5th Physics Project Board

2025 AWP WP*PWIE*: *P*lasma-*W*all *I*nteractions and *E*xhaust

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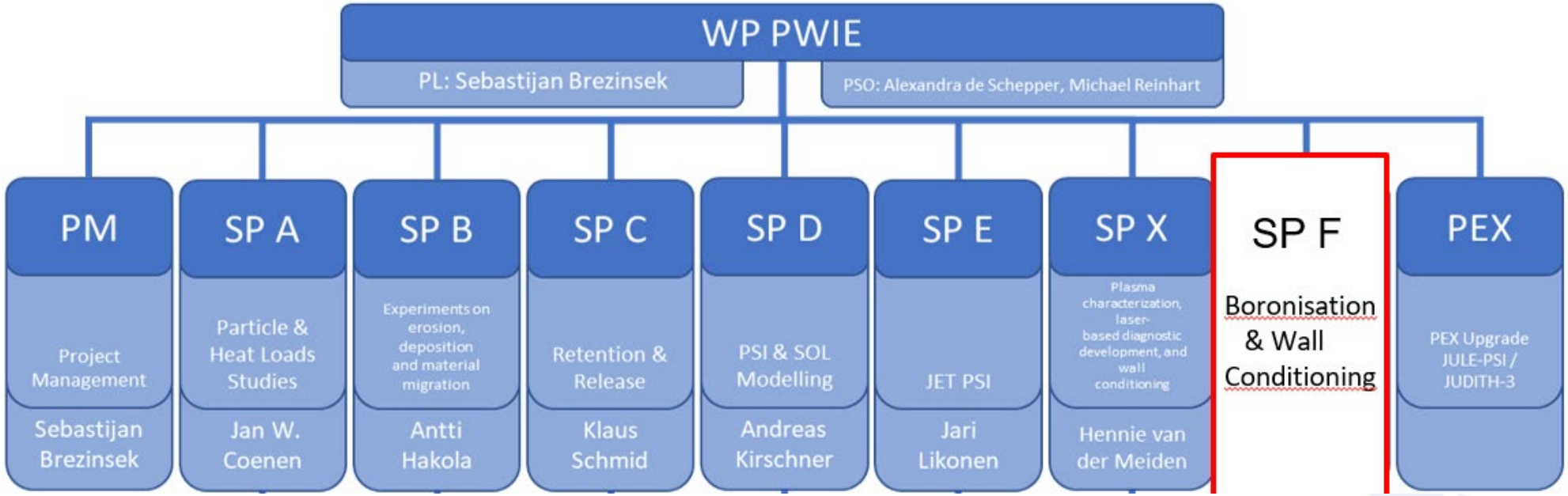
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

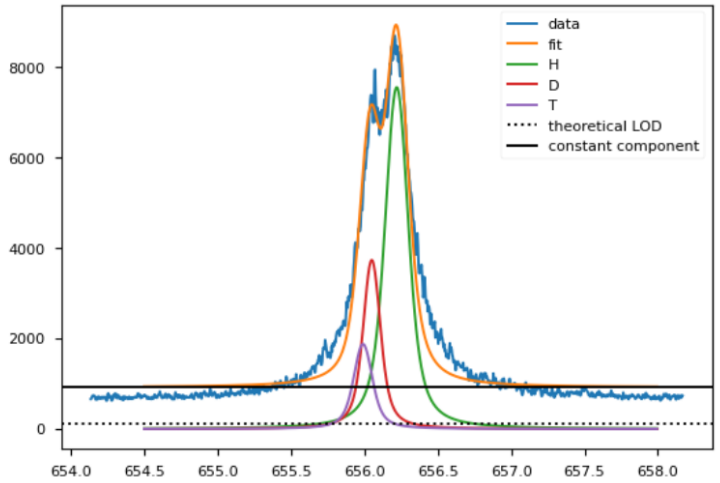
AWP 2025 – Revision of the original program / WBS WPPWIE

- Main structure and activities for reactor remain as in initial 2021 plan with some adaptions
- In view of the ITER re-baselining changes to indicative plan
  - General activities related to Be (LIBS, fuel recovery assessment, ITER simulations etc.) were closed in 2023
  - Remaining activity is the JET-DT tile analysis (LIBS and ex-situ) with Be and W tiles to assess retention, migration, dust formation. Data feeds into benchmark of PWIE codes to validate physics models (low Z can be exchanged)
  - Number of new activities to high priority ITER items related to clean W first wall operation and usage of Boron added
- PCR in July 2024 provided initial support for critical activities for DEMO, ITER and COMPASS-U

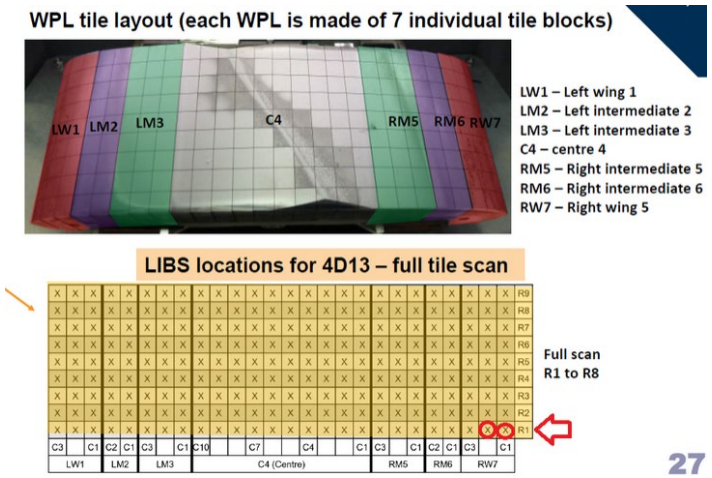


First JET-LIBS data on RH (October 2024!)

little D and T – no W at this place



Bulk-Be part with Be deposit



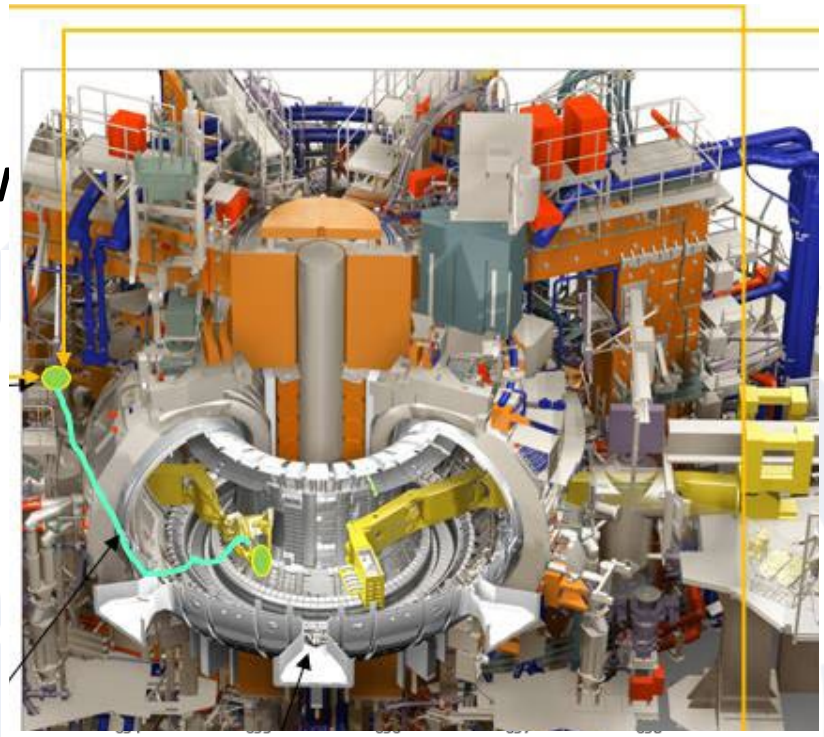
Technical demonstration of LIBS on RH arm in a nuclear activated device
SUCCESSFULLY PERFORMED!!

Opens new area of in-situ material composition and fuel content analysis!

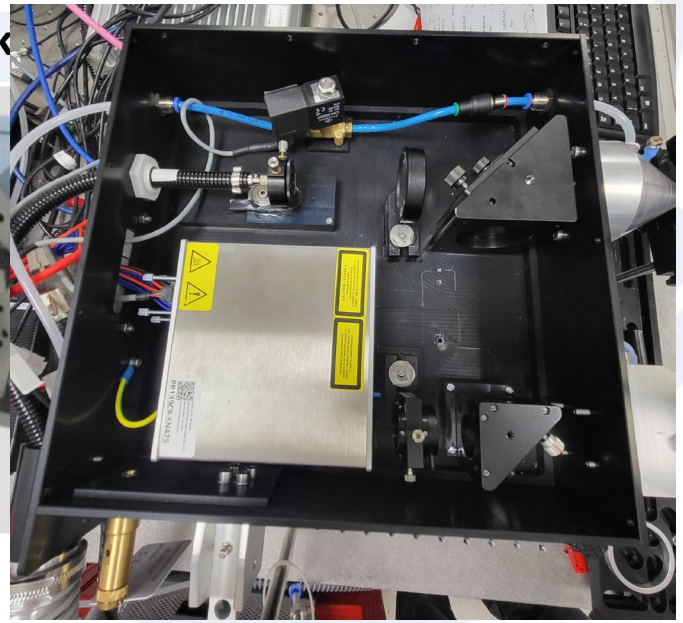
Thanks to Jari and SP E team… as well as the JET RH-team and UKAEA!

Several 10 000 of spectra to be analysed using also AI
⇒ 2025 analysis campaign
⇒ Input to PWIE modelling

W



Bulk



AWP 2025 – Main objectives I

- Material qualification for DEMO and other facilities with plasma and combined load, damage evolution, limits
- Support of WEST and ASDEX Upgrade experiments, analysis, and interpretative modelling (PWIE aspects only e.g. migration, 3D aspects, layer formation, stability) => TSVV-6, PWIE-AI-SOL
- Address T-retention by trapping/diffusion/permeation in damaged tungsten/EUROFER PFCs
- Prompt re-deposition physics of W and properties of re-deposited W (experiments and modelling) => TSVV-7
- Analysis of JET-LIBS data and prepare/start for post-DT tile analysis => PWIE-AI-LIBS
- Support of W7-X PWIE in long-pulse operation, wall conditioning, material migration, dust, transfer to W
- Properties of cold, recombining plasmas in view of molecular assisted processes in H,D => TSVV-5
- Development and application of laser-based technologies for in-situ and in-operando studies (W, steel, B)
- Support of COMPASS-U (and JT60SA regarding transfer to W by modelling, divertor design, and PFC test)

In general very strong links with: WPTE and WPW7X as they offer platform to bridge: laboratory results with tokamak / stellarator via modelling

Links in specific areas with WPAC, WPMAT, WPDIV, WPPRIO, WPSA, WPDC….

AWP 2025 – Main objectives II

- **Supporting ITER re-baselining and addressing critical question in experiments / modelling:**
  - Simulation of first wall W erosion, W deposition, and W screening in limited, start-up and diverted plasmas
  - Boronization and B layers: homogeneity, B layer properties, lifetime, and impact of B on wall conditions
  - T retention (scaling law), T removal techniques (ICWC, ECWC), T quantification (laser-techniques), active removal of B layer by erosion, dust formation, dust properties, and dust removal (=>TOMAS and other facilities)
  - Advanced modelling of B physical and chemical erosion process as input for PWIE models (MD simulations)
  - Qualification of ITER TFW design solutions in HHF devices (inertial and actively cooled) PFCs
  - W PFCs damage predictions under VDE and RE impact in ITER
  - Supporting ITER first mirror performance in the presence of boron (boronization / boronization + plasma)

Linked to ITPA activities and needs of revised ITER research plan

New/updated activities in 2025: Focus on WEST support

- SP B : Understanding the formation of WEST-like deposits with W
  - Final analysis of WEST-like deposits from long-pulse operation: stability and dust conversion factor
  - Mimic WEST-like divertor plasma conditions and pulses in MAGNUM-PSI (and PSI-2)
    - Thermal cycling of actively cooled W PFCs in NAGNUM-PSI and secondary upstream W source
    - Role of surface temperature, thermal stresses, impurities, oxide formation, duty cycle etc. as parameters
    - Pre- and post-characterisation and spectroscopy
  - ERO simulations for linear plasma experiments (same A&M data for WEST)
  - Dust formation and characteristics (tbc with FTD)
- SP D: Simulation of WEST long-pulse plasmas in full 3D geometry (incl. ripple)
  - Plasma boundary simulation with SOLEDGE3X-EIRENE
  - ERO2.0 simulation of WEST long-pulse devices incl. W local redeposition and MB shaping
  - Dust simulation
- SP A: HHF exposure of W MB exposed in WEST
  - Damage evolution under e-beam loading
  - Deposit stability assessment

Joint Meeting WPTE/PWI in Aix in September

MAGNUM-PSI: Simulation of WEST high fluence campaign

- Mimic high W influx from WEST main chamber into W divertor by artificial impurity source
- Test experiments in Ar plasma to get high W source in plasma
- Final step: try to mimic ITER conditions => Lower W flux from wall into divertor => different balance of W erosion/deposition

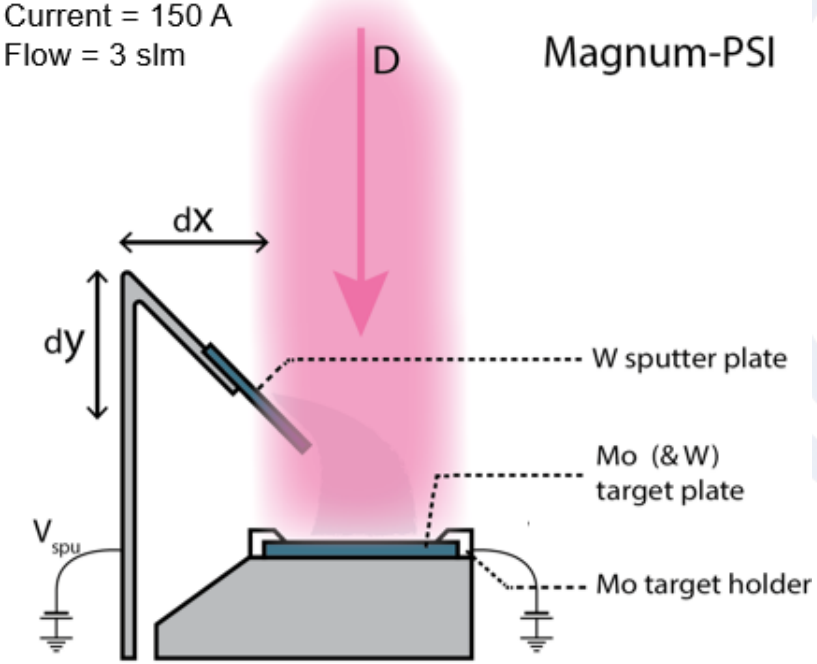
Method- initial experimental testing

Sputter & redeposition using Ar plasma

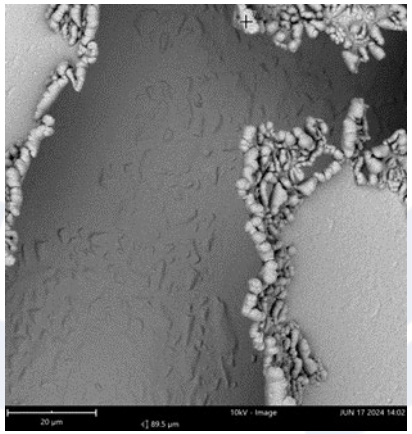
Initially use Mo sputtering target (availability)

- Biased Mo sputtering target mounted above sample
  - (~15mm wrt center of plasma)
- Sputtered Mo entrained and redeposited on Mo sample and steel witness plate.
- Changing V_{spu} to impact sputter Yield & deposition rate

H plasma
B = 1.2T
Current = 150 A
Flow = 3 slm



Flaking Mo layers observed



New/updated activities in 2025: Focus on first wall W erosion

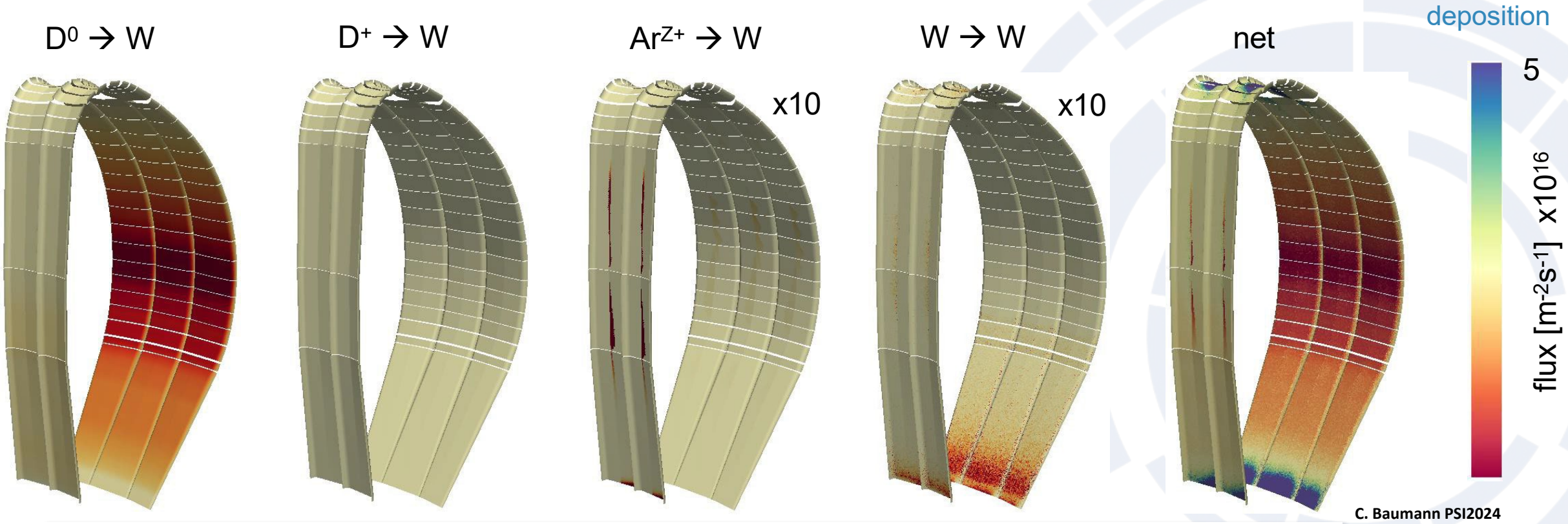
- SP D : Simulation of fluxes to the first wall and W sputtering
  - CXN and ion flux composition in simulations for COMPASS-U, AUG, (JET), ITER and DEMO SOLPS-ITER H-mode plasma simulations (ELM-averaged)
  - Poloidal distribution of CXN with energy and angular distribution (universal EIRENE solution)
  - Role of inner and outer wall W source variation with change of CXN, D+, impurity ionisation level
  - ERO2.0 simulations / WallDYN-3D simulations for AUG, JET, ITER
  - Comparison of cases with extended grid to the wall and normal grid to assed far-SOL profiles
- SP B: Gross and net W erosion at the first wall (manipulators) jointly with WPTE
  - Experiments with wall clearance variation and light impurity seeding
  - Pre- and post characterisation of materials with different sputtering threshold and FIB cuts
  - Comparison with PSI-2 plasma experiments

$\Rightarrow$WPTE/PWIE Proposal of dedicated W (and B) migration experiment in AUG at high fluence (1-2 days identical plasmas)

Joint Meeting WPTE/PWI in Aix in September

Example of DEMO first wall erosion simulations with ERO2.0

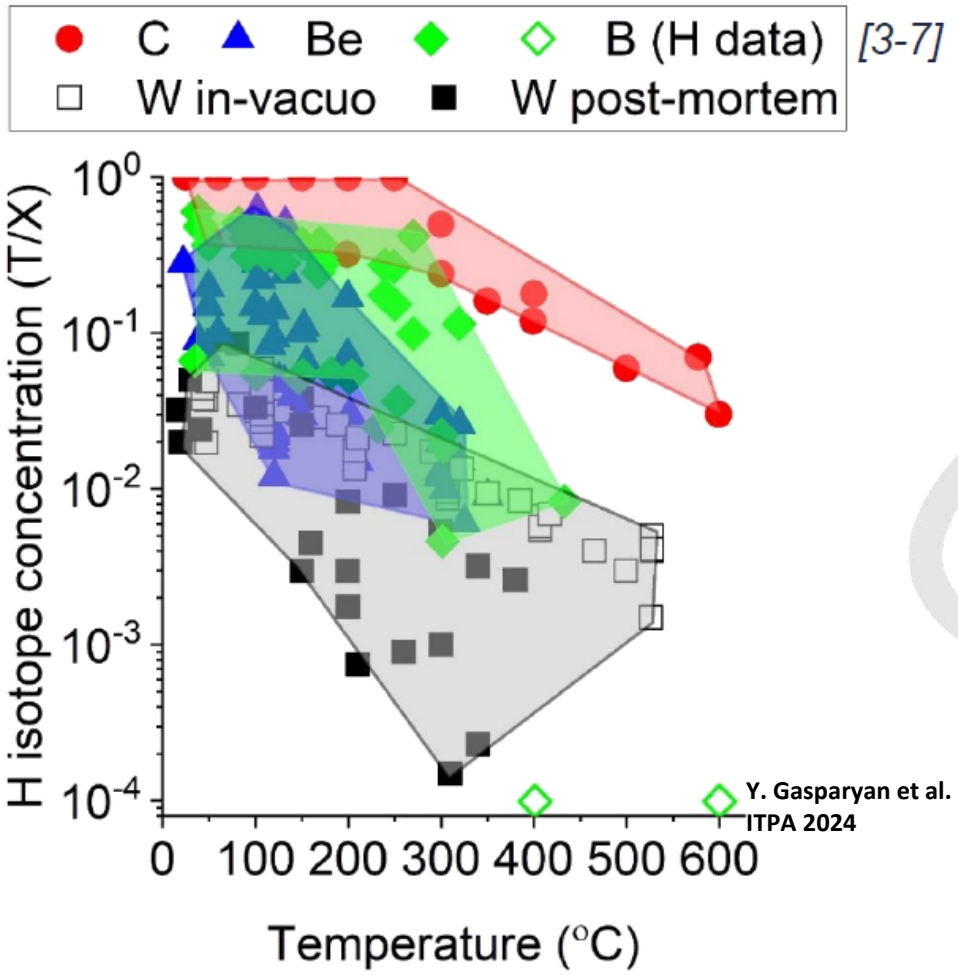
Assumption: Te=2eV at wall



- Main chamber erosion by D-CXN; divertor erosion by seeding impurities and self-sputtering
- Uncertainties about plasma conditions at wall (turbulence, shoulