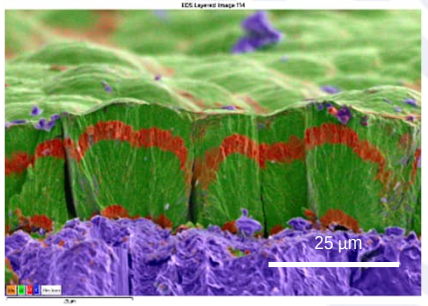


C O Mo W

Surface: depth profile



Cross section: mapping



C O Mo W

- Low deposition
- No erosion

SPE.E2 TDS analysis and fuel removal assessment of JET divertor samples (UKAEA)

General Information

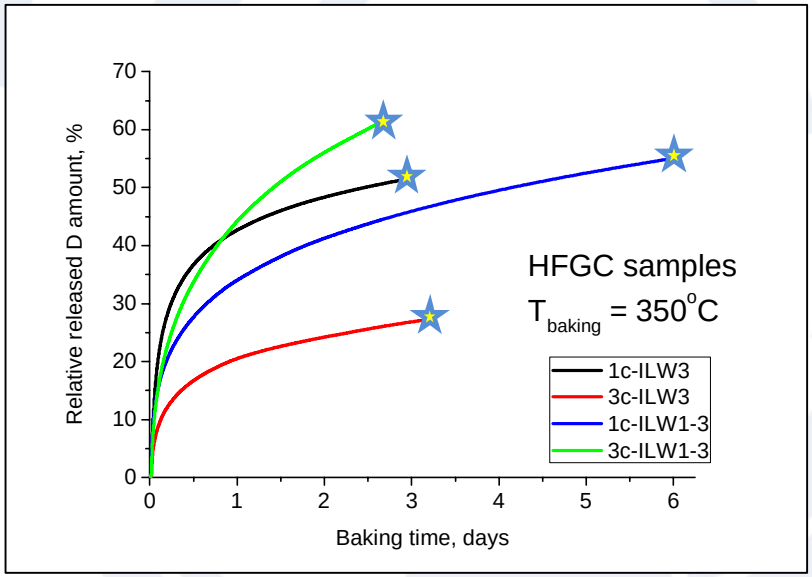
- Baking TDS runs were performed for divertor (W-CFC with predominantly Be deposits) and limiter (bulk Be) samples from JET ILW, at ITER-relevant temperatures (350°C divertor, 240°C first wall), for 60-140 hrs.
- IBA and SIMS measurements before and after baking used to determine near-surface removal efficiency, TDS measurements used to determine bulk removal efficiency).

Approach

- IBA,TDS and SIMS analysis of divertor samples

Results

- Difference in the near-surface and bulk removal efficiency observed:
  - Divertor samples (350°C) → near-surface efficiency lower than bulk.
  - Limiter samples (240°C) → near-surface efficiency much higher than bulk.
- Overall removal efficiency:
  - Divertor samples (350°C) → ~30-60%.
  - Limiter samples (240°C) → ~4%.
- In-situ monitoring tools potentially more sensitive to near-surface region than bulk → there is a possibility that this does not exactly reflect the overall removal efficiency during baking.
- A temperature regime is possible where baking is inefficient for tritium removal and instead drives it inwards.



SPE.2 Fuel removal assessment of JET divertor samples (VTT)

General Information

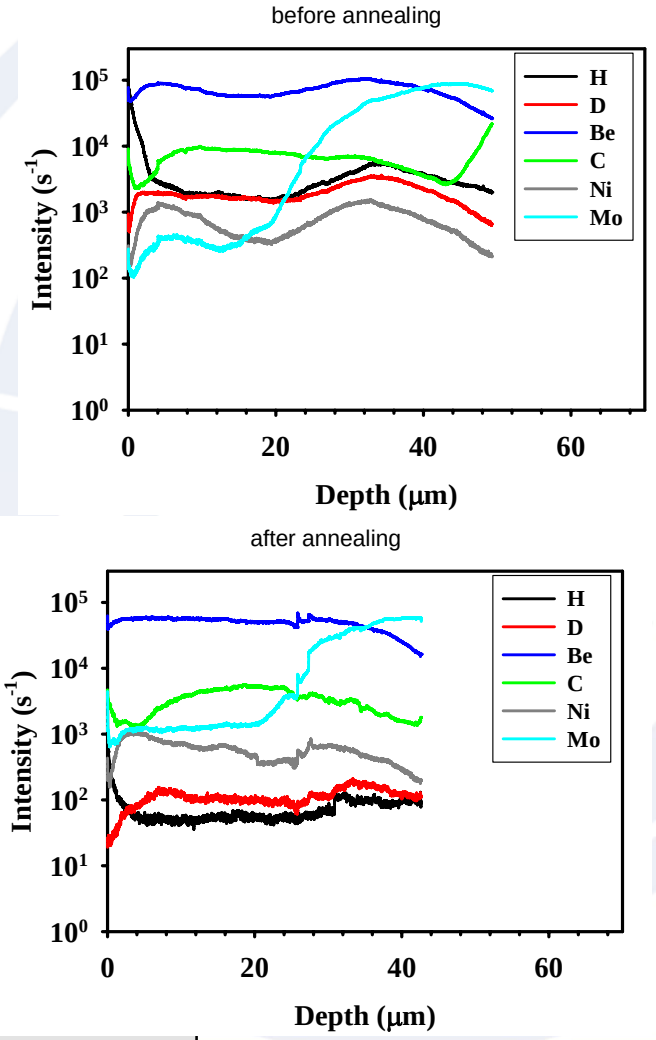
SIMS measurements before and after baking used to determine near-surface removal efficiency

Approach

- SIMS analysis of divertor samples

Results

- Annealing of the sample at 350 °C had a clear effect on the H and D depth profiles
- Overall H and D amounts have decreased markedly
- H surface peak is lower and thinner than before the annealing indicating the H has been released during the annealing.
- Dip for D extends now to a depth of ~7 μm so D has been released from near surface region. Another effect of the annealing is that interfacial peaks for H and D have now disappeared almost completely.



Deliverable: **PWIE-SP E.2.T-T002-D006**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

SPE.3

SP E.3 - Post-mortem analysis of PFC and other objects in JET (26PM)

LID-QMS of JET samples in FZJ (SPE3)

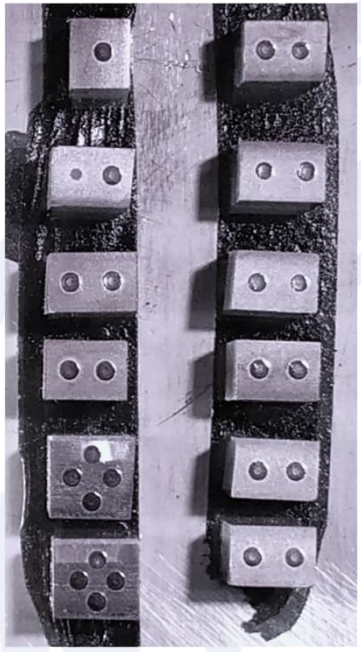
W lamella cuts on top surface (154, 155, 161, 162, 168, 169, 175, 176, 182, 183, 189, 190) from lamellae B02, B12, B13, B17, B23 and B24 measured with ∅2 mm laser spot.

He and D_2 in comparable amount on top of lamella

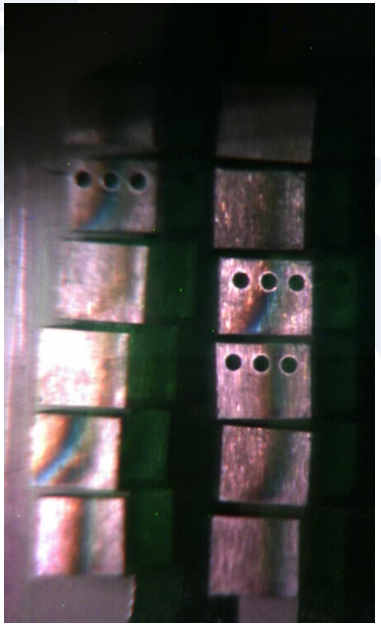
Side surfaces have visible deposition:
LID-QMS on side surfaces ongoing (sides also contain He and D_2)

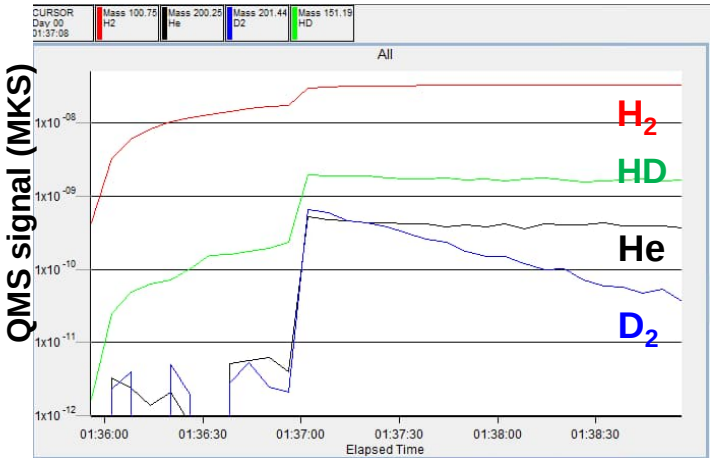
Metallography and TDS measurements delayed

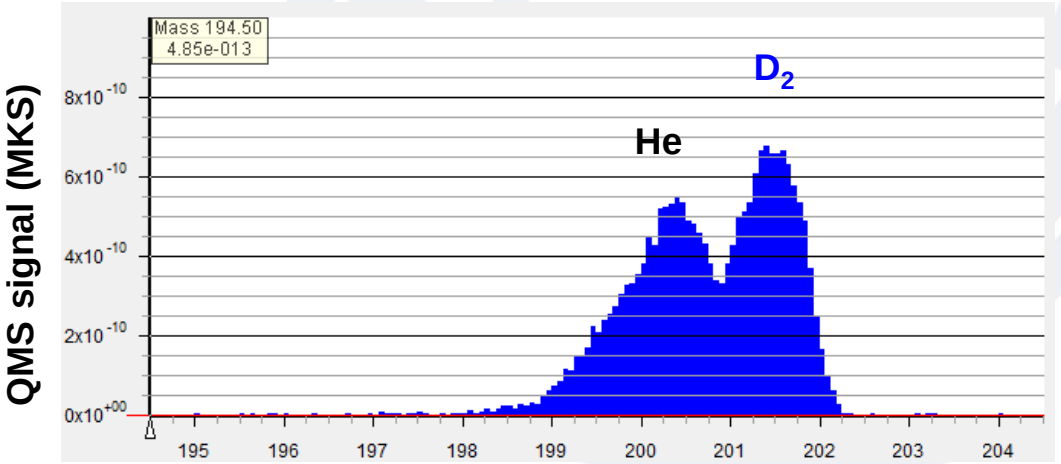
Top surface



Side surface





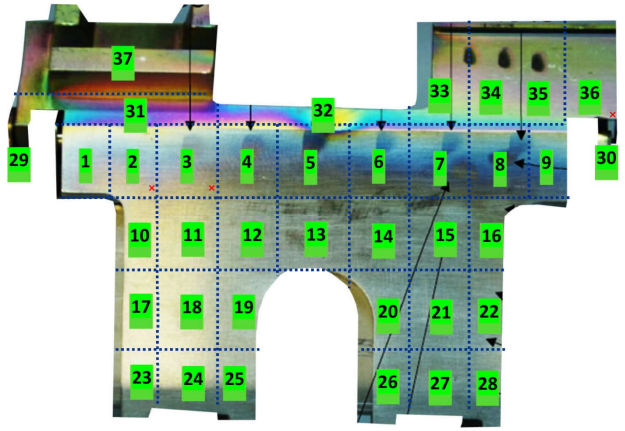


Deliverable: **PWIE-SP E.3.T-T002-D001**
Status: ***ongoing***
Facilities:
Linked WP or TSVV: **-**

SPE.3 Analysis of JET plasma facing components with TDS and GDOES (IAP)

General Information

Analysis of chemical structure of deposits on louvre clip



Task and questions to be addressed

- The aim of the work was to determine the chemical structure of co-deposited layers
- Modelling of Be, W migration to be done under SP D

Approach

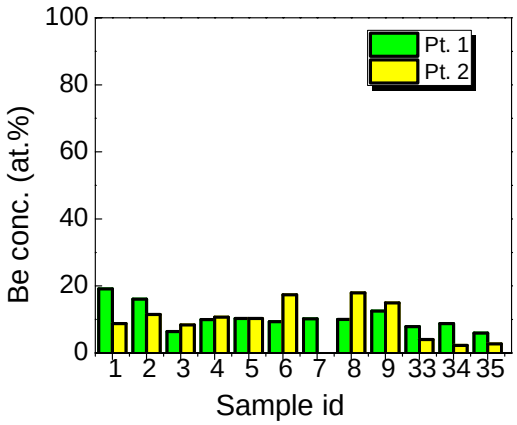
- 12 samples sectioned from Inner divertor Louvre clip were analyzed by XPS
- Analyses were performed on 2 points (Pt1: top & Pt2: lower part) on each sectioned sample

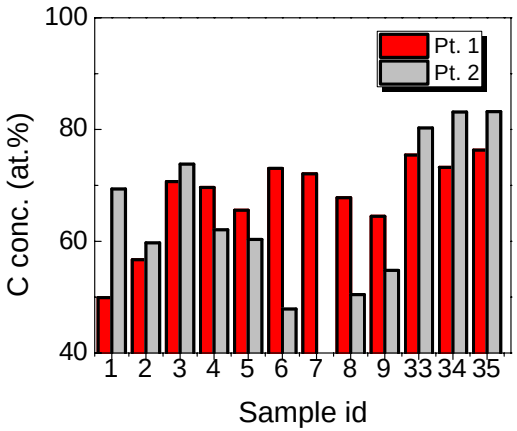
Deliverable: **PWIE-SP E.3.T-T002-D002**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

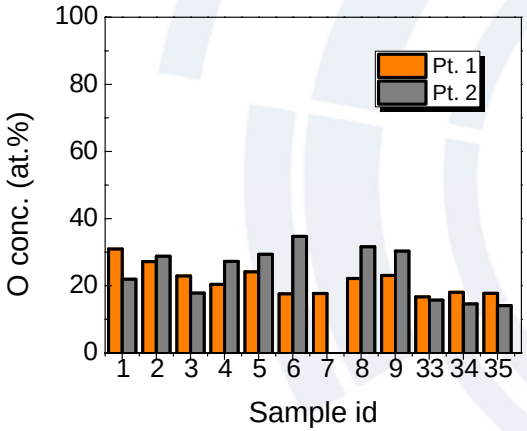
SPE.3 Analysis of JET plasma facing components with TDS and GDOES (IAP)

Results

- Surface composition of consists in a mixture of Be, C and O
- Content of Be, C and O for each sample and summarized on Figs. Bellow



