WPJET2 – Fuel retention

Anna Widdowson
With many thanks to WPJET2 Team

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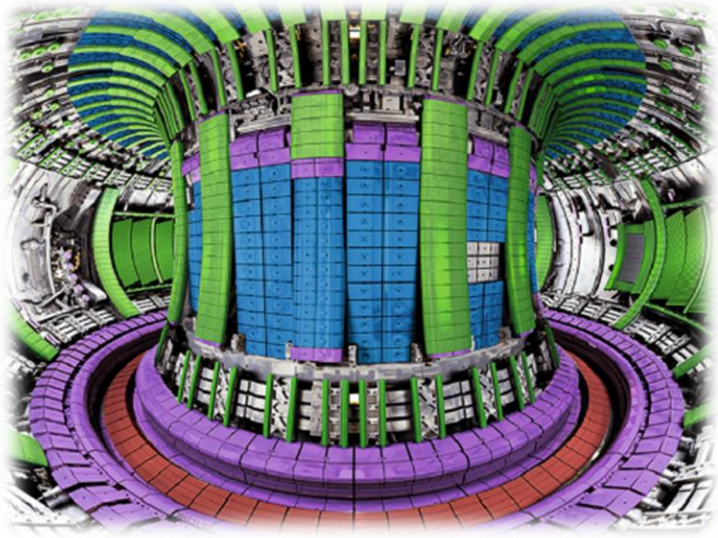
Overview of fuel retention studies in JET after 2015-16

W/CFC Divertor and limiter tiles

Beryllium limiter tiles

Calibration samples for T measurements



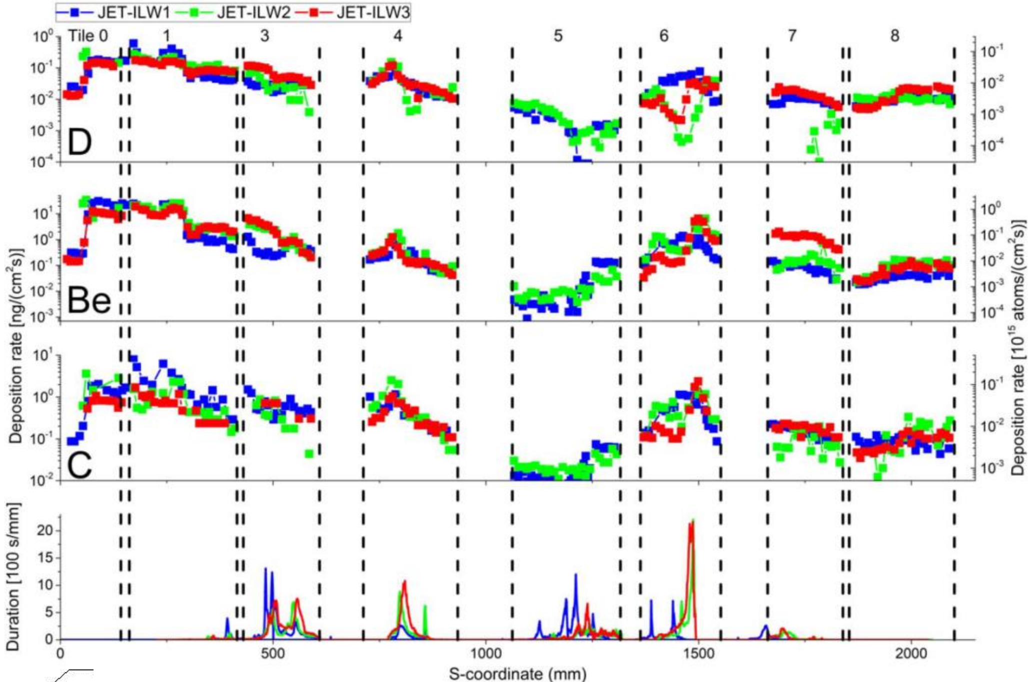
W/CFC Divertor and limiter tiles from 2016-2017 shutdown

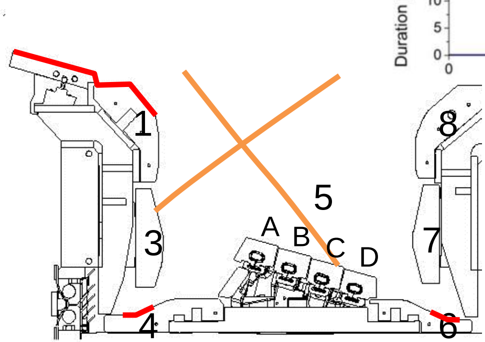
Two successful meetings in 2020 to compare data and identify actions: –
(i) IBA labs & (ii) TDS labs
Full comparison of fuel retention summary in divertor for ILW1, ILW2, ILW3 by IBA
Comparison of cumulative fuel retention – on-going
Fuel retention after long term storage – on-going
Fuel retention from TDS and remaining inventory using NRA – ongoing
OUTLOOK: Work will be completed in 2021

No.	Deliverable description	Organisation	Due date
WC-D-49	IBA of samples from sectioned tiles. Study according to competence & capabilities of laboratories and allocated funding	NCSRD, VR	May-20
WC-D-51	TDS (and full combustion by UoL) of samples from sectioned tiles. Study according to competence & capabilities of laboratories and allocated funding.	CCFE, IAP, UoL	Jun-20
WC-D-54	Shipment of ILW-1 and ILW-2 samples and W/CFC cuts (1/4 samples) after TDS from CCFE to IST for measurements of fuel retention after long-term storage	JOC	Jan-20
WC-D-55	NRA fuel retention measurements after long-term storage	CCFE, IST	Jun-20
WC-D-56	NRA fuel retention measurements in W/CFC samples after TDS	CCFE, IST	May-20

Divertor deposition from ILW-1 to ILW-3

- Qualitatively similar distributions in all campaigns
- Maximum deposition on tiles 0, 1
- Higher deposition on tiles 4, 6 in ILW-2 and ILW-3





S. Krat, Phys. Scr. T171 (2020) 014059
Mayer et al, IAEA-FEC 2020

Divertor deposition from ILW-1 to ILW-3

- More or less constant deposition rate of D
- Slowly varying deposition rate of Be
- Decreasing deposition rate of C from ILW-1 to ILW-3

Deposited mass (g)

	ILW-1	ILW-2	ILW-3
D	0.9	0.7	0.9
Be	53	60	46
C	13	7	6

Deposited mass rate (µg/s)

	ILW-1	ILW-2	ILW-3
D	13	10	11
Be	771	877	544
C	189	102	71

Concentration (at.%)

	ILW-1	ILW-2	ILW-3
D	6.0	4.6	7.4
C	14.6	7.7	8.3

S. Krat, Phys. Scr. T171 (2020) 014059
M. Mayer, IAEA-FEC 2020

Deposition in the tungsten divertor: Cumulative comparison underway

Be deposition and D retention

Comparison for cumulative vs summed data

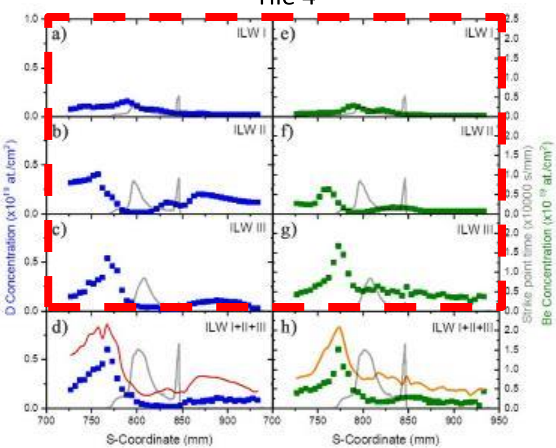
i.e., 2011-16 vs 2011-12 + 2013-14 + 2015-16

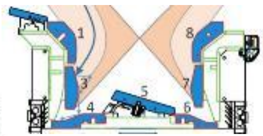
Tile 4 and Tile 6 comparison completed

Other tiles to be accessed – fuel retention and deposition

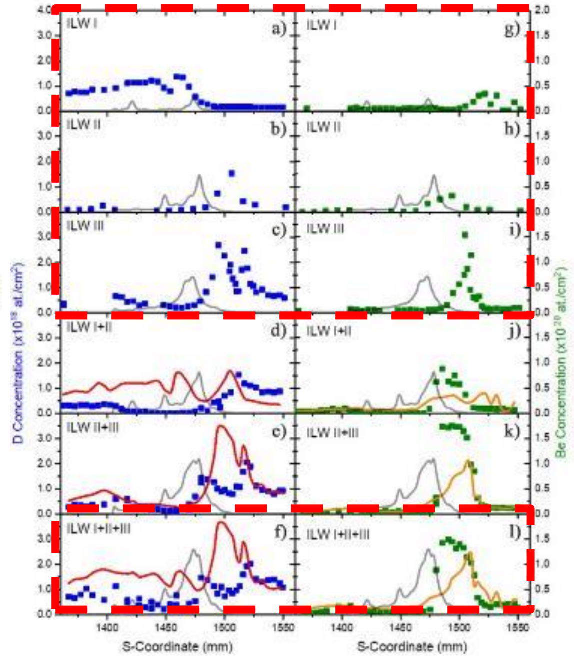
Catarino, Phys. Scr. T171 (2020) 014044

Tile 4





Tile 6



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Comparison of IBA data

Overall good agreement of data from IPP and IAP providing IBA data for WPJET2.

