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Analysis of full WEST divertor tiles after C4 campaign by TOF ERDA

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**http://west.cea.fr/WESTteam*

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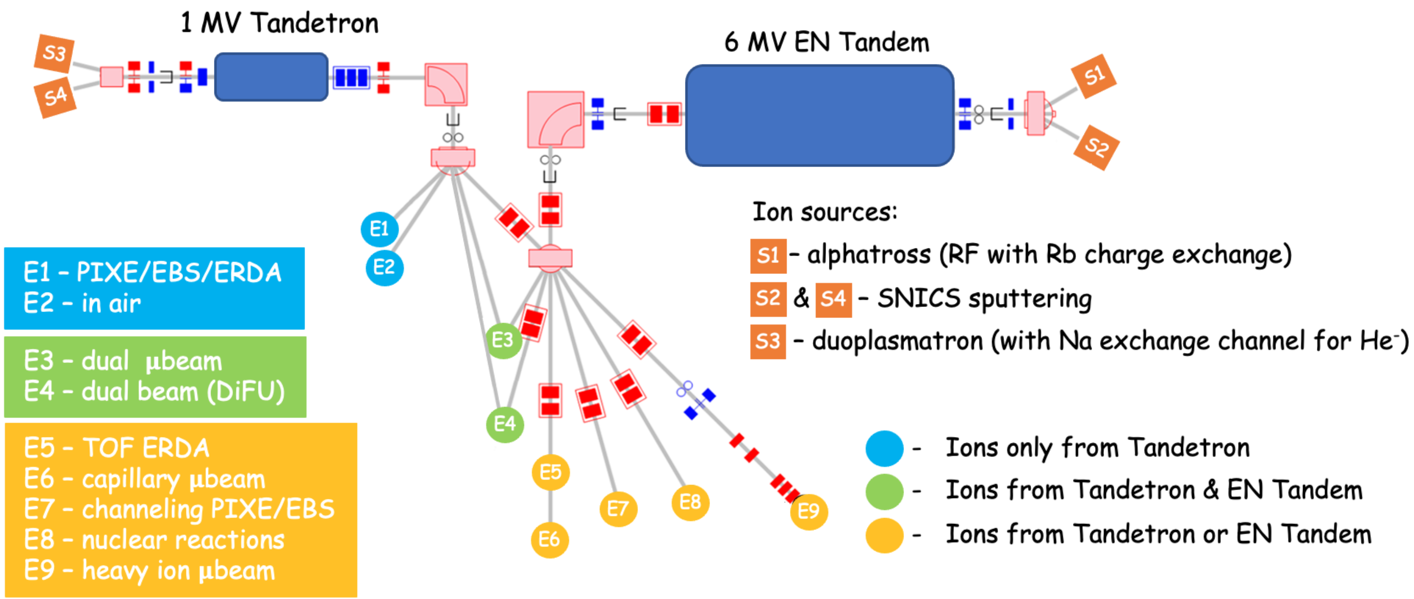
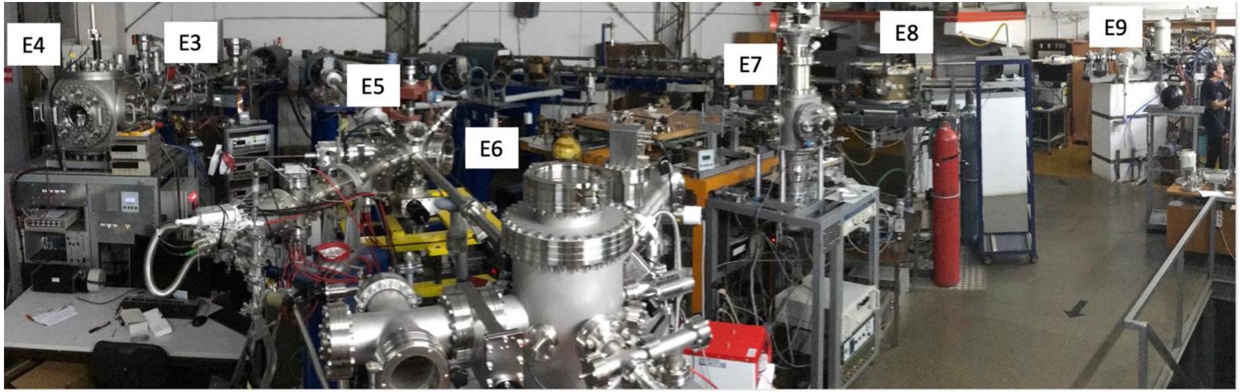
RBI accelerator facility

- participating in EUROfusion project since 2014

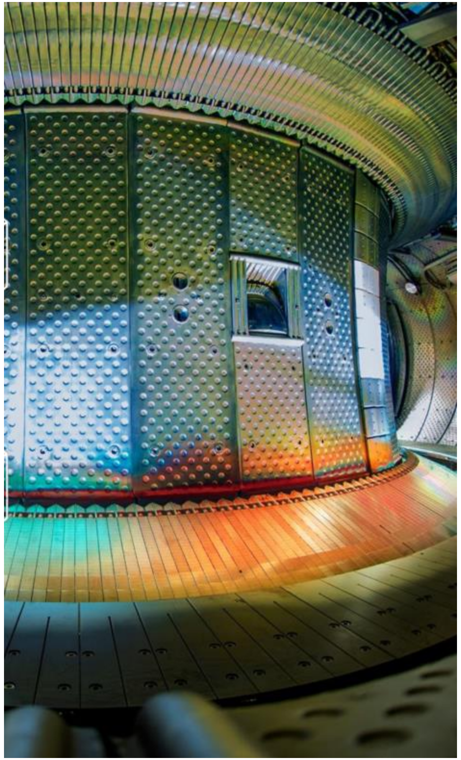
- responsible for IBA





Outline

- WEST C4 campaign
- Previous IBA results on WEST C4 marker tiles
- Assessing the He content by TOF ERDA
- NRA and SIMS results on selected samples
- Conclusions



WEST C4 campaign

- dedicated He campaign (~45 min. plasma operation) was executed at the end of the C4 campaign in 2019 in the full tungsten WEST tokamak, cumulating ~2000 s of repetitive L mode discharges

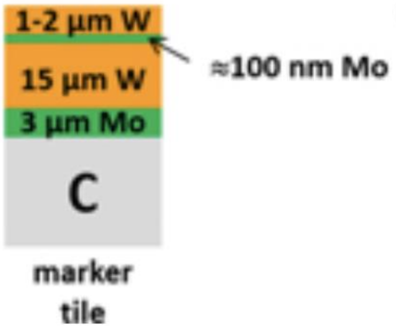
- goal to investigate W surface morphology changes under He plasma exposure in a tokamak environment (formation of He nanobubbles and W fuzz)

- campaign designed to meet conditions for W fuzz formation @ OSP on inertial PFU E_{inc}> 20 eV, fluence> 10^{24} He/m^2, T_{surf}>700°C

Previous IBA results on WEST C4 marker tiles

Post mortem RBS and NRA performed on erosion marker tile to assess net erosion/deposition pattern, film composition and D content