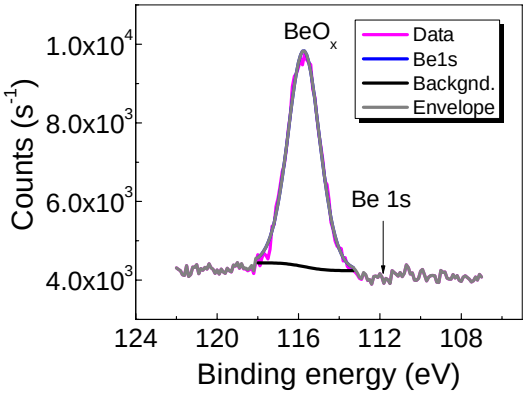


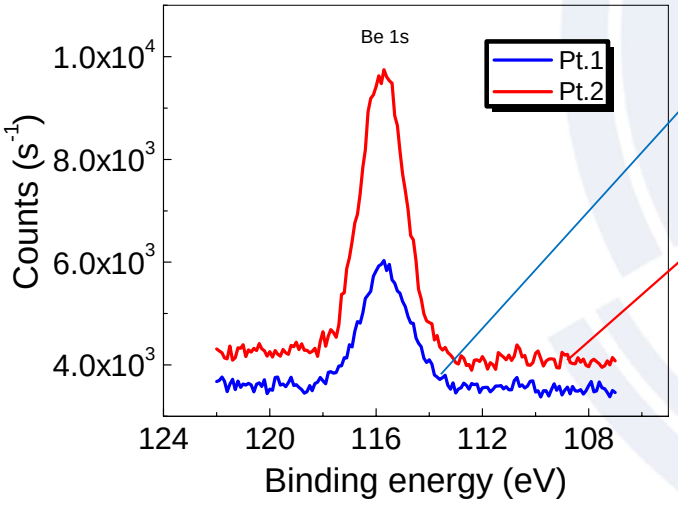


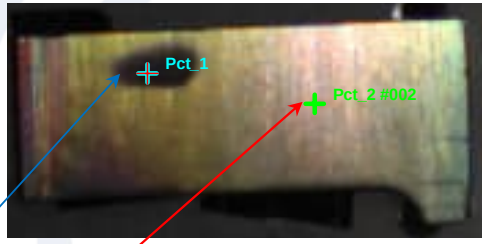
SPE.3 Analysis of JET plasma facing components with TDS and GDOES (IAP)

Results

- All samples indicated the presence of Be bonded with O; no transition specific to metallic Be was noticed
- The Be 1s position (111.8eV) is shifted towards higher binding energy indicating the formation of Be oxides







SPE.3 Electron microscopy (SEM, TEM, FIB) and nanoindentation of JET plasma facing components (IPPLM)

General Information

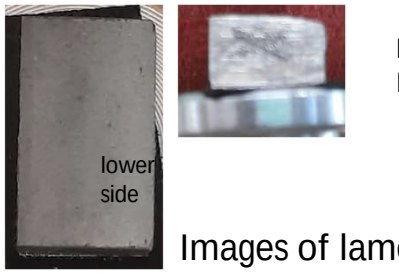
Examined samples lamella 106 from stack C of the bulk divertor Tile 5
SPE3_D003: Electron microscopy (SEM, TEM, FIB) and nanoindentation of JET plasma-facing components

Task and questions to be addressed

The aim of the work was to (i) determine possible lamella damage caused by plasma-wall interaction, (ii) assess surface modification of the material caused by the plasma–wall interactions, including redeposition, and (iii) assess sub-surface structure changes.

Approach

- On the sample, microscopic observations of the lamella surface, along with studies of the chemical composition of the surface and dust particles were carried out.
- To characterize the near-surface zone, FIB cross-sections were made in areas with three characteristic morphologies: a) in surface depression, b) in convex, potentially re-melted areas, and c) through cracks.
- Thin foil was cut out from the lamella 106 for microscopic observation.

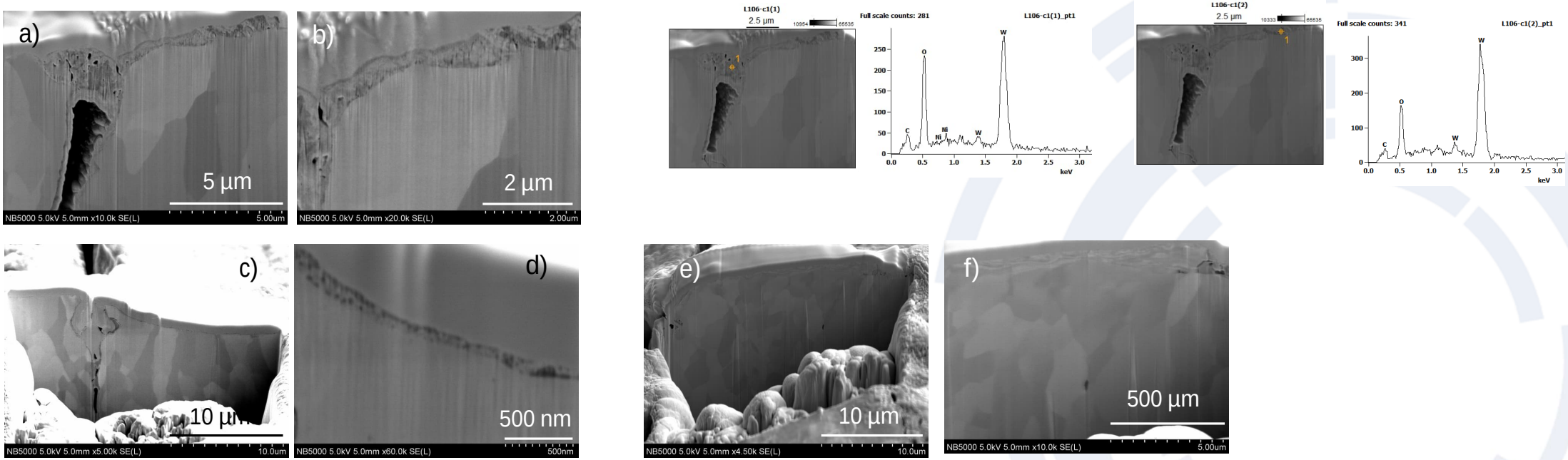


Lamella 106 from stack C
Dimensions 10 × 6 × 2.5 mm^3

Images of lamella 106.

Deliverable: **PWIE-SP E.3.T-T002-D003**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

FIB cross-sections observations



SEM images of lamella 106 FIB cross-sections.

- *At the crack mouths, we see the presence of a material with a different chemical composition than the substrate, Figs. a,c.*
- *The presence of a thin film of redeposit has been locally revealed (in surface cavities), Figs. a-d. The deposit shown in Fig. a,b is relatively thick (0.8 µm) and porous and no layering can be distinguished. Differences in the contrast of this zone are indicative of differentiation in chemical composition. The deposit revealed in Fig. d is much thinner, around 170 nm.*
- *A zone with changed morphology (likely re-solidified) was observed in some places, Figs. e-f.*

SPE.3 Electron microscopy (SEM, TEM, FIB) and nanoindentation of JET plasma facing components (IPPLM)

General Information

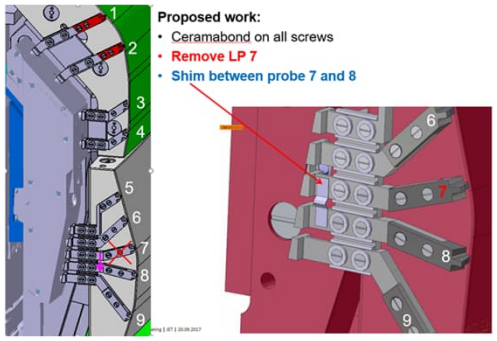
Examined samples: Langmuir probes 5, 7, 8 and 9 from module 16IN, Tile 3 (removed in 2015)
SPE3_D003: Electron microscopy (SEM, TEM, FIB) and nanoindentation of JET plasma-facing components.

Task and questions to be addressed

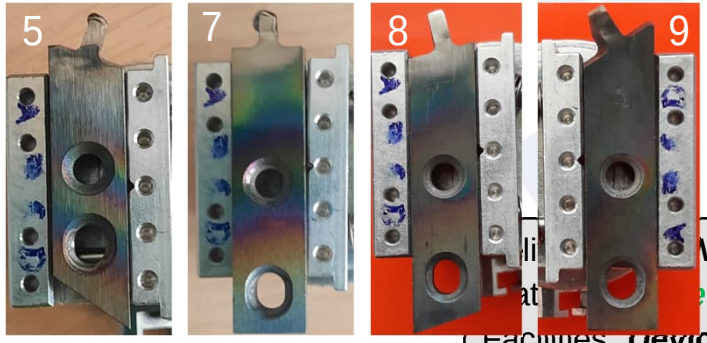
The aim of the work was to (i) determine possible probes' damage caused by plasma-wall interaction, (ii) assess surface modification of the material caused by the plasma–wall interactions including redeposition and (iii) assess sub-surface structure changes.

Approach

- On each sample, microscopic observations of the probe's surface along with studies of the chemical composition of the surfaces were carried out.
- At two samples FIB cross-sections were carried out to conform possible recrystallization.
- In addition, XRD measurements were conducted on the LP-5 from module 16W, Tile 5 (in connection with a forthcoming article).



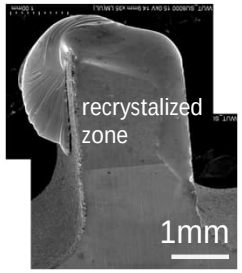
Scheme of the installation of the probes at Tile 3.

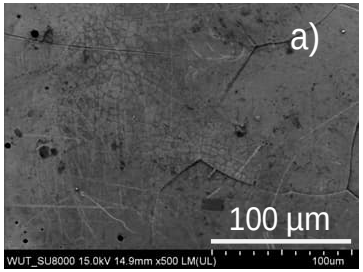


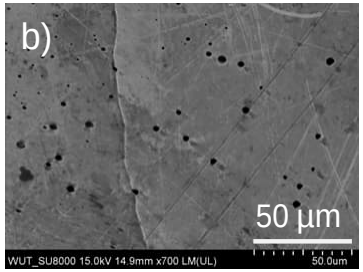
Images of probes no 5, 7, 8 and 9.

li… …VIE-SP E.3.T-T002-D003
at… …*eted*
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

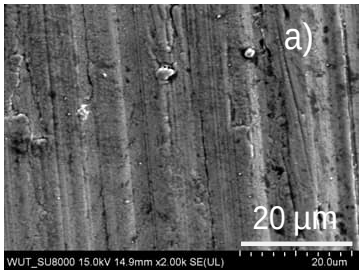
Probe 7 – tip morphology

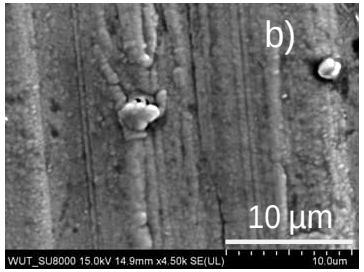


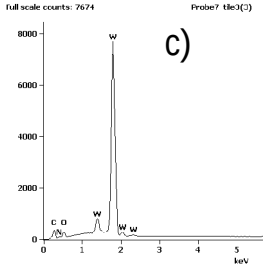




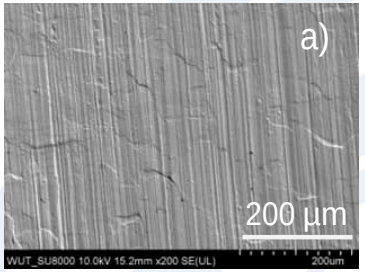
SEM images of the tip, resolidified zone.

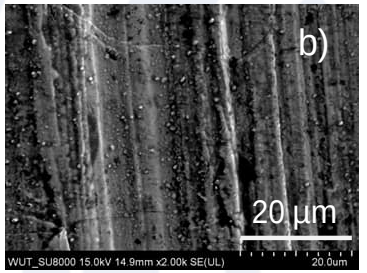


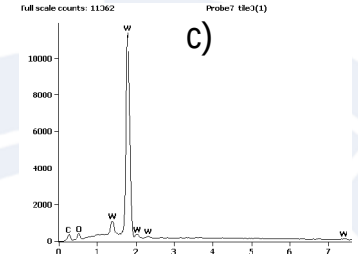


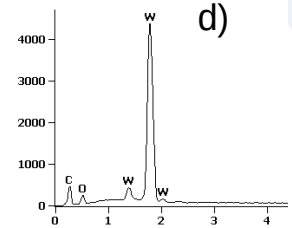


SEM images of the tip together with the corresponding EDX spectrum, bottom part.









SEM images of the tip (a-b) and EDX spectra from c) the clean and d) dirty area, recrystallized zone.

- *The melt damage of the top part of the tip was observed. Below this area recrystallized zone is present. On part of the base visible colored tarnish.*
- *The re-solidified zone shows grain boundaries (grain size up to 150 µm), cracks, and pores.*
- *In the recrystallized zone, the grain boundaries are visible (up to 100 um in some places). Additionally, there are areas where dirt/re-deposit visible on the surface. EDX analyses showed elevated levels of carbon and oxygen in that area.*
- *In the bottom part of the tip, there are no signs of surface remelting nor grain boundaries network visible.*

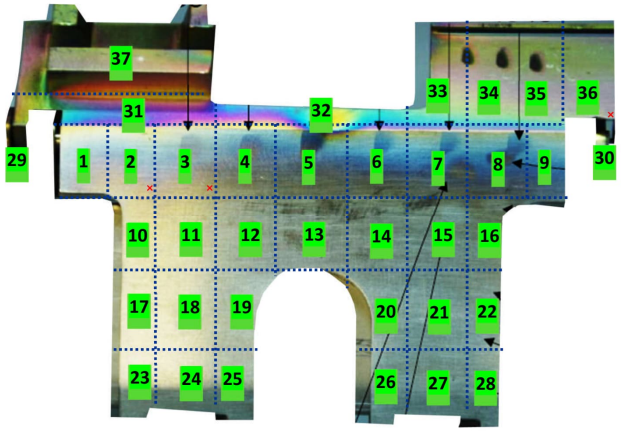
University of Latvia, Faculty of Science and Technology, Institute of Chemical Physics

General Information

- Fuel (tritium) retention analysis in JET samples, chemical analysis of the co-deposits

Task and questions to be addressed

- Louvre clips: chemical structure of co-deposits using FT-IR



Approach

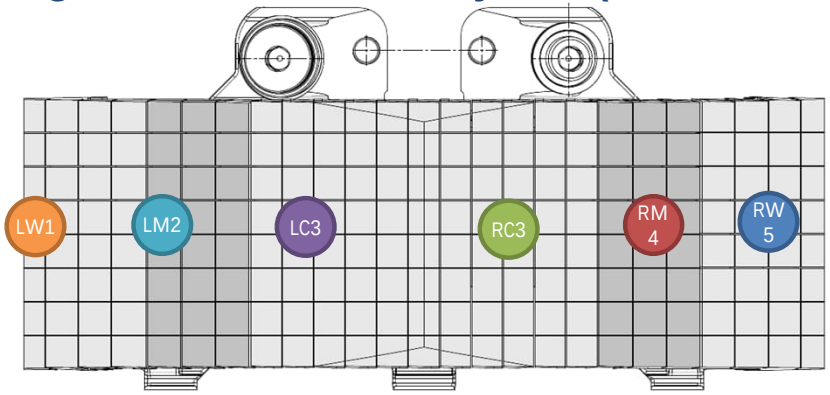
- FT- IR analysis of louvre clip samples to be performed
- Same samples that were analysed at IAP by XPS
- Louvre clip samples not delivered yet

Results - fuel retention, baking

- work on FT-IR analysis method optimization performed

Deliverable: **PWIE-SP E.3.T-T002-D004**
Status: ***ongoing***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

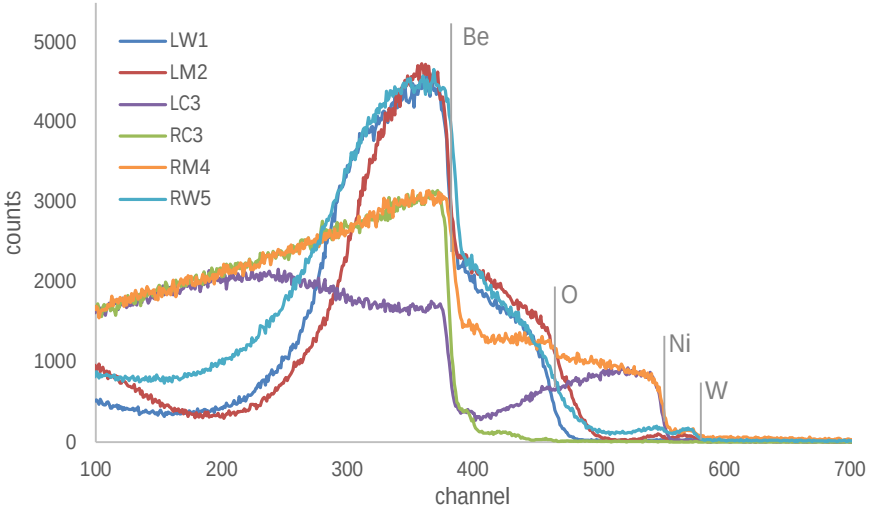
SPE.3 Characterization of JET plasma facing and diagnostics components using ion beam analysis (RBS, NRA), IST



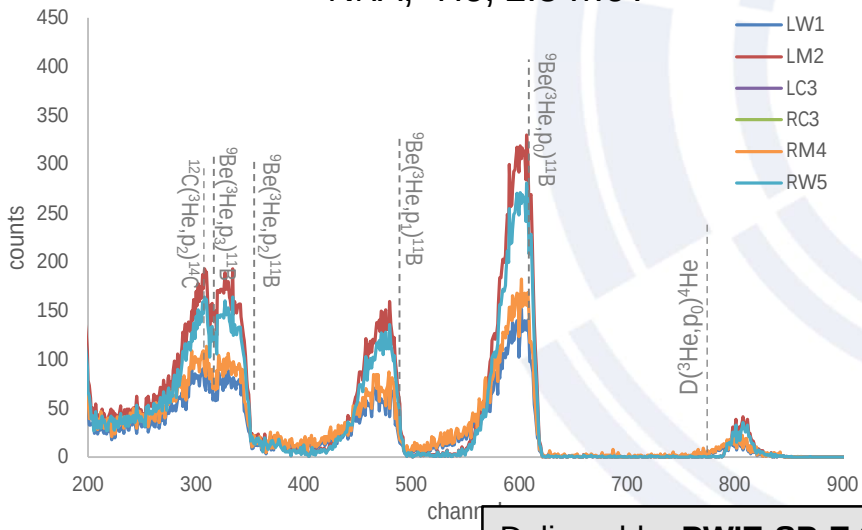
2XR9 and 4D23 (in vessel 2012-2016)

measurements completed
analysis missing (prediction 12/2024)

EBS; H; 2.3 MeV



NRA; ^{3}He; 2.3 MeV



Deliverable: **PWIE-SP E.3.T-T002-D005**
Status: ***ongoing***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

SPE.3 Characterization of JET plasma facing and diagnostics components using ion beam analysis (RBS, NRA), IST

Mirror cassette 3E (in vessel 2010-2012)

General Information

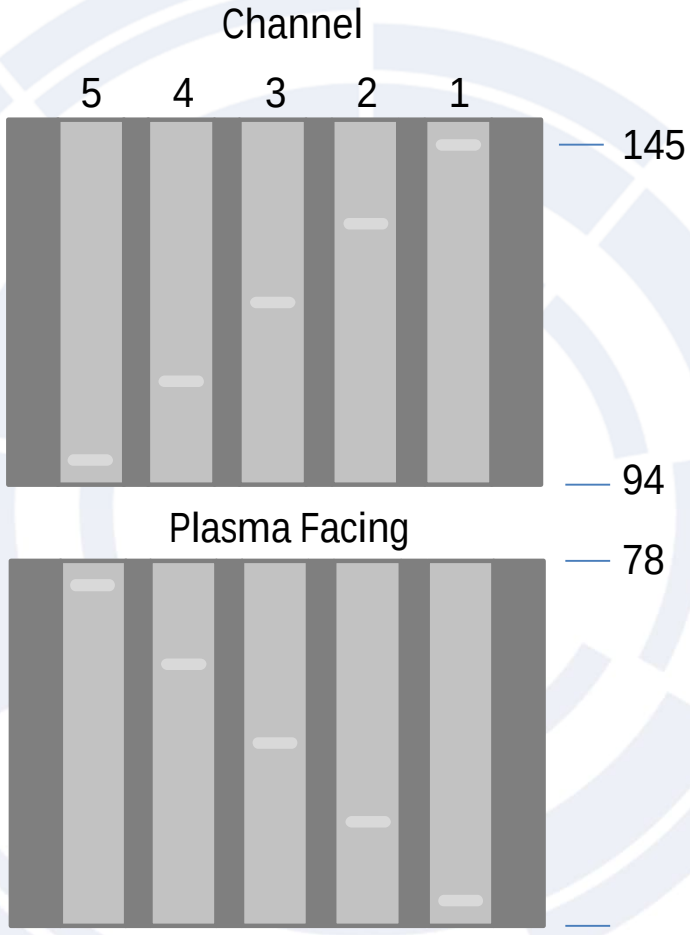
- Investigation of metal migration in the mirror cassette
- Validation of ERO simulations

Approach

- IBA analyses performed for channels 1 and 2
- Additional IBA analyses to be performed from channel 5

Results

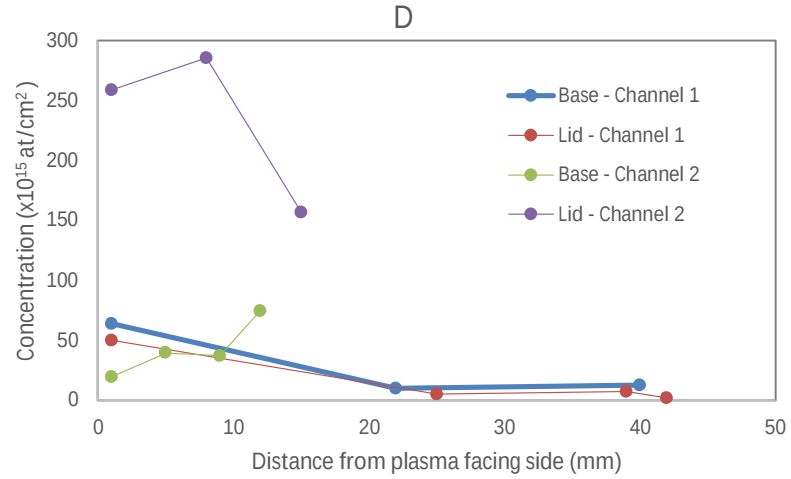
- Thin deposits containing D, Be, C and W
- Impurity amounts decrease to background level at ~20mm from cassette entrance
- Impurity amounts not same on base and lid

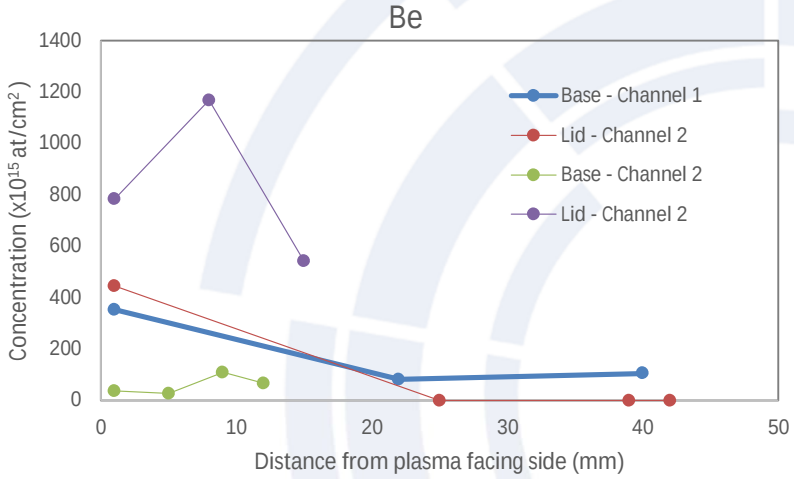


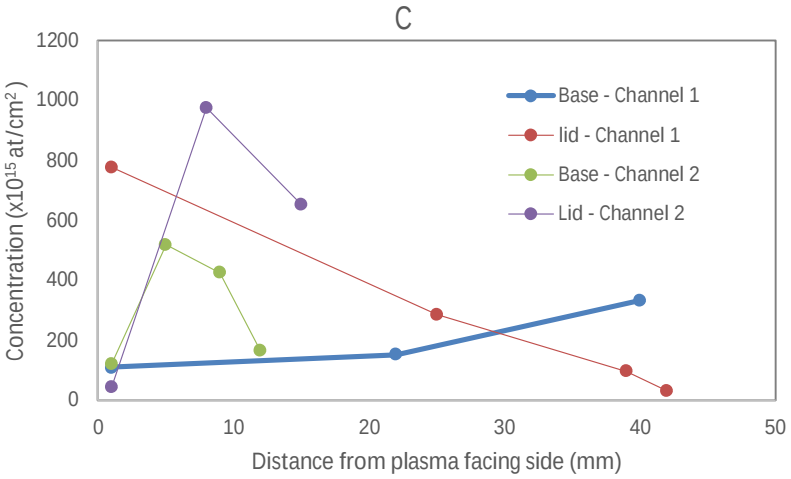
Deliverable: **PWIE-SP E.3.T-T002-D005**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

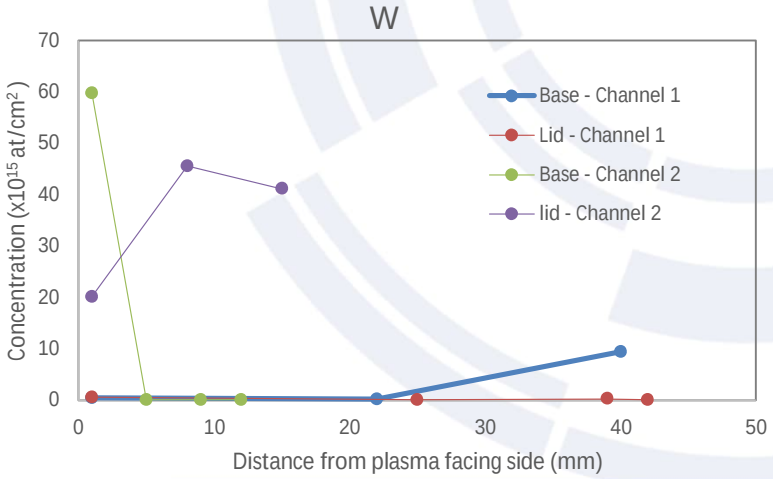
SPE.3 Characterization of JET plasma facing and diagnostics components using ion beam analysis (RBS, NRA), IST

Mirror cassette 3E (in vessel 2010-2012)









SPE.3 Characterization of JET plasma facing and diagnostics components using SIMS (VTT)

General Information

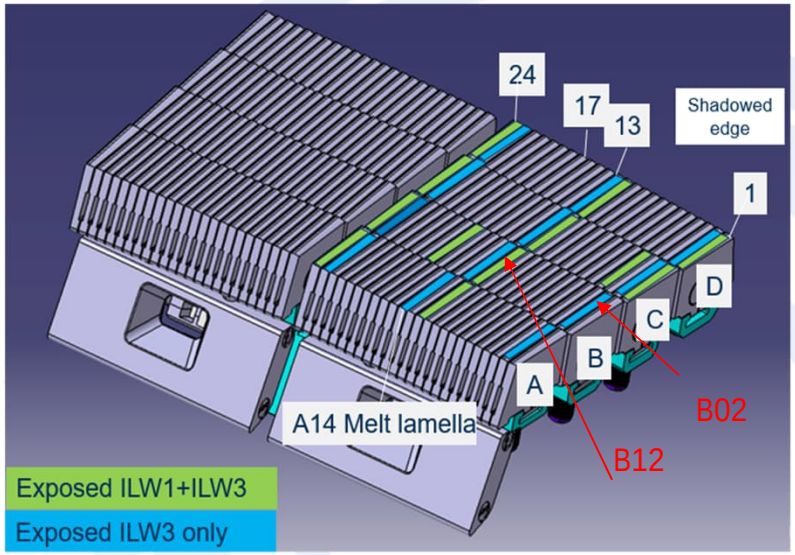
- Investigation of Be deposition and fuel retention on W lamellae samples

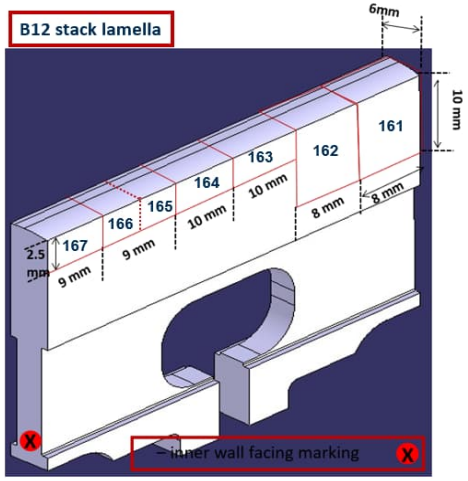
Approach

- SIMS analysis of lamellae 160/B02 (ILW3), 167/B12 (ILW1+3),174/ B13 (ILW3), 181/B17 (ILW1+3), 188/B23 (ILW3) and 195/B24 (ILW1+3) from stack B of the bulk divertor Tile 5

Results

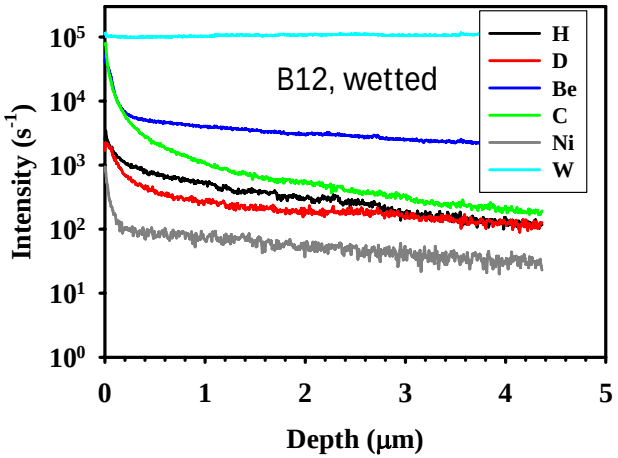
- Thin deposits containing H, D, Be and C
- D typically near surface (< 0.5 µm)

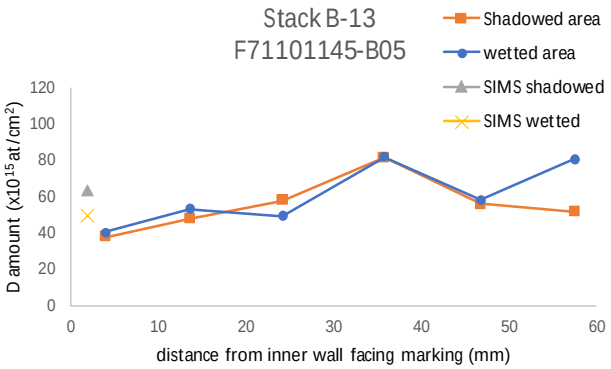


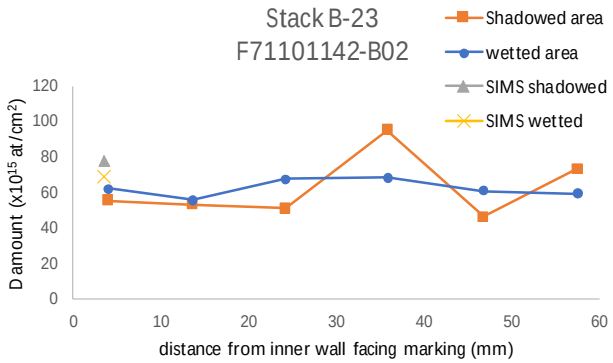


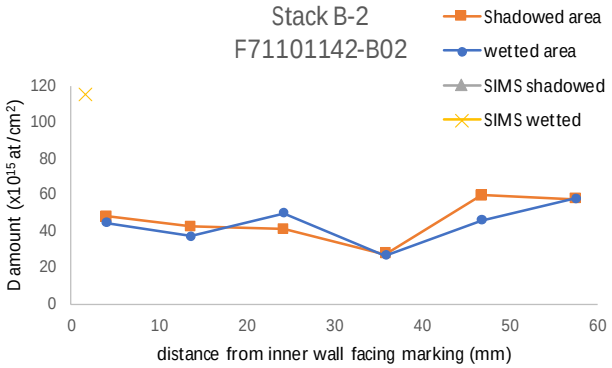
Deliverable: **PWIE-SP E.3.T-T002-D007**
Status: ***completed***
Facilities: **Device name (days allocated)**
Linked WP or TSVV: **if applicable**

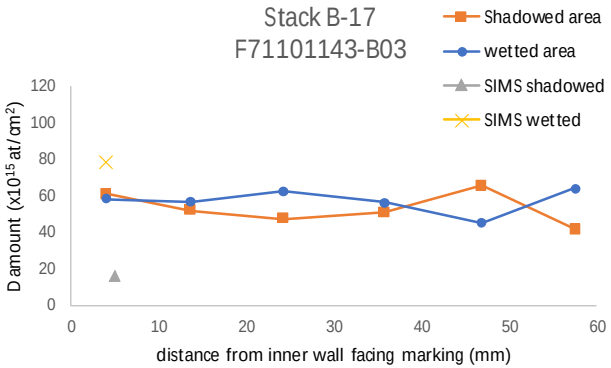
SPE.3 Characterization of JET plasma facing and diagnostics components using SIMS (VTT)

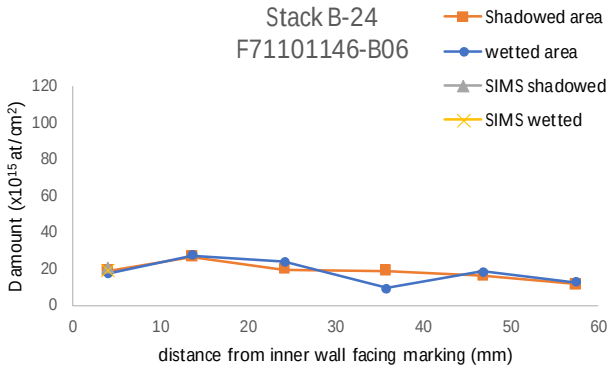












SPE.E3 Characterization of limiter samples and diagnostic components using TDS (UKAEA)

General Information

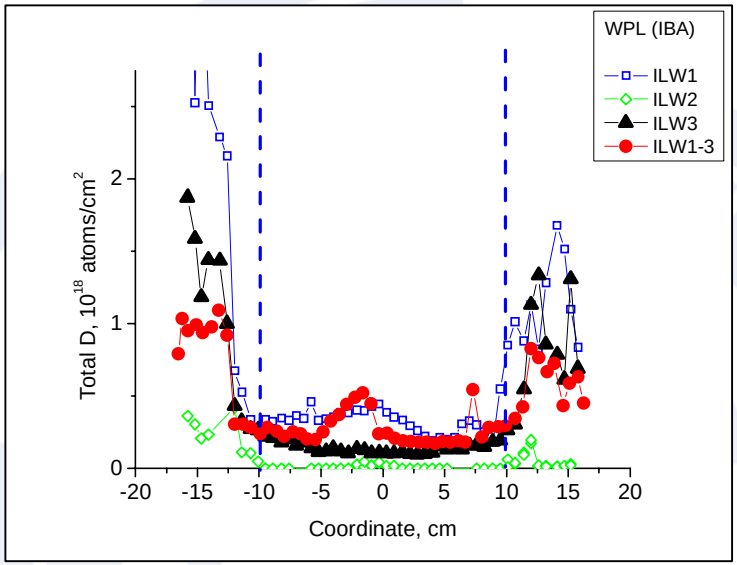
- Comparison of D retention in Be limiter samples after single and multiple ILW campaigns.
- Samples removed after ILW3 → in vessel either during single campaign (ILW3 only) or during all 3 campaigns (ILW1-3).

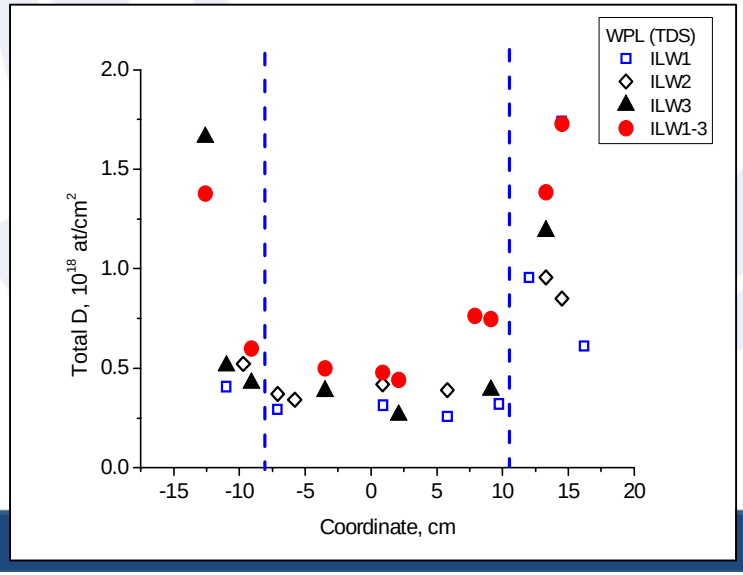
Approach

- IBA and TDS analysis of limiter tiles

Results

- Increase of plasma exposure time leads to non-linear increase of retention.
- Near-surface D content is dependent on recent conditions → near-surface D content is highly susceptible to wall conditioning (GDC, isotope exchange by protium plasma).
- Bulk D content is dependent on cumulative conditions → bulk D content accumulates (increases) even in the presence of wall conditioning.
- Regardless of desorption from near-surface region, D content present within the bulk is being "pushed-in" by combination of ion implantation and increase of temperature during plasma operation.
- Wall conditioning doesn't stop the inward diffusion and eventual permeation.





Concluding remarks

- Preliminary experiments at VTT using JET ILW3 samples were performed
- Several delays in LIBS experiment due to technical issues at UKAEA
- Several visits to UKAEA for setting up the LIBS tool, setup was changed quite a few times (e.g. lenses, cone)
- LIBS experiment at JET was successfully completed in October (840 locations)
- Need to arrange access to the JET data, please let me know if you don't have access
- Data analysis
  - ENEA: Matlab code, how automatic?
  - IPPLM: machine learning and digital signal processing algorithms
  - Coria: MERLIN?
- Planning meeting early 2025
- SP E.2 and E.3 activities have proceeded well and only few tiles/components to be analysed in 2024-25

- DTE3 tiles will be available in spring 2025
- Planning of tile shipments will be made in December 2024
- Type A containers required
- Main activity under SPE is data analysis of JET LIBS spectra
- Additional reference LIBS measurements including few DTE3 samples to be made at VTT (May-June 2025)

Backup slides

SPE.1 LIBS at JET Main Objective and Activities

Scientific question:

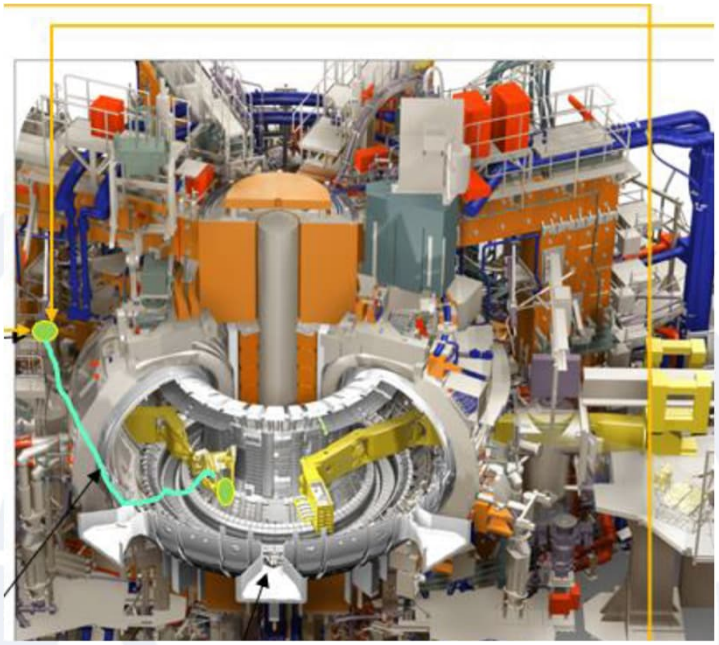
- Task will concentrate on in-vessel analysis (H isotope retention, composition of layers) using LIBS on a remote handling arm at JET

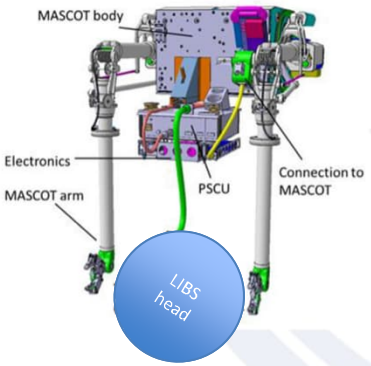
What shall be done:

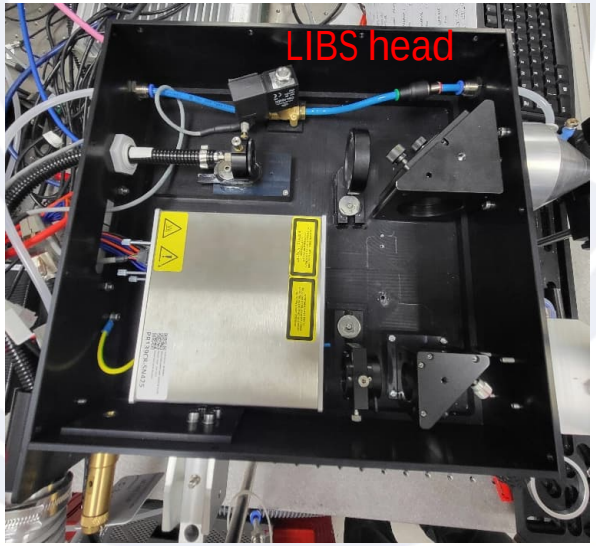
- LIBS experiment at JET in October 2024
- ~870 locations inside JET vacuum vessel will be analysed

Main goals:

- Data analysis of LIBS spectra
- Determine H isotope ratios and composition of co-deposited layers







Involved RU: CU, ENEA, FZJ, IPP_LM, ISPP_UL, UT, VTT
Status: Continuation
Total resources: 27PM

WP collaboration: UKAEA

SPE.2 Cutting of DTE3 tiles and sample distribution

Main Objective and Activities

Scientific question:

- The Task will concentrate on coordination (VTT), sample preparation and sample distribution for DTE3 divertor and limiter tiles, and diagnostics components removed during the 2024 shutdown.

What shall be done:

- Samples from W-coated CFC divertor tiles will be prepared using coring technique (VTT)
- IAP will cut samples from Be limiter tiles and metallic diagnostic components
- Samples will be distributed between RUs participating in SPE programme

Main goals:

- Completion of sample preparation and distribution of samples

Involved RU: IAP, VTT
Status: New
Total resources: 10PM

WP collaboration: UKAEA

SPE.3 Completion of ILW3 post-mortem analyses and first analysis of DTE3 samples

Main Objective and Activities

Scientific question:

Investigation of material migration from the limiters and the main wall towards the divertor resulting in formation of co-deposited layers on the divertor tiles, and characterisation of hydrogen isotope retention including tritium.

What shall be done:

- Post-mortem analysis of ILW3 and DTE3 samples and components using various analysis techniques (ion beams, TDS, electron microsopy…)

Main goals:

- Completion of characterisation of remaining ILW3 tiles and metallic components, and first analyses of JET DTE3 divertor and limiter samples.

Involved RU: FZJ, IAP, IPPLM, ISPP_UL, IST, VR, VTT

Status: New

WP collaboration: UKAEA

Total resources: 9