14ING1C Tile 1 (in-vessel 2015-16) - full set of data exists from both laboratories.

IPP – 4 MeV, SIMNRA

IST – 2.3 MeV, WinNDF

Thick films (<300 mm) – good agreement

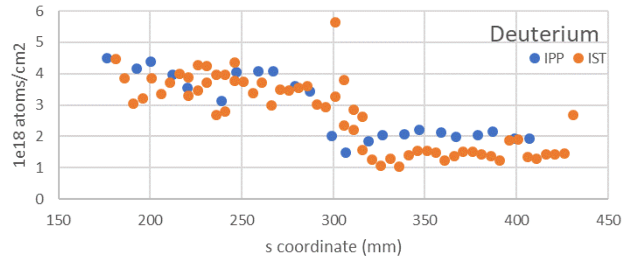
Thin films (>300 mm) – IPP > IST for D,

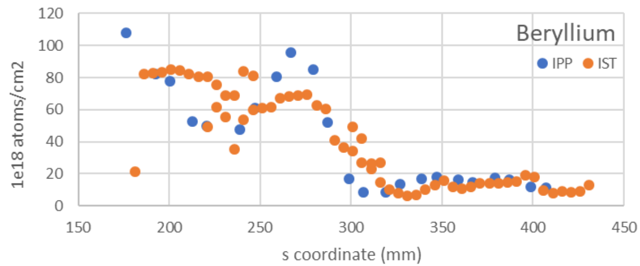
- Greater penetration into W coating surface
- Fuel penetrates into W coating

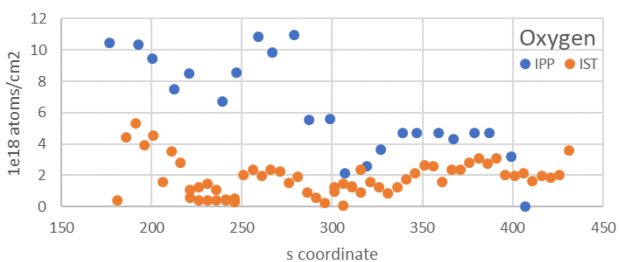
Poor agreement with oxygen

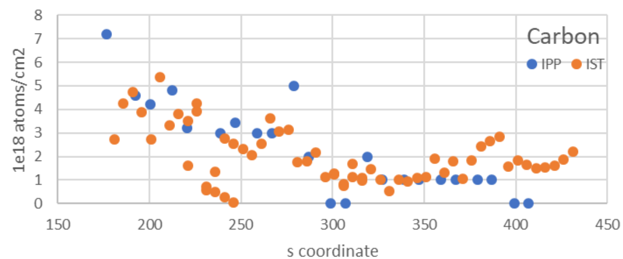
- O resonance at 2.8 MeV accessed by IPP

Next step: Exchange raw data for analysis









Fuel retention after long term storage

Tiles identified for reanalysis: -

- 2BNG4C Tile 4 divertor (in-vessel 2011-12)
- 2IWG3A Tile 1 (in-vessel 2015-2016)
- 2B4C beryllium dump plate (in-vessel 2013-2014)

Reanalysis on-going, to be followed by comparison of data measured previously.

Analysis of tritium containing DTE1 samples: SIMS, TDS, pyrolysis, IBA

MkIIA DTE1 divertor tiles: Tritium analysis and retention after long term storage

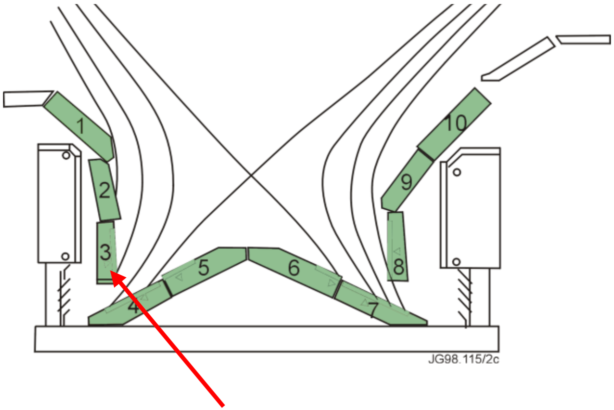
Tiles 3 (6IN3) and 4 (4BN4) exposed during DTE1

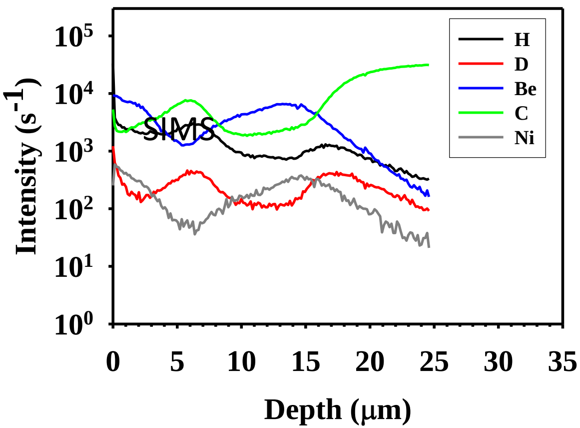
Samples cored in VTT in December 2019

SIMS, TDS, pyrolysis and IBA

SIMS analyses

- Co-deposited layer spalled off in some areas of the tiles due to long storage and handling (~20 years)
- Layered structure on sample from bottom of tile 3, layer thickness ~18µm.
- D retained in co-deposited layer and at interface between co-deposit and CFC tile.
- SIMS profiles for D will be quantified using TDS and ion implanted Be sample





TDS comparison of pre-DTE1 and DTE1 samples

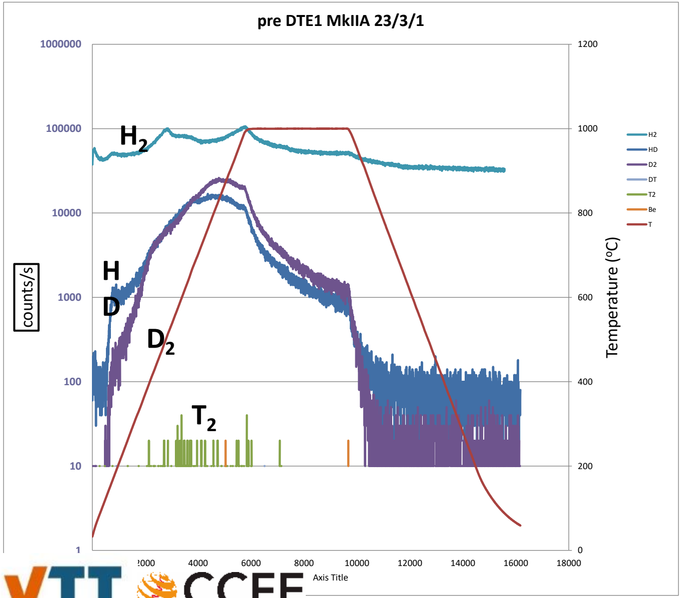
Mass 5 and 6 in DTE1 sample attributed to DT and T_2

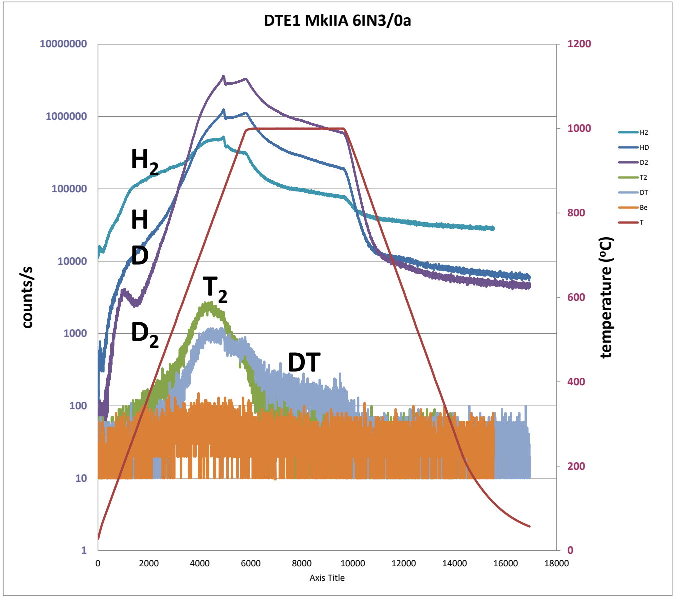
Cross calibration with pryolysis of DTE1 sample & TDS of tritiated sample at CCFE

NRA for deuterium retention completed at IST

- Tile exposed in 1996 before DTE1 campaign
- no DT signal, T_2 and Be signals very small
- D amount: 2.8E17 cm^{-2}

- Most likely mass 5 and 6 represent DT & T_2
- D amount: 1.1E19 cm^{-2}
- T amount: 1.9E16 cm^{-2}



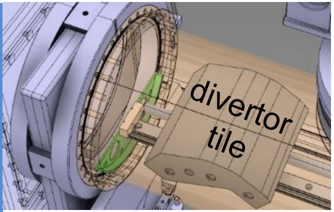


LID and TDS of JET samples in FZJ: FREDIS status

FREDIS (Fuel Retention Diagnostic Setup): designed for JET tile analysis

Two thermal release methods: **laser heating (LID)** and **oven heating (TDS)**

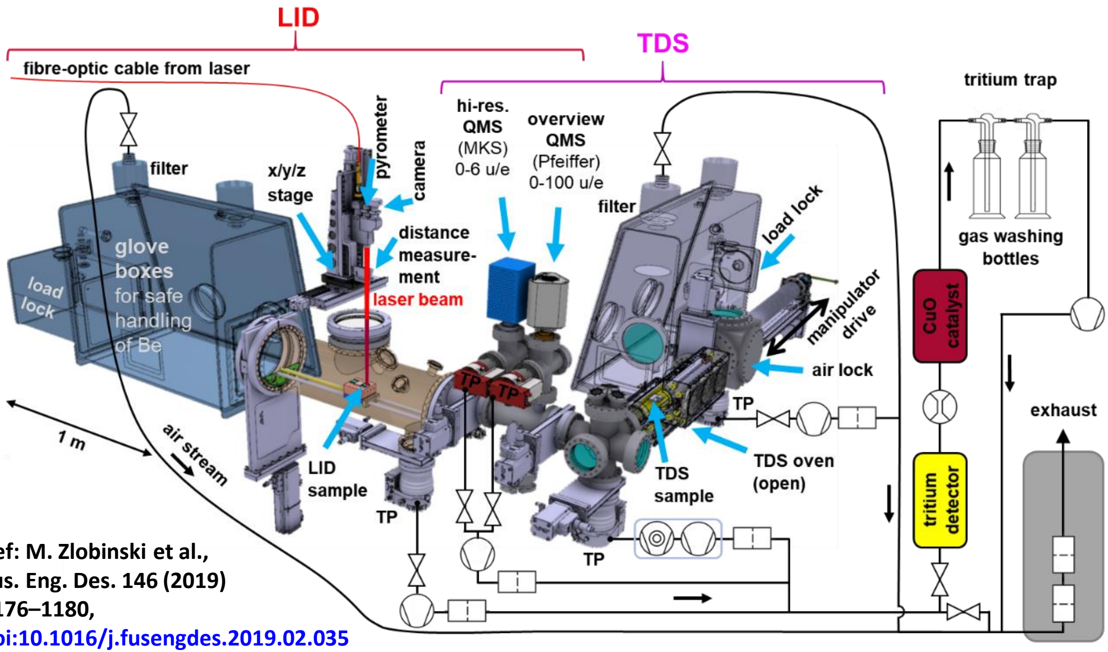
Common quantification by Quadrupole Mass Spectrometry (QMS)



2019-2020: upgrade to Be and tritium **completed**

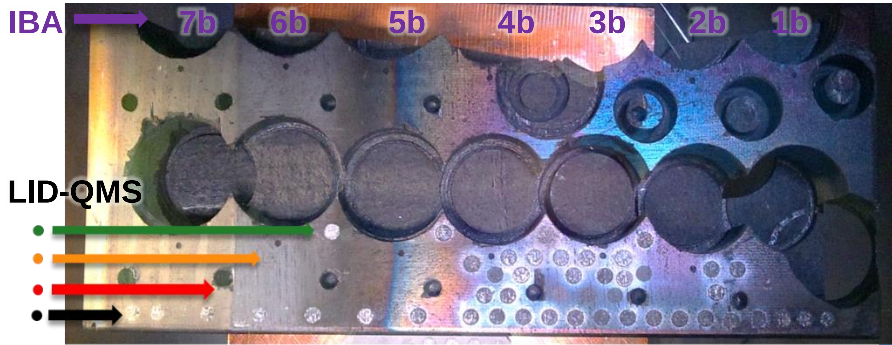
fully PLC-controlled tritium cleaning incl. tritium trap **in operation**

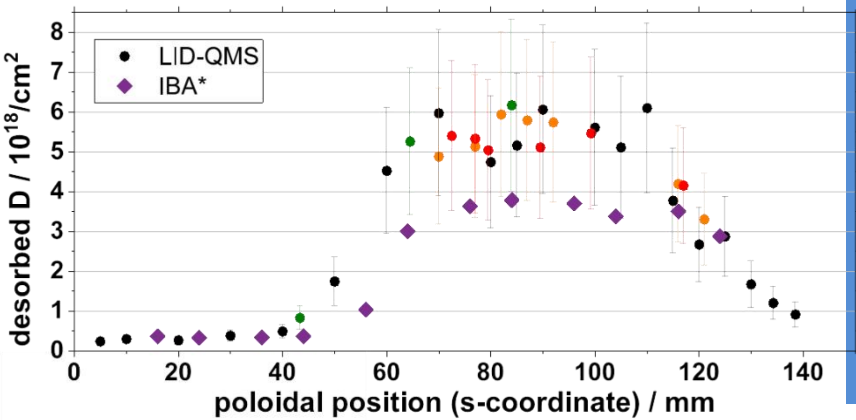
tritium handling limit of lab: 2.5E10 Bq for gaseous T 2.5E13 Bq for bound T



Ref: M. Zlobinski et al., Fus. Eng. Des. 146 (2019) 1176–1180, doi:10.1016/j.fusengdes.2019.02.035

Fuel retention analysis: Laser-Induced Desorption (LID)





Sample: Tile 0 (=HFGC 14 N LH) after ILW-3 campaign

Spots 3 mm diameter heated by one short laser pulse (1-5 ms pulse duration)

Desorbed gases quantified by Quadrupole Mass Spectrometry (QMS)

Complete D desorption reached at >1 MJ/m^2 incident laser energy density with 1 laser pulse/position

next samples:
divertor Tile 1 (14 IN G1 C ILW-3), Be limiter (2XR10), W lamellae

This LID-QMS method is in preparation to be applied *in situ* in JET and ITER.

- ❖ LID-QMS retention results agree quite well with IBA*
- ❖ IBA values lower probably due to different toroidal position at the end of deposition region (in cores 1b-7b)

***Ref: S. Krat et al, Phys. Scr. T171 (2020) 014059 doi:10.1088/1402-4896/ab5c11**

Beryllium limiter tiles from 2016-2017 shutdown

Two successful meetings in 2020 to compare data and identify actions: –
(i) IBA labs & (ii) TDS labs

Full comparison of fuel retention summary in divertor for ILW1, ILW2, ILW3 by IBA

Comparison of cumulative fuel retention – completed

Fuel retention after long term storage – on-going

Fuel retention from TDS and remaining inventory using NRA – **COMPARATIVE STUDY**

Tritium analysis – TDS, dissolution, others... – **COMPARATIVE STUDY**

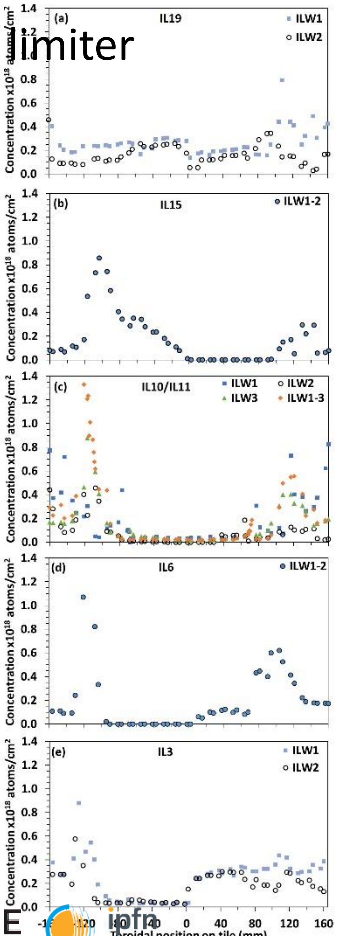
DELAY: Distribution of ILW1-3 Be samples from WPL and DP in November 2020

OUTLOOK: Work will be completed in 2021

No.	Deliverable description	Organisation	Due date
Be-D-73	IBA of Be samples after TDS	IST	May-20
Be-D-65	Shipment of samples to laboratories	JOC, CCFE	Apr-20
Be-D-66	Dissolution for tritium depth profiling	UoL	Jul-20
Be-D-67	TDS and full high temperature outgassing of samples from sectioned tiles. Study according to competence & capabilities of laboratories and allocated funding.	CCFE, IAP, UoL	Jul-20
Be-D-69	Deuterium micro-beam analysis of carbon on plasma-facing surfaces and in the castellation: 3 samples	NCSRD	Aug-20
Be-D-70	Reports	All involved	Feb-20
Be-D-71	Return of all samples to CCFE	All involved	Oct-Nov-20

Fuel retention in beryllium limiters

Inner limiter



Fuel retention in beryllium limiters completed

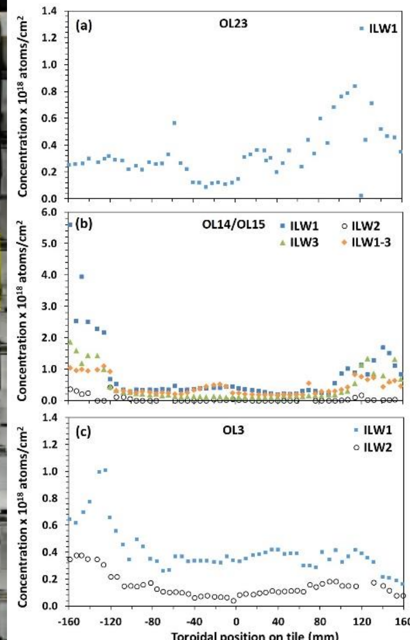
D retention is concentrated in deposits on the ends of limiter tiles in the mid-plane region

Deuterium retention lowest in high heat load/erosion areas at midplane inner/outer limiters & dump plate ridge

Higher fuel retention in outer limiter compared with inner limiter

Deposits for ILW1-3 tiles thicker than analysis depth therefore total deuterium underestimated

Outer limiter



Widdowson, (2020). Physica Scripta, T171, 014051. https://doi.org/10.1088/1402-4896/ab5350

Global fuel retention in beryllium limiters

Contribution to total fuel retention in surface of beryllium limiter tiles <0.03%

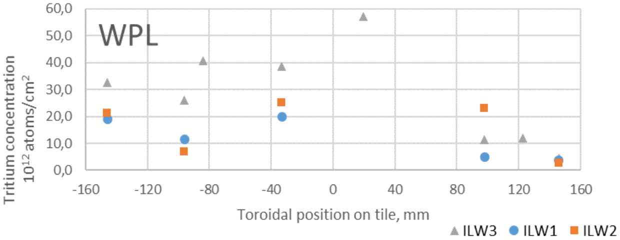
	ILW1	ILW2	ILW3
Total D atom puffed*	$2.6x10^{26}$	$2.6x10^{26}$	$2.2x10^{26}$
Inner limiter	$1.4x10^{22}$	$0.8x10^{22}$	$1.2x10^{22}$
Outer limiter	$5.2x10^{22}$	$0.8x10^{22}$	$3.2x10^{22}$
Dump plate	$1.2x10^{22}$	$0.9x10^{22}$	$1.6x10^{22}$

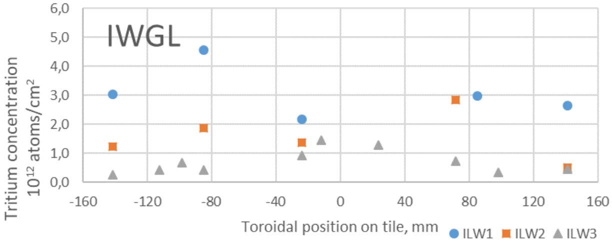
* JET gas inventory, GIMs only, 300K

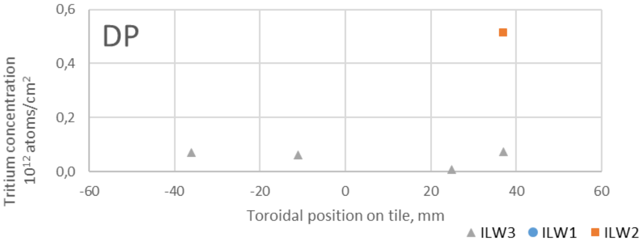
Widdowson, (2020). Physica Scripta, T171, 014051.
https://doi.org/10.1088/1402-4896/ab5350

Tritium in the beryllium limiter tiles – ILW1,2&3

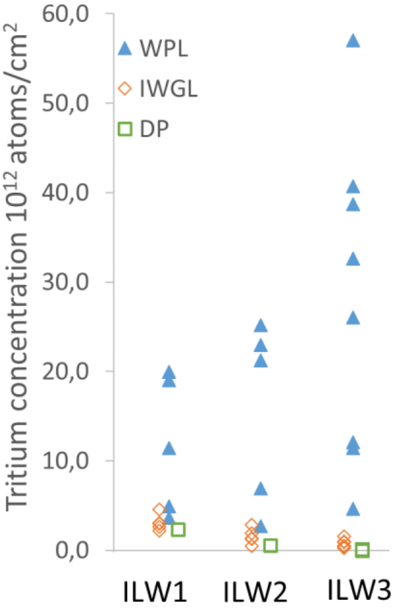
Tritium concentration distribution across the tiles

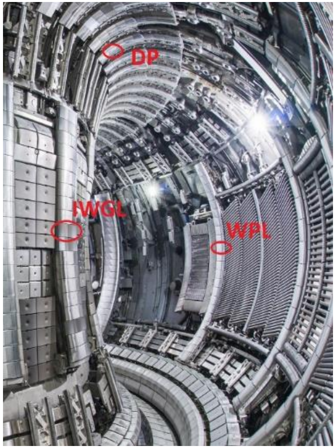






Summary of tritium concentration in tiles





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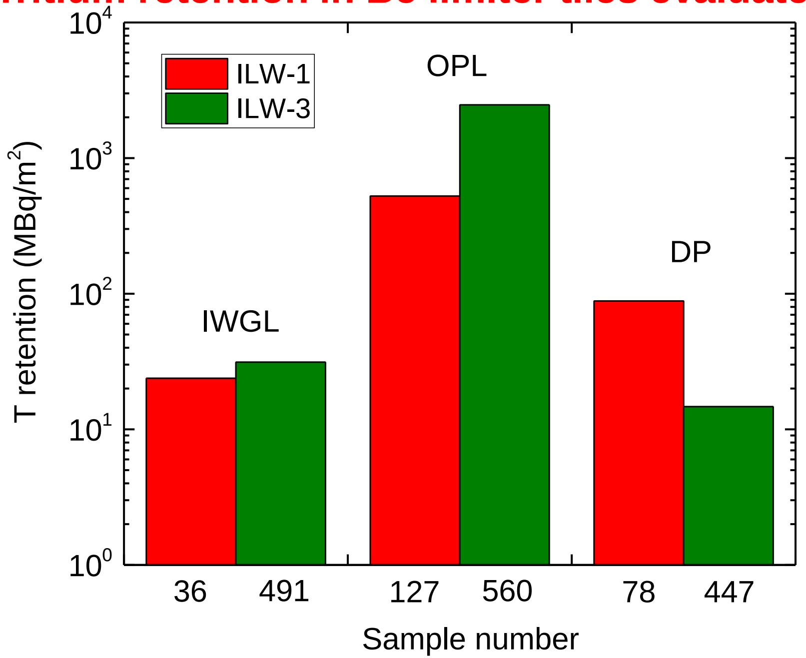
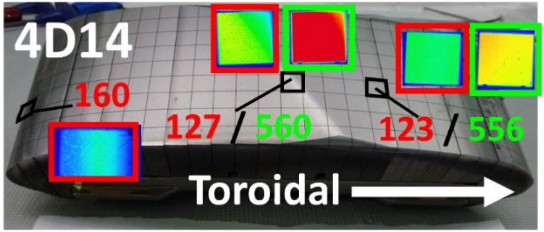
Highest T concentrations are in outer wall tile (WPL) – as for deuterium
Lowest T concentrations in upper part of the vessel (DP)

Global Tritium distribution by radiography (Tritium Imaging Plate)

Tritium retention in Be limiter tiles evaluated from the radiation intensity.



IWGL – Inner Wall Guard Limiter
OPL – Outer Poloidal limiter
DP – Dump Plate



ILW-1 ILW-3

PSL intensity

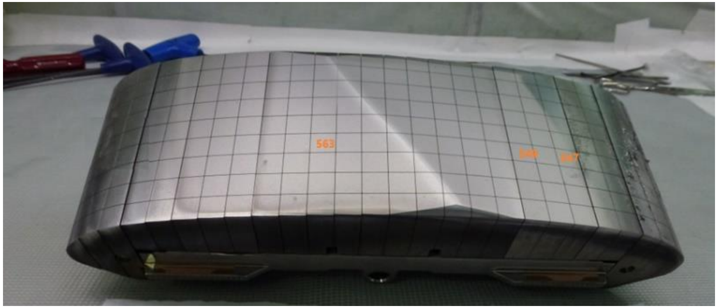
low high

Highest T content is found in the surface region of outer poloidal limiters.

Comparison of tritium measurement methods

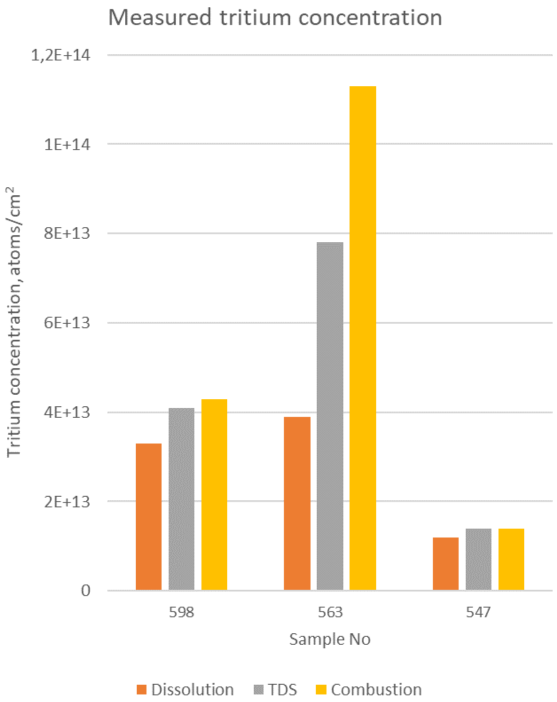
Three samples cut in 4 pieces to perform 4 different tritium measurements (QMS data is being processed)

TDS (scintillation counter), QMS, combustion and dissolution



Tritium concentration, atoms per cm ^{2}

Sample	Dissolution	TDS	Combustion
598	$3.3 \cdot 10^{13}$	$4.1 \cdot 10^{13}$	$4.3 \cdot 10^{13}$
563	$3.9 \cdot 10^{13}$	$7.8 \cdot 10^{13}$	$11.3 \cdot 10^{13}$
547	$1.2 \cdot 10^{13}$	$1.4 \cdot 10^{13}$	$1.4 \cdot 10^{13}$



Surface tritium measurements: beta detector

- Samples mounted in a jig to maintain 2 mm between the sample surface and the detector window
- β radiation emission of T distributed on the sample surface in 2π direction measured;
- Surface activity calculation from reference samples:

$$A=R\cdot 2\cdot 100/\mu$$

A = activity (Bq), R = CPS in 2π of the detector,
2 = conversion factor 4π/2π, μ = efficiency (%).

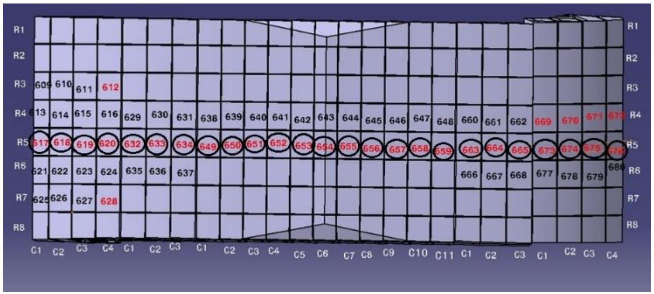
Tritium surface monitor **LB 1230UMo** with LB 1230 open window gas flow proportional counter detector,
Berthold type (USA)

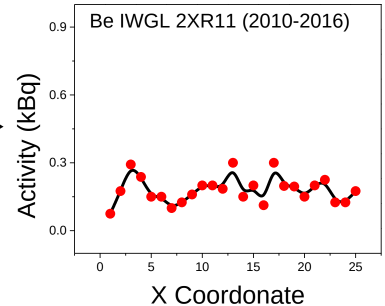
Surface tritium analysis: beta detector

T measurements and determination T content on *ILW1-3* Be tiles

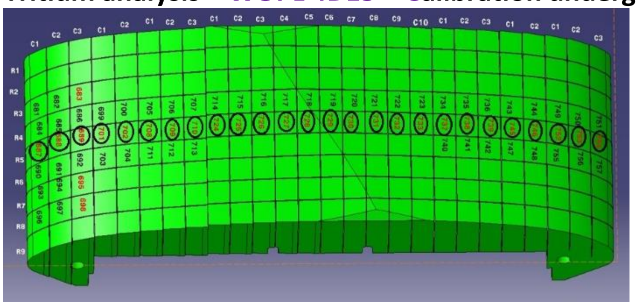
T activity higher on outer limiter than inner limiter

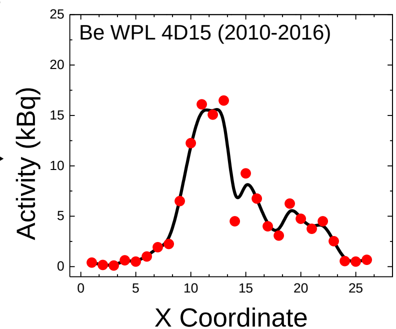
Tritium analysis – IWGL 2XR11– Calibration undergoing





Tritium analysis – WOPL 4D15 – Calibration undergoing





Comparison of TDS results on Be limiter tiles

- AIM 1 – to compare the results of the TDS measurements taken on “identical” samples in different labs.

- AIM 2 – to compare the results of the measurements of tritium content between different techniques.

- SAMPLES – castellations cut from Be limiter tiles and Be upper dump plate, all removed after ILW3 campaign 2015-2016 → cut into four “quarter-pieces”.

- LABS:
  - IAP (Romania) – sample prep (cutting with a slow dry saw) and TDS.
  - FZJ (Germany) – TDS.
  - CCFE (UK) – TDS.
  - University of Latvia – dissolution (for tritium).
  - IST (Portugal) – IBA.

Analysis plan

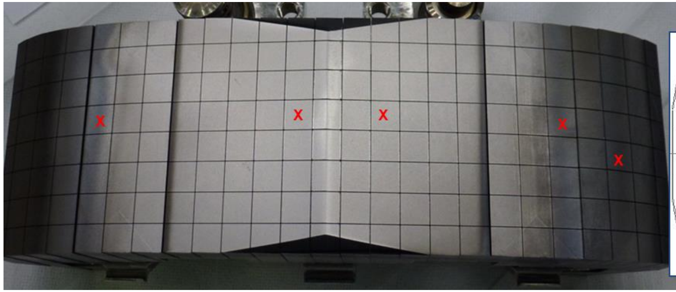
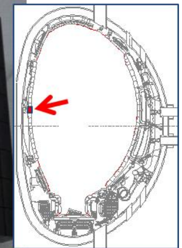
- TDS measurements comparison:
  - ➢ Compare total deuterium content.
  - ➢ Compare shapes of the spectra and positions of peaks.

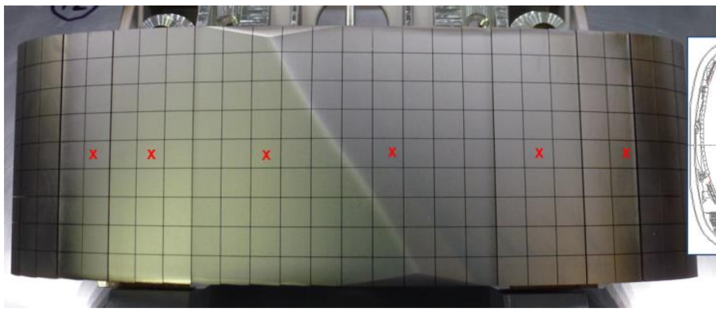
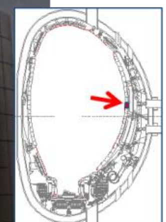
- Tritium measurements comparison: **TDS** vs **dissolution**
  - ➢ Compare total tritium content.

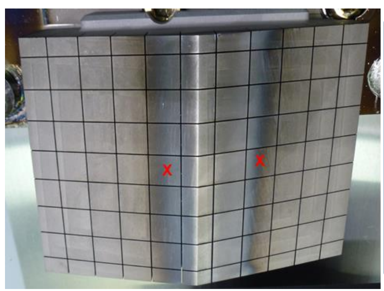
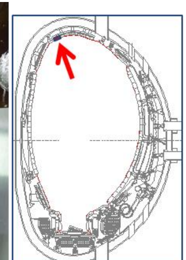
- Comparison of TDS and IBA:
  - ➢ Compare total deuterium content.

- Determination of retained content after TDS with IBA: **IST**.
  - ➢ IBA before TDS.
  - ➢ IBA after TDS.
  - ➢ Determination of the fraction of deuterium that wasn't released during TDS run.

Castellation samples from ILW3 Be tiles

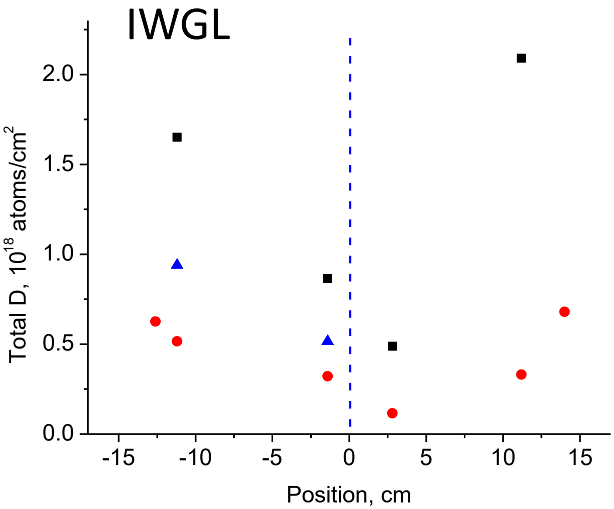



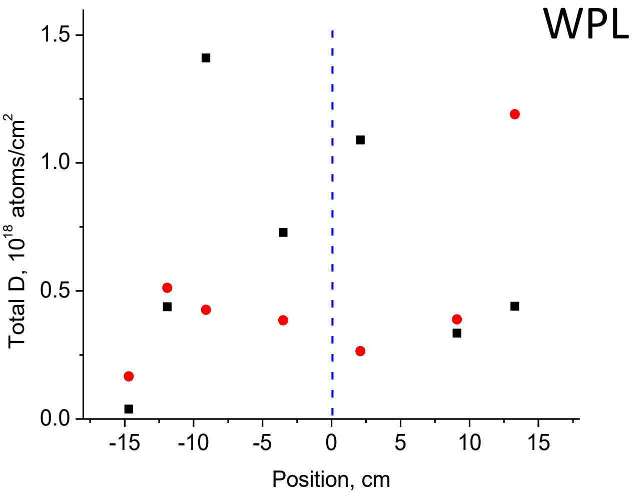



Comparison of deuterium content

D content same order of magnitude

Maximum difference factor 5, generally factor 3 - 4

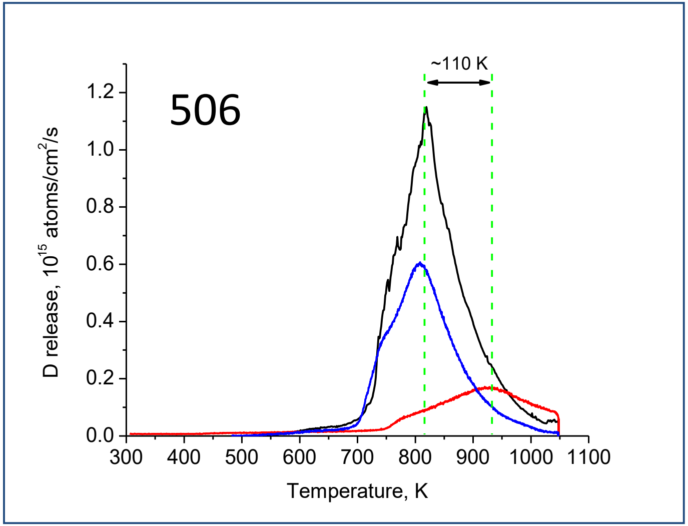


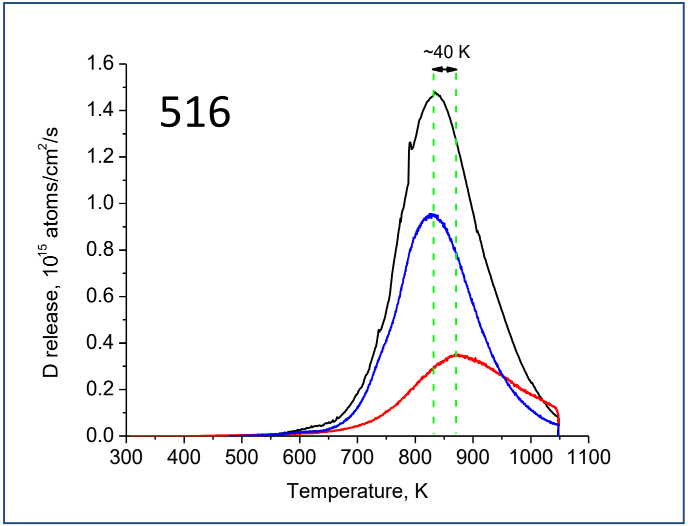


Comparison of deuterium spectra – IWGL

Variation in heating

Variation in total desorption

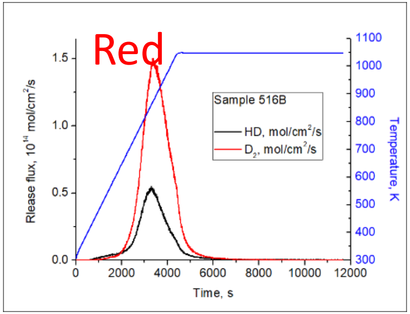


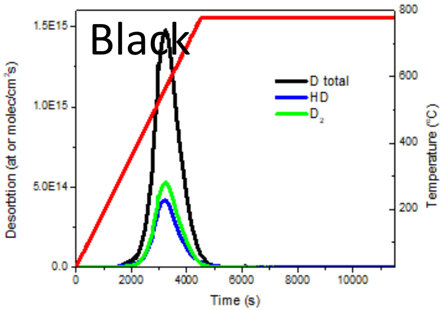


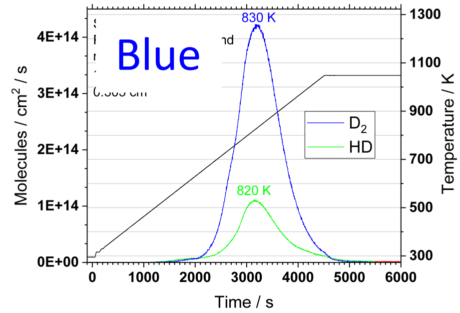
Comparison of the contribution of HD

Variation of D2 & HD ratios

	Red	Black	Blue
	UDP		
465	22.63	31.38	
	IWGL		
483	14.36	24.52	
503	24.61	31.01	
506	25.95	31.71	26.54
516	16.05	30.19	11.93







Observations

Each lab knows which area to work on!

Total inventory

- ➢ Same order of magnitude
- ➢ Variations up to factor 5
- ➢ Calibration
- ➢ ALSO different quarters are not completely identical

Variations in desorption spectra

Shapes of the spectra are comparable

- ➢ Similar profile changes between labs

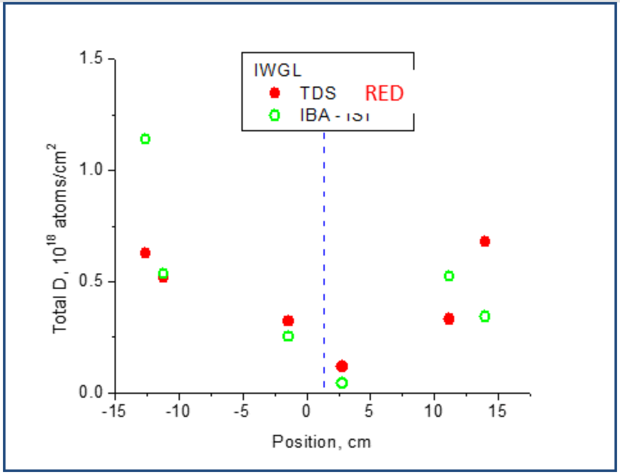
Shift in position of maxima

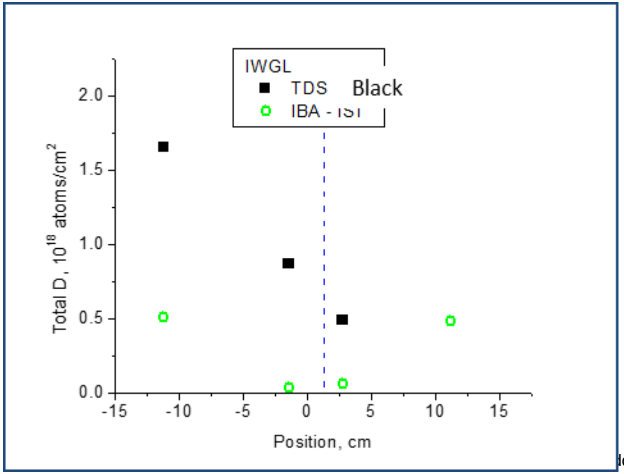
- ➢ Temperature uncertainty particularly at high temperature

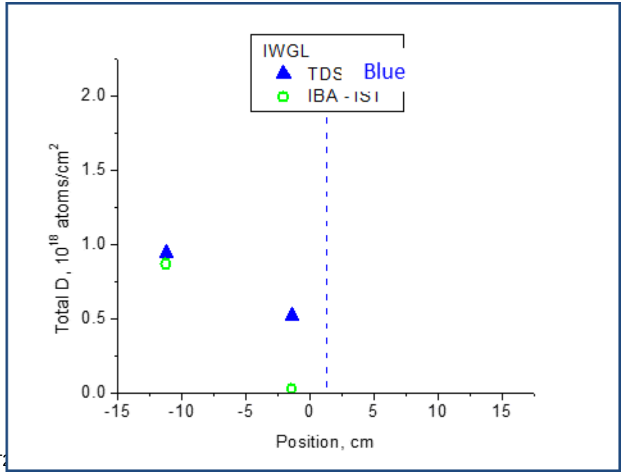
Comparison with IBA – Fuel inventory

Overall trends determined by IBA of quarter samples coincide with those determined by TDS.

Mostly total inventories determined by TDS are higher than those determined by IBA.







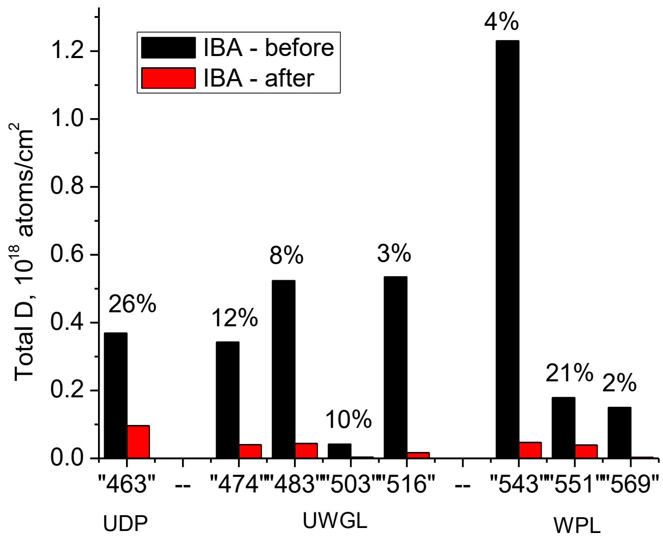
Comparison with IBA – Fuel remaining after TDS

IBA data before and after TDS

First few samples, more to be analysed

Significant proportion of deuterium still present after the TDS in these samples

Two samples identified to heat to 1000°C instead of 775 ° C



Comparison of tritium content in beryllium samples

Tritium measurements comparison: **TDS** (CCFE, IAP, FZJ) vs **dissolution** (UoL)

Only data where comparison between TDS and dissolution is shown

Analysis of other samples ongoing

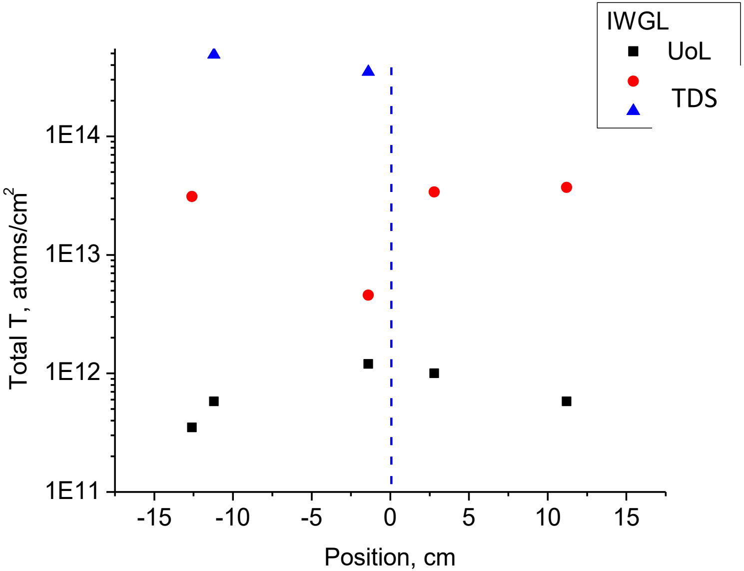
	Sample ID	Black T atoms/cm²	Red T atoms/cm²	UoL T atoms/cm²	Blue T atoms/cm²
DUMP PLATE	460		x	**$5.9*10^{9}$**	
	463		x	$4.9*10^{11}$	
	465	x	$1.25*10^{13}$	**$5.6*10^{10}$**	
	483	x	$3.71*10^{13}$	$5.8*10^{11}$	
	503	x	$3.39*10^{13}$	$1*10^{12}$	
	506	x	$4.58*10^{12}$	$1.2*10^{12}$	$3.5*10^{14}$
	516	x	x	$5.8*10^{11}$	$4.9*10^{14}$
	524		$3.11*10^{13}$	$3.5*10^{11}$	
WPL	543	x	x	$1*10^{13}$	
	569	x	x	$4.8*10^{13}$	
	580	x	x	$3.3*10^{13}$	

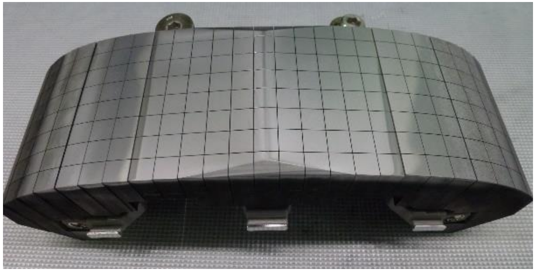
Conclusions – tritium analysis of beryllium samples

Large variation in tritium data between TDS and dissolution

- ➢ Usefulness of TDS for this level of T inventory uncertain.
- ➢ Dissolution → T distributions obtained.

Continuation of T reference samples work → better understand the detection limits (see later).





Calibration samples for T measurements

Design and manufacture mirror-like H, D, He-implanted samples to be used in the calibration of masses 2, 3 and 4 for TDS of PFC with low T contents

Design and manufacture H,D, He-containing deposited layers to be used in the calibration of masses 2, 3 and 4 for TDS of PFC with low T contents

Manufacture tritiated samples for calibration

Determine H,D,He content in implanted and plasma-deposited samples with ToF ERDA

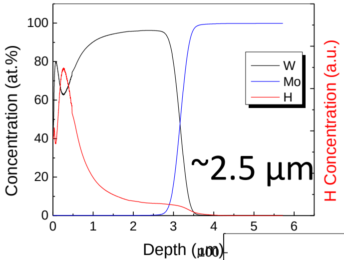
Determine T content in the tritiated samples

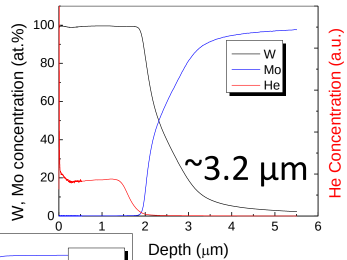
OUTLOOK: Analysis will be completed end 2020/early 2021

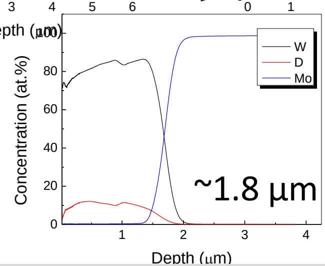
No.	Deliverable description	Organisation	Due date
TM-01	Production of 20 Mo mirror-like samples, diameter 10 mm, thickness 3 mm	VR [IAP]	Nov-19
TM-02	Coating of Mo mirrors with 1-2 µm layer of W	VR [IAP]	Dec-19
TM-03	Implantation of mirrors with H, D, He	VR (16),VTT (8)	Dec-19 – Jan20
TM-04	Surface analyses with NRA and ToF ERDA: one sample from each production batch	VR, VTT	Feb-20
TM-05	Perform TDS with implanted calibration samples	CCFE, IAP, UoL	Mar-Apr-20
TM-06	Production of magnetron-deposited W layers containing H,D, He (deposition on mirror like surfaces)	IAP	Dec-20
TM-07	Surface analyses with NRA and ToF ERDA: one sample from each production batch	VR [IST]	Feb-20
TM-08	Perform TDS with implanted calibration samples	CCFE, IAP, UoL [FZJ]	Jul-20
TM-09	Manufacture tritiated samples for calibration of T measurements and determine T content	IAP	Jan-20
TM-10	Perform TDS with implanted calibration samples. [T]	CCFE, IAP, UoL [FZJ]	Sep-20
TM-11	Reports	All involved	Oct-20

Reference sample preparation by *HIPIMS* at IAP

Production of magnetron-deposited W - IAP
Layers containing H, D, He
Analysis by GEDOES & TDS







Analysis by ERDA, NRA, RBA at VR and IST

ToF ERDA (preliminary):
EU2-34: Hydrogen 1.18 at%
EU2-35: Helium 13.6 at%
EU2-36: Deuterium 1.67 at%, Hydrogen 0.40 at%

RBS:
34: 2.3×10^{19} /cm² (3.7µm)
35: 1.1×10^{19} /cm² (1.8 µm)
36: 1.9×10^{19} /cm² (3.0 µm)

NRA: EU2-36: 8.8×10^{17} D/cm² (in 3.0 µm assuming a density of 19.6 g/cm³)

Reference sample (Mo) preparation by LEIS at VR

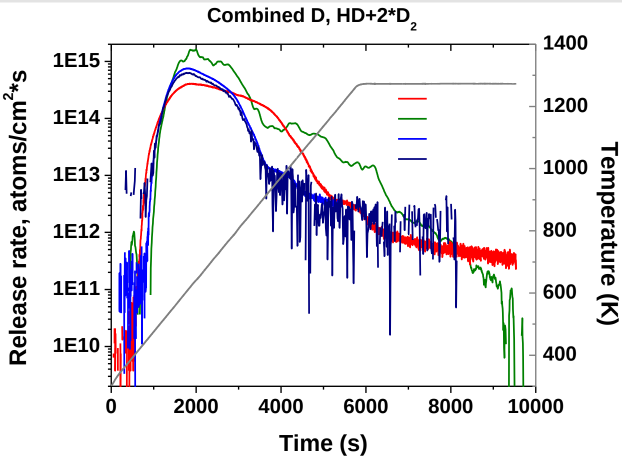
Irradiation with Helium

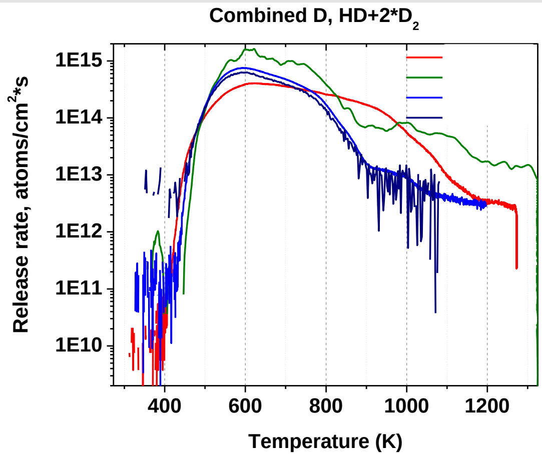
Analysis - not done yet
Typically 10% retention

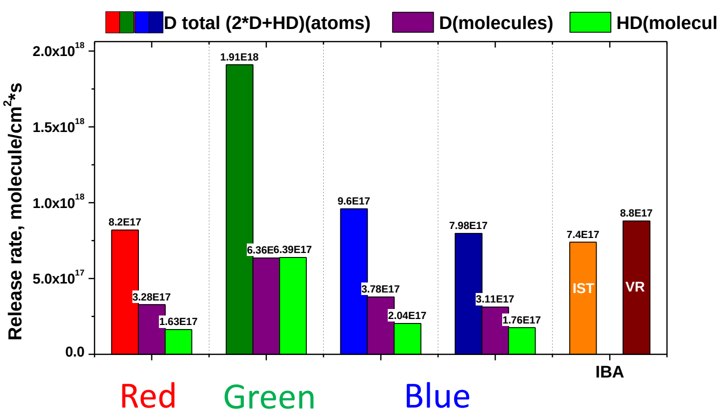
Irradiation with Deuterium

Measured concentration:
2.5×10^{16}/cm²

W-D sample (HIPIMS) TDS comparison – TOTAL D

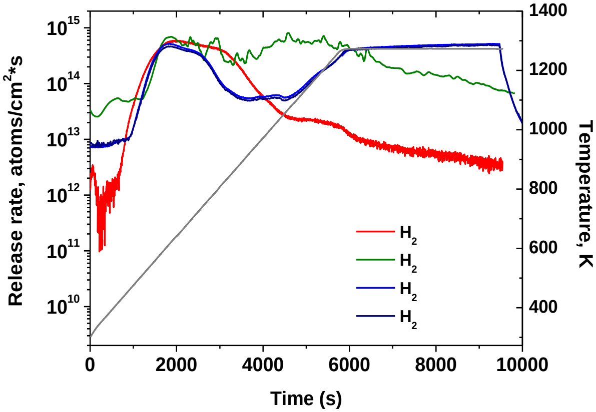


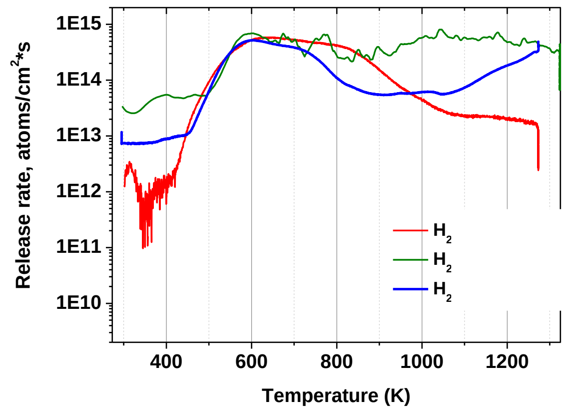


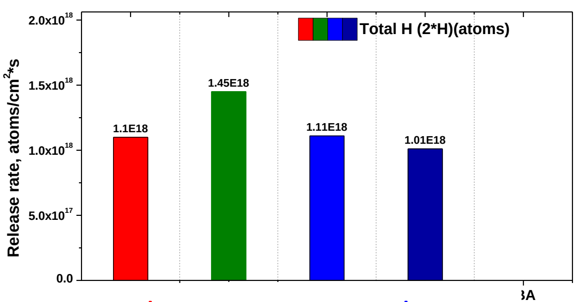


Facility	TOTAL Inventory: D atoms/cm²
RED	$8.2*10^{17}$
GREEN	$1.9*10^{18}$
BLUE	$9.6*10^{17}$
BLUE	$7.9*10^{17}$
IBA (IST)	$7.4*10^{17}$
IBA (VR)	$8.8*10^{17}$

W-H sample (HIPIMS) TDS comparison – H signal



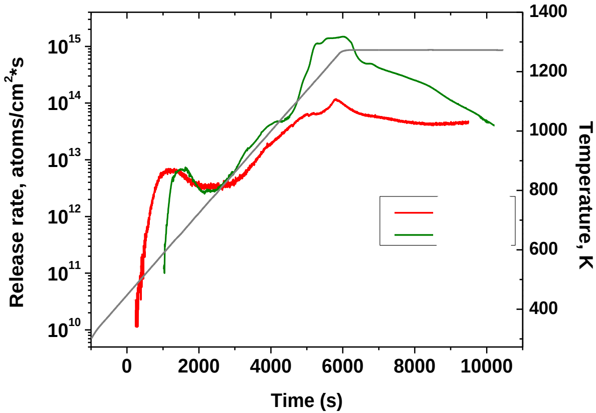


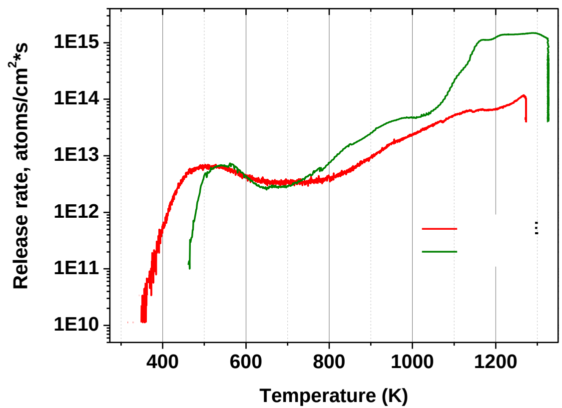


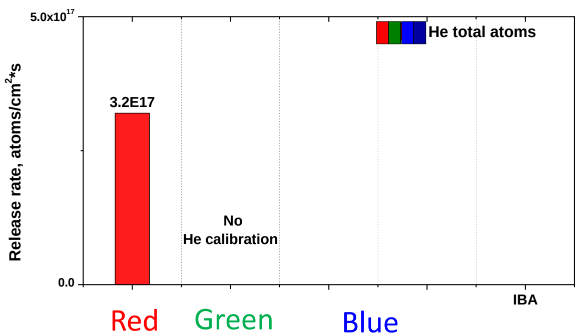
Red Green Blue

Facility	TOTAL Inventory: H atoms/cm^2
RED	$1.1*10^{18}$
GREEN	$1.45*10^{18}$
BLUE	$1.11*10^{18}$
BLUE	$1.01*10^{18}$
IBA	

W-He sample (HIPMIS) TDS comparison – He signal







Facility	TOTAL Inventory: He atoms/cm²
RED	$3.2*10^{17}$
GREEN	No calibration
BLUE	
BLUE	
IBA	

TDS reference sample conclusions

Inventory values within factor 2.2

- Similar values as compared with IBA data

Temperature peak positions

- Low temperature peak position is almost identical for all facilities
- 2nd peak varies – discrepancy at higher temperatures

Useful comparison for all laboratories to improve measurements

OUTLOOK: Remaining HIPIMS and implanted reference sample analysed by end 2020/early 2021

Analysis of tritiated samples

Sample preparation at IAP

IAP	2 micron 100% W, Tritiated with desired T content	Mo	10 mm x 10 mm surface 1 mm thickness 10 mm x 10 mm 3 mm thickness for LID	4e14 atoms T (250 kBq) 4E17 T atoms (160 MBq)	1. W coating performed 2. Tritiation calibration performed 3. Tritiation performed	IAP - surface analysis using Tritiated testosterone polystyrene matrix as reference. IAP - Total combustion IAP - Total combustion	CCFE 3 (TDS/Pyrolysis/offgas) IAP 3 (Surface analysis/total combustion/TDS) FZJ 4 (2 LID - 3 mm, 2 TDS) Latvia 3 (TDS/QMS/Dissolution) HR 2 (D beam IBA)

Analysis – December 2020

TDS:

10K/min RT to 1000 deg C, holding @1000^0 C for 1 hour, CCFE, FZJ *, IAP, UoL^

*FZJ to measure multiple samples due to sensitivity issues

^UoL to start with 5K/min for safety reasons (1/4 sample) – based on first quarter results, Decision to run at 10K/min

Full combustion/dissolution:

UoL - technical details tbc

IAP - technical details tbc

LIDS:

FZJ - technical details tbc

Other deliverables on-going

Be-coated Inconel tiles from the inner wall cladding

No.	Deliverable description	Organisation	Due date
IN-D-26	Outgassing, Tritium measurements	UoL	Jul-20

Tungsten lamellae, Tile 5 after ILW-3

No.	Deliverable description	Organisation	Due date
WL-D-33	IBA: NRA and EPS	IPP, VR	May-20
WL-D-40	TDS	CCFE, IAP	Jun-20

Dust from vacuum cleaning and deposited on dust monitors

No.	Deliverable description	Organisation	Due date
D-D-22	Chemical composition (QMS, FTIR) and tritium content	UoL	Jun-20

Conclusions

Majority of deliverable on fuel retention have been completed.

Main fuel retention conclusions from WPJET2 achieved and published

COMPLETED

Analysis of fuel retention in divertor tiles ILW1, ILW2, ILW3 and some cumulative data

Analysis of fuel retention in limiter tiles ILW1, ILW2, ILW3 and cumulative data

Collaboration through IBA and TDS dedicated workshops to consolidate results

ON-GOING

Measurement of fuel retention after long period - IBA

Continue comparison of cumulative data for divertor tiles

Final TDS analyses

Final tritium analyses

OUTLOOK

All deliverables will be completed during 2021

CHALLENGE

Converge on data to produce JET-ILW overview on material migration, fuel retention and surface modification from plasma interaction