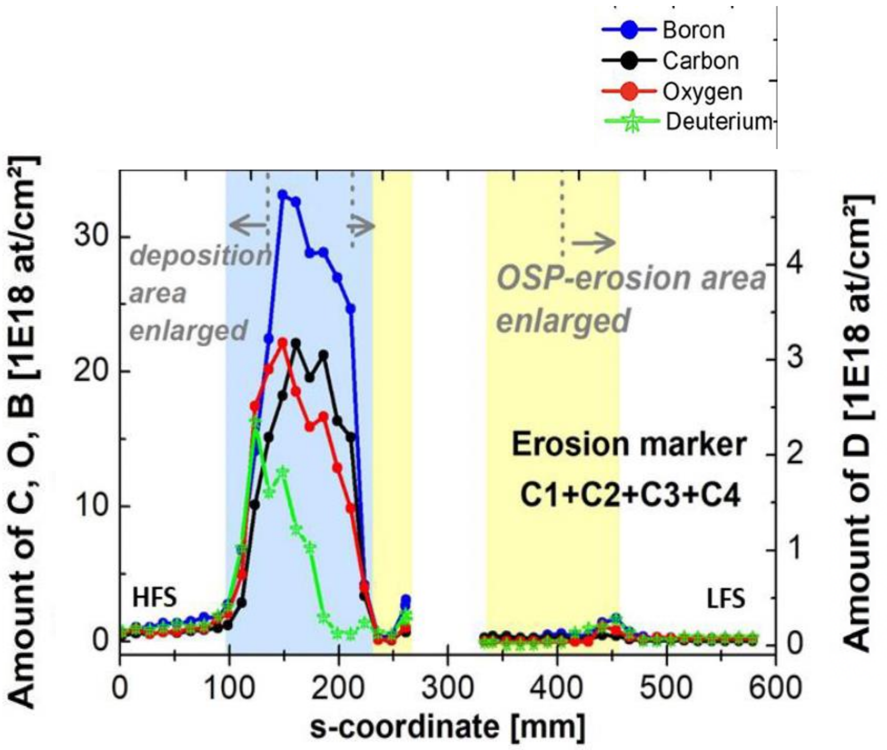
- IBA : up to ~1.5 μm for light impurities (B, C, O)
- up to ~3 μm for D
- Cannot fully probe thick deposited layers
- No information about He content
- No indication of W fuzz confirmed
- "Nanoholes" evidenced in post C4 deposits, but similar features also seen after C3 : cannot be attributed unambiguously to He



M. Balden, Phys. Scr. 2021

OSP erosion area enlarged, ISP erosion area shifted after C4

- Thick deposition area on the HFS also enlarged
- C, B, O significantly increased after C4 (longer plasma duration + increased number of boronisation)
- D content follows B/C profiles, but D depleted after C4 near the strike point area : impact of He plasmas?



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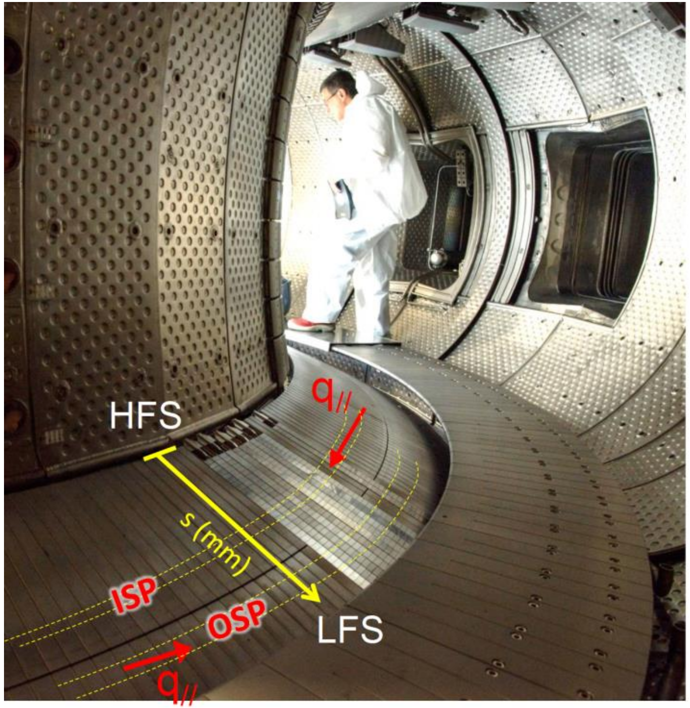
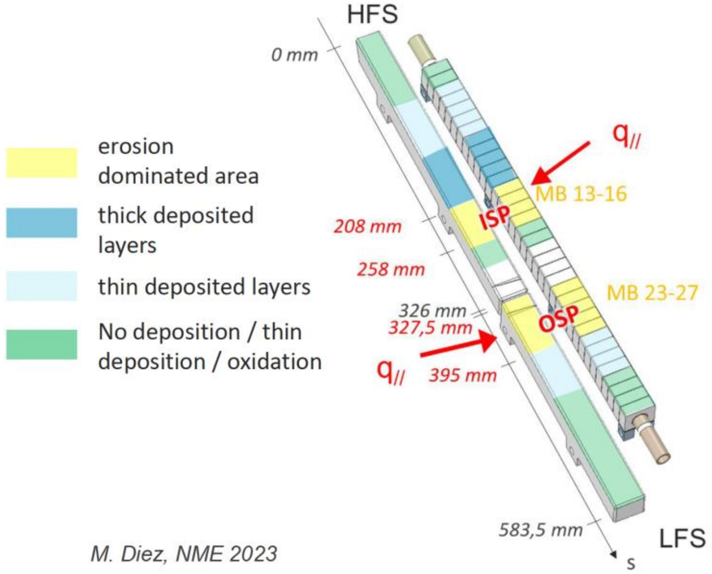
WEST divertor erosion/deposition pattern

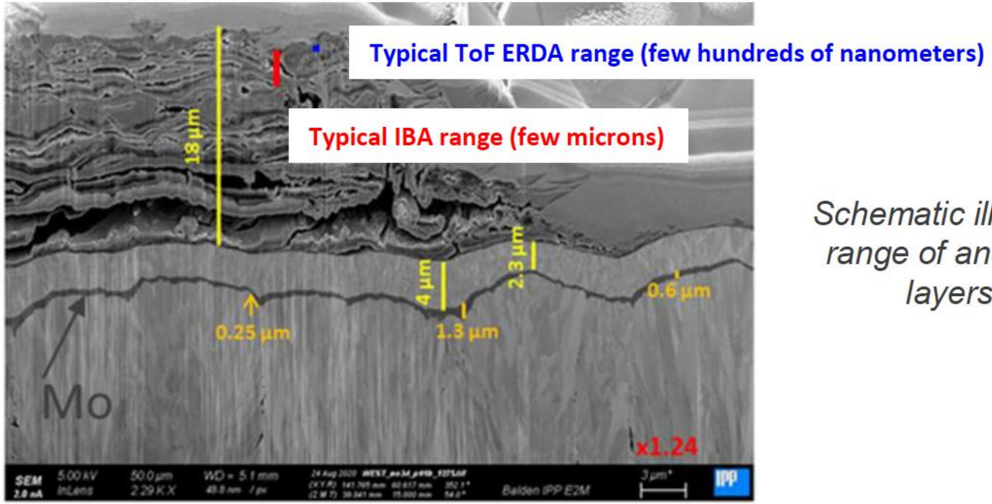
- OSP / ISP = erosion dominated area
- Thick deposited layers (> 10's microns) on the HFS, close to ISP
- Thin deposits elsewhere (< micron)





M. Diez, NME 2023

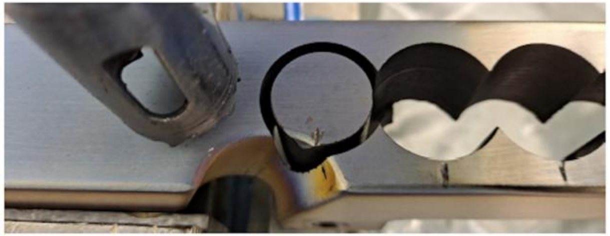
Assessing the He content by TOF ERDA



Schematic illustration of IBA/ToF ERDA range of analysis on WEST deposited layers (erosion marker tile)

Thermal Desorption Spectroscopy - requires very high temperatures (not possible very often)
Glow Discharge Optical Emission Spectroscopy - needs to be calibrated against known reference samples
Laser Induced Breakdown Spectroscopy - needs to be quantified with the help of some other technique

Inertial standard inner/outer tiles from **sectorQ4A** (max OSP/max ISP) cored for ToF-ERDA at the VTT, Finland



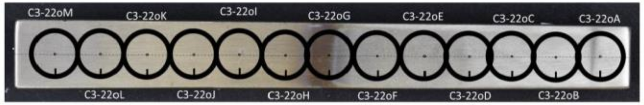
Q4A-18oM

- 17 samples from inner sector – 7iA to 7iQ
- 13 samples from outer sector – 18oA to 18oM

TOF ERDA was performed along the poloidal direction, from high-field side (HFS) to low-field side (LFS).

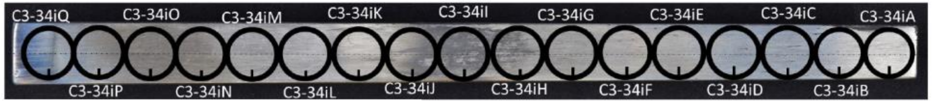
outer#18, sectorQ4A

LFS PFR



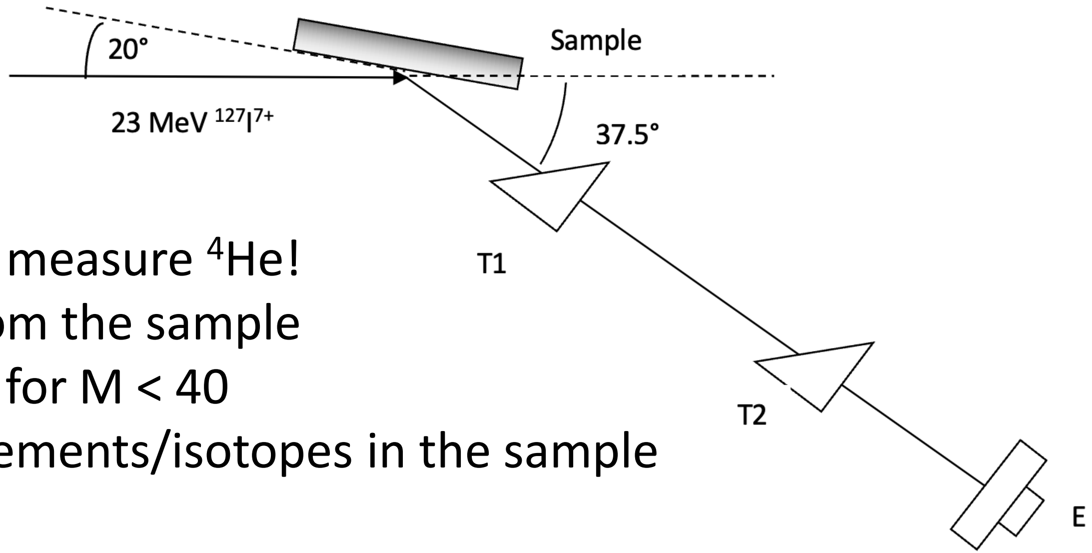
inner#7, sectorQ4A

PFR HFS



- each sample was measured in the middle
- beam spot size ～2x3 mm^2

Time-Of-Flight Elastic Recoil Detection Analysis (TOF ERDA)



- The only IBA technique that can measure ^{4}He!
- Heavy MeV ions recoil atoms from the sample
- Mass resolution is better than 1 for M < 40
- Simultaneous detection of all elements/isotopes in the sample

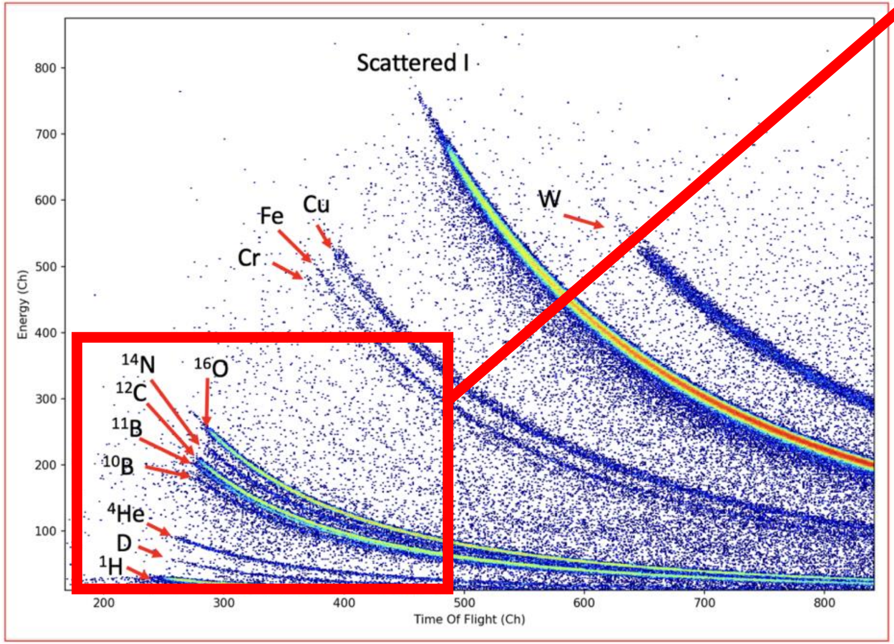
Problems:

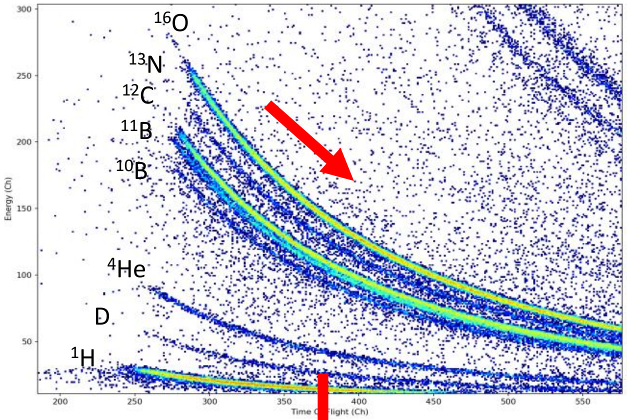
- Surface roughness
- Difficult to distinguish neighboring mid Z elements due to recoil signal overlap

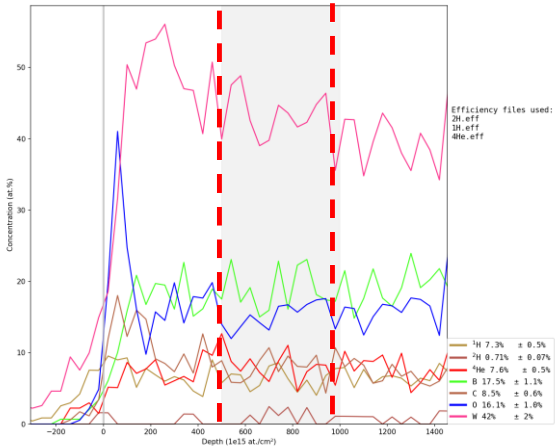
TOF ERDA with 23 MeV $^{127}I^{6+}$

- analysis range dependent on matrix (100-250 nm)
- analysis of layers near surface!

Sample Q4A-7iG – TOF ERDA spectrum



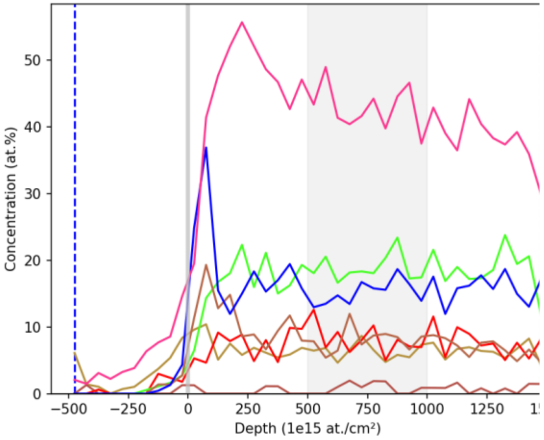




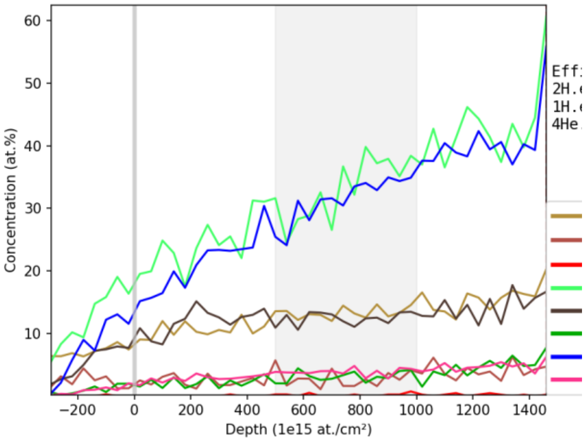
- depth profiles and at% of all elements/isotopes

TOF ERDA depth profiles

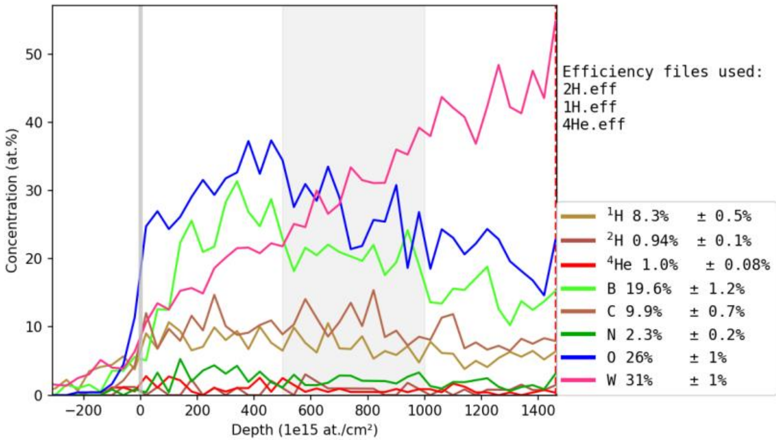
18oF (s=433 mm)
erosion part OSP



7iF (s=104,5 mm)
thick deposit



18oH (s=470 mm)
thin deposit LFS



Distribution of elements homogeneous in depth – surface O peak

Very rough sample

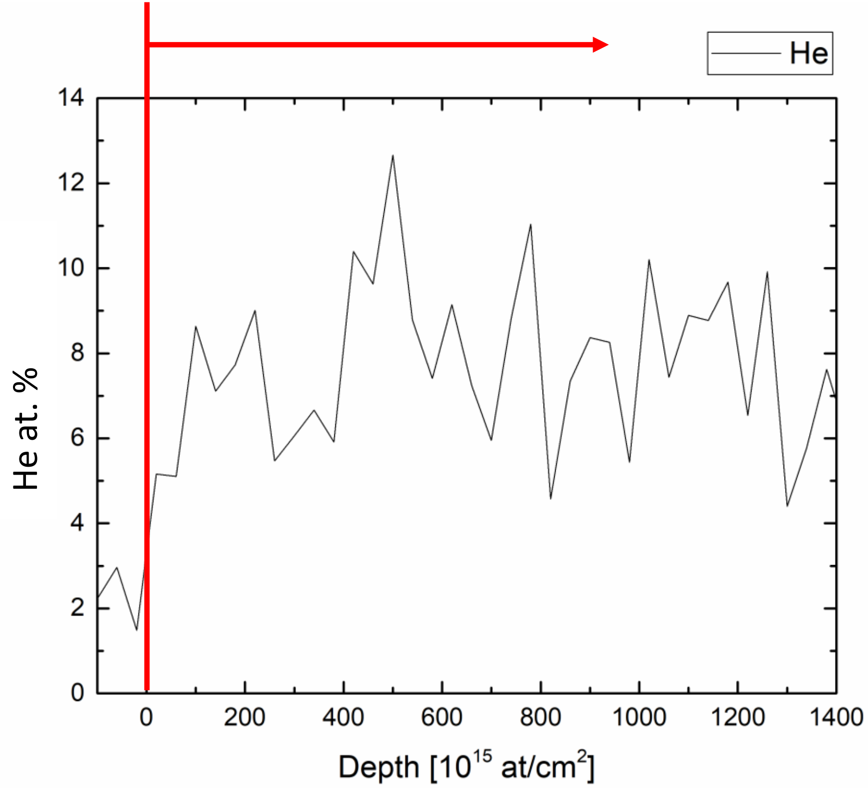
Concentration in the near surface region is not homogeneous

Composition near the surface: thick deposits (B, C, O, H), erosion ISP (B, O, W, He, H), erosion OSP (W, C, He, B)

- POTKU software used to analyse the spectra K. Arstila et al.,NIM B 331 (2014) 34

He depth profile

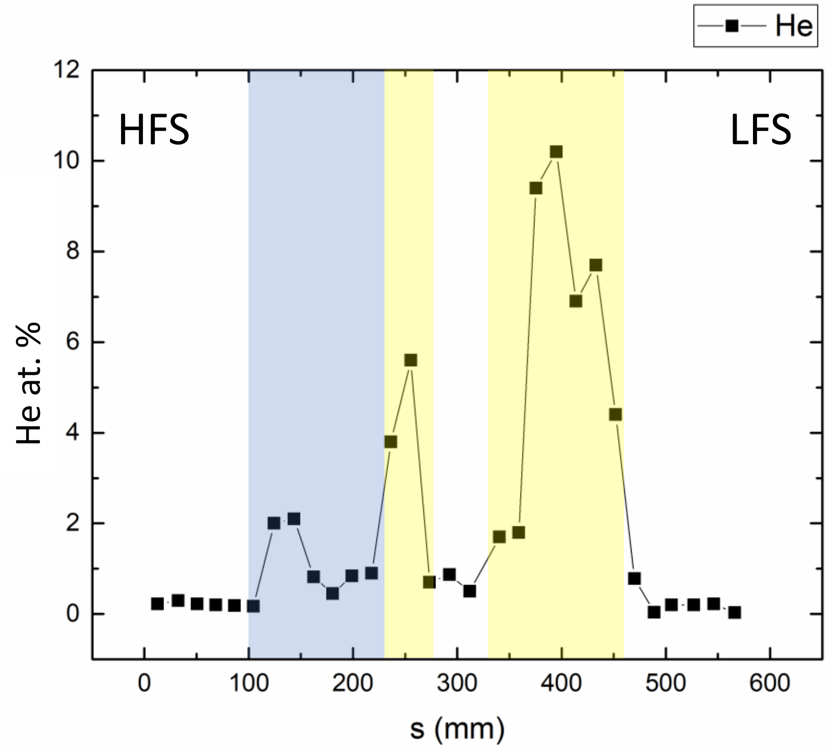
18oF (s=433 mm) – erosion part OSP



- conversion to thickness in nm matrix dependent and not very easy due to unknown material density

- end of He profile not seen 160-170 nm

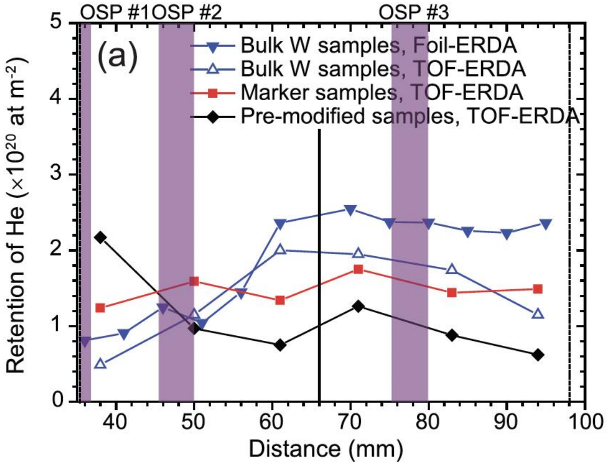
TOF ERDA He concentration (at.%) in poloidal direction



- significant He content found in the strike point area (up to ~ 6% at ISP and ~ 10% at OSP)

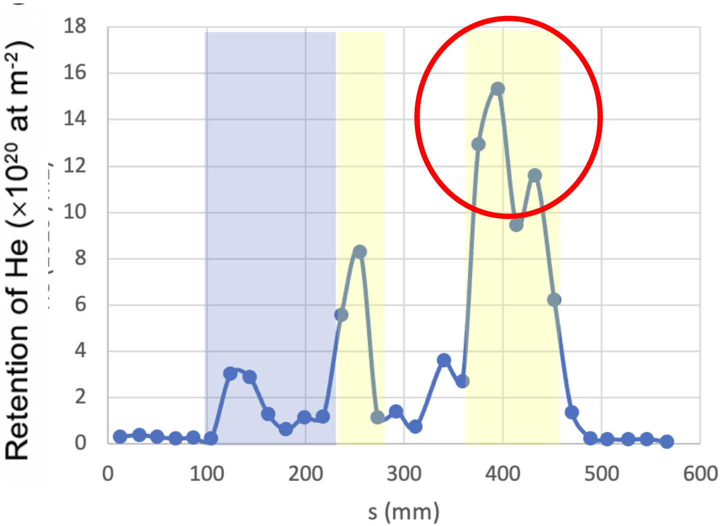
Comparison with dedicated helium campaign in 2015 in the full W ASDEX upgrade

- it was expected in both cases that conditions for fuzz formation have been met E_{inc}> 20 eV, fluence> 10^{24} He/m^2, T_{surf}>700°C



- dedicated helium campaign in 2015 in the full W ASDEX upgrade, H mode, one day

A. Hakola et al., Nucl. Fusion 57 (2017) 066015

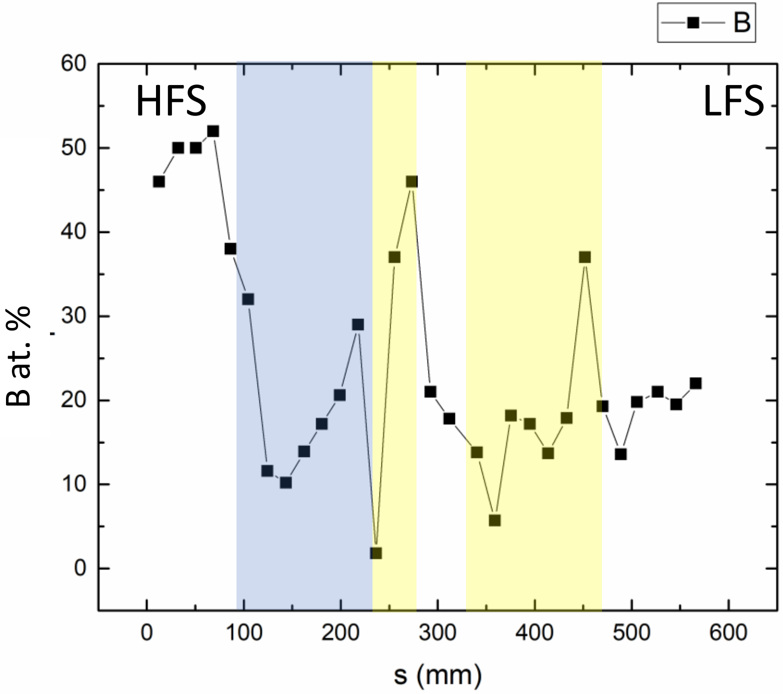


WEST C4 – L mode, more days

surface density >10^{21} He/m^2 at the OSP

- difference in He retention – differences in exposure and in the local erosion/deposition balance due to different plasma conditions in both devices

B concentration

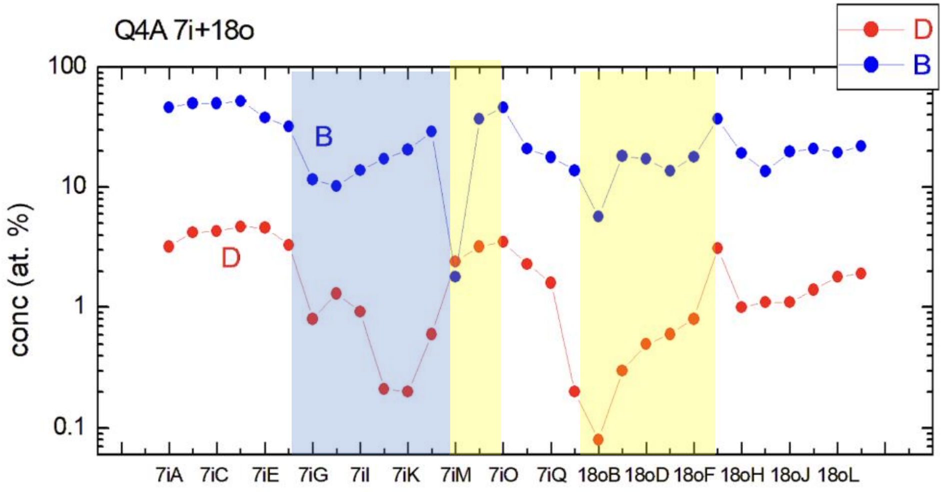


- presence of B in the top layer even if no boronization was performed during the He campaign at the end of C4

- Boron mainly found on the HFS of the inner tile - in agreement with the results obtained on the ITER-like PFUs with other techniques such as NRA and SIMS

- two further regions with increased boron conc. (around 40 at.%) were also detected at the edge of the ISP region toward the high-field side far scrape-off layer (SOL) while the second peak is toward the private flux region

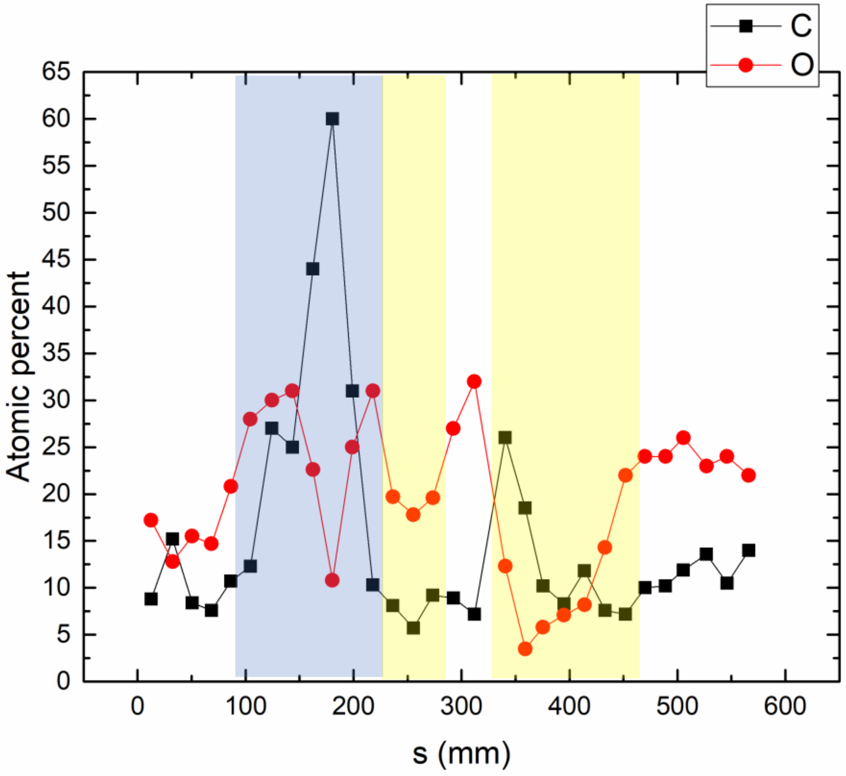
D profile vs. B profile



- D profile is following B profile in the near surface regions and is following less C profile (conclusion from previous NRA measurements which goes deeper)

C and O profiles, impurities

- very strong peak of C at the thick deposit

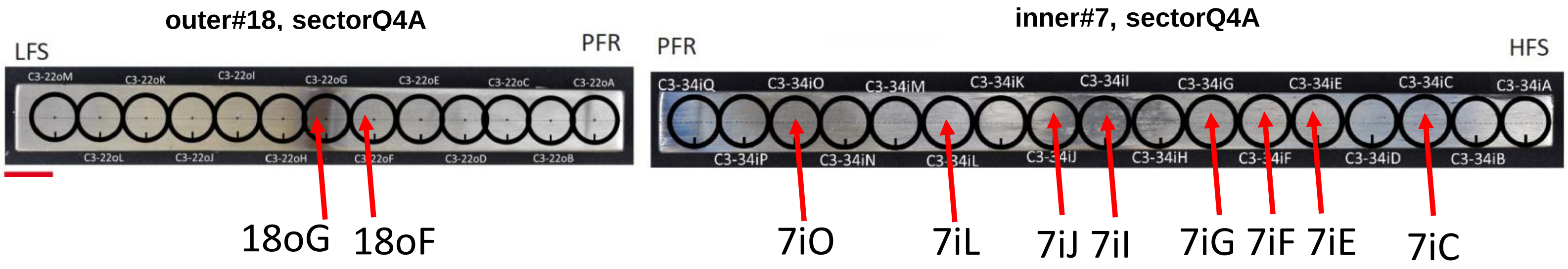


Few % of metallic impurities detected (Cu, Fe, Cr ...)

NRA measurements on selected samples

2.6 MeV ^{3}He beam, NRA detector at 135 deg, beam spot size 1x1 mm^{2}

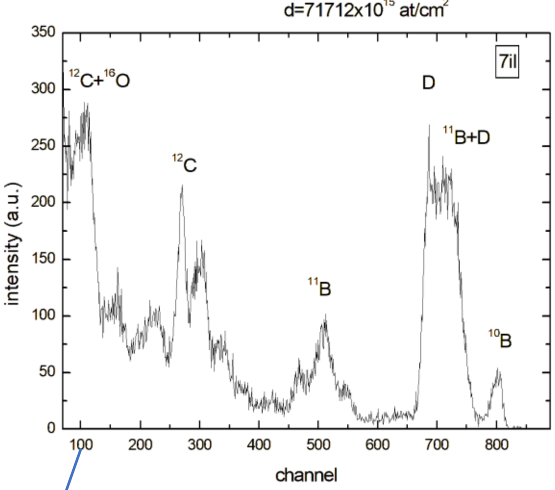
- measurements were performed close to the spots measured by TOF ERDA

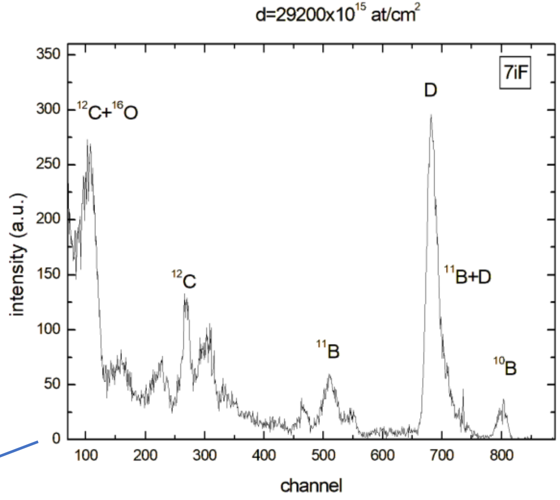


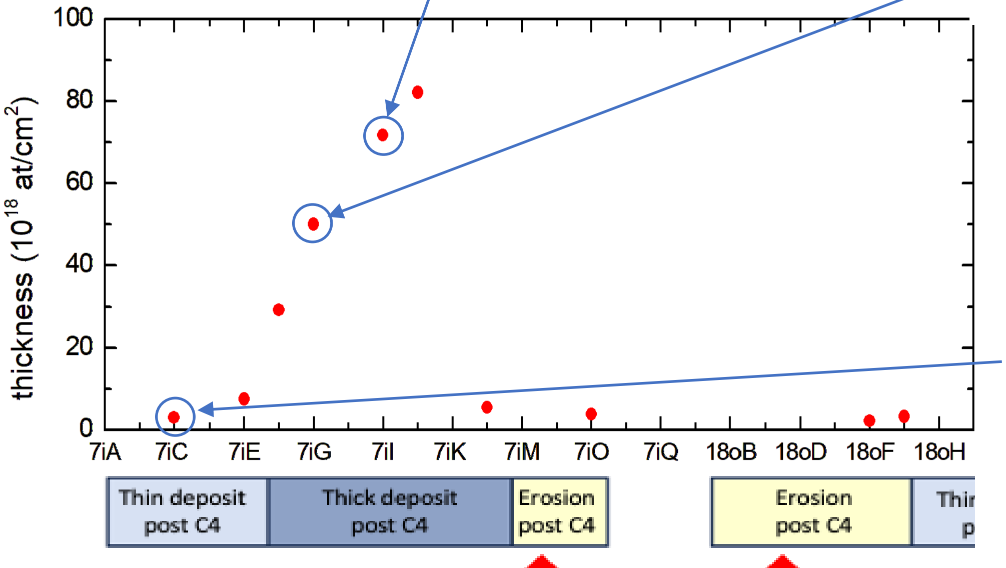
Spectra were analysed using SIMNRA (M. Mayer, SIMNRA User's guide, Report IPP 9/113, Max-Planck-Institut für Plasmaphysik, Garching, Germany, 1997)

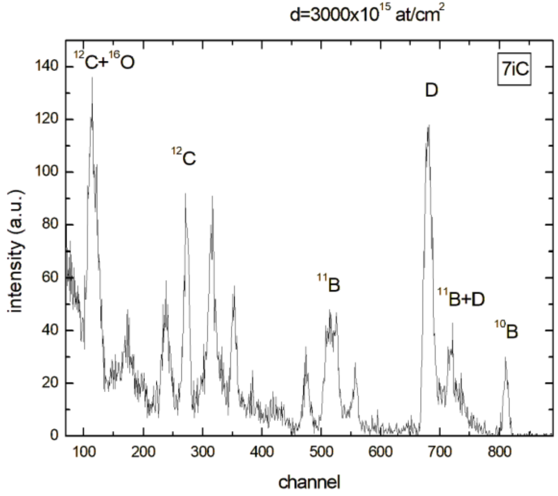
Cross sections used:
Boron - L.C. McIntyre et al., NIMB 118 (1996) 219
Carbon - G.Provatas et al., NIMB 500-501 (2021) 57
Deuterium- B.Wielunska et al., NIMB 371 (2016) 41
Oxygen - M. Guitart et al., NIMB450 (2019) 13

- NRA spectra of thick, thin and sample with intermediate thickness

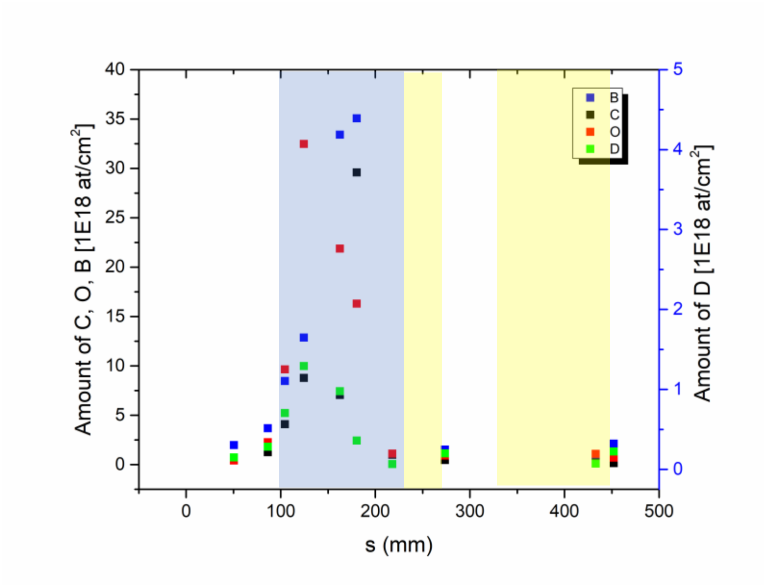


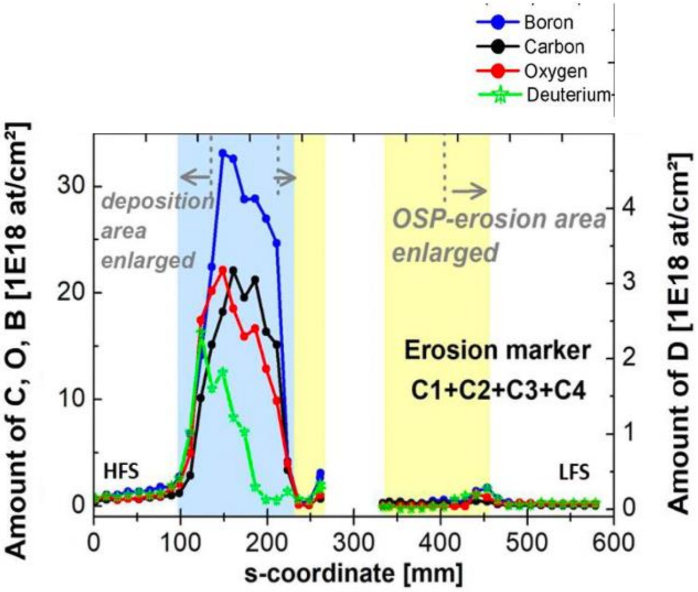






Comparison with previous NRA analysis of C4 erosion marker tiles





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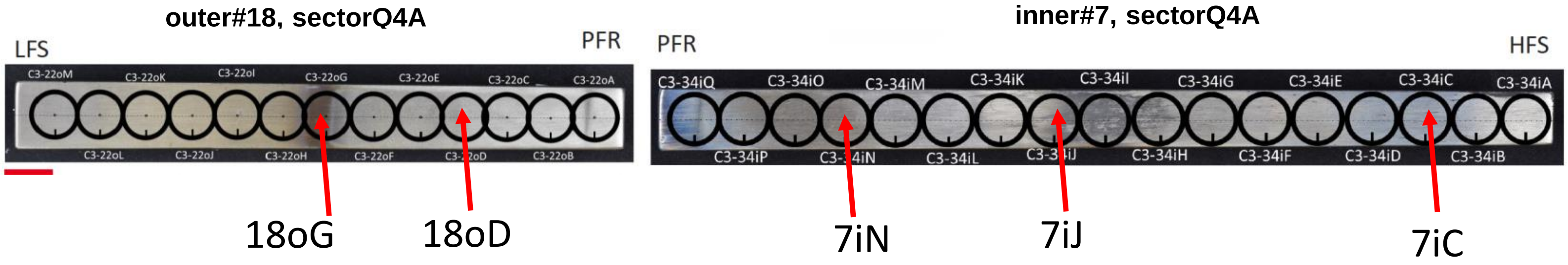
- D and B in good agreement, C and O in fair

SIMS measurements on selected samples

- SIMS (Secondary Ion Mass Spectrometry) measurements carried out at VTT using the double focusing magnetic sector instrument (VG Ionex IX-70S)

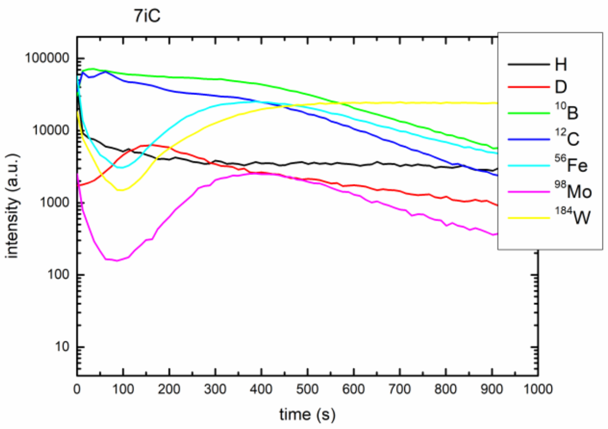


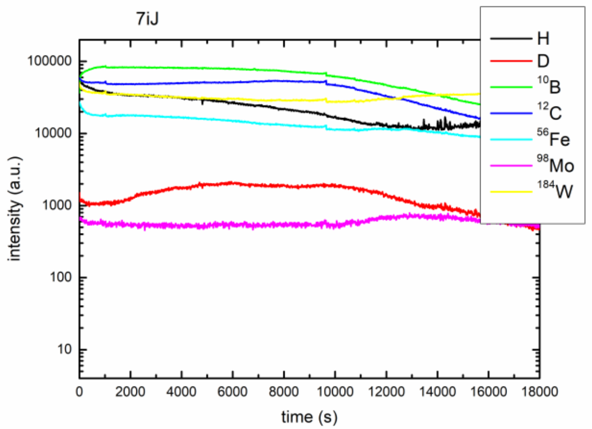
- The following mass signals were profiled: H, D, ^{10}B, ^{12}C, ^{56}Fe, ^{98}Mo, and ^{184}W; here ^{56}Fe is representative of various metallic impurities

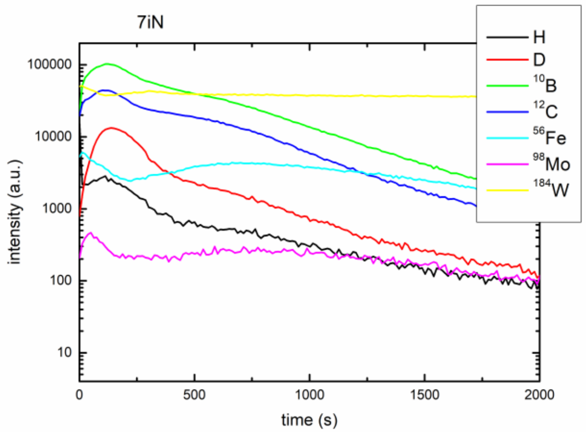
standard tile

- Measurements typically extended through the topmost co-deposited layer until the W signal from the topmost coating reaches saturation
- In some cases also profiling down to the bottom Mo separation layer or the graphite substrate (especially for strongly eroded samples)

SIMS results – inner tile







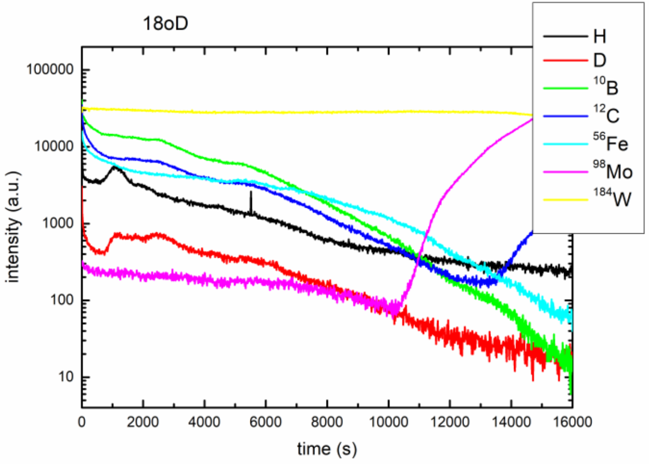
Conversion to depth - 0.5 nm/s

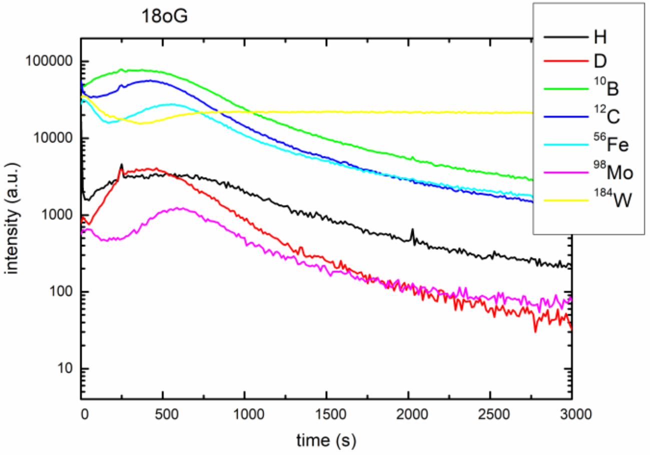
7iC (s=50.5 mm) - thickness ~200-300 nm, dominated by B and C while D only present closer to the W interface

7iJ (s=180.5 mm) - thickness up to 5-6 microns, B and C strongly present throughout the layer; in addition metals present throughout the layer

7iN (s=255.5 mm) erosion zone – thickness ~100-200 nm and B, C and D peaks (surface peak- implantation?)

SIMS results – outer tile





18oD (s=395 mm) erosion – only very thin layers at the surface and only a few micrometers of the underlying W and Mo layers left (substrate reached ~6 um)
18oG (s= 452 mm) surface deposit – thickness ~300-400 nm with B, C, and D peaks but also metals somewhat deeper than where the light impurities show peaks

Conclusions

- full WEST divertor tile analysed by TOF ERDA - information about H, D, He, B, C, O, Cr, Fe, Cu, W, analysed depth was up to 250 nm
- Although no He fuzz was observed by SEM significant He content found in the strike point area (up to ~ 6% at ISP and ~ 10% at OSP)
- He end of the profile not seen for almost all studied samples – He goes deeper that 150 nm
- Comparison with dedicated helium campaign in 2015 in the full W ASDEX upgrade, larger retention of He >10^{21} He at/m^2 in the OSP region. He not saturating so rapidly?
- In different He experiments we have noticeable amounts of the He gas itself accumulating on the samples, even if the complex balance between erosion, deposition, nanostructure formation, and annealing may have prevented the fuzz from being developed
- Next step to perform TEM and FIB to check He nano bubles or nanostructures

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Thank you for your attention!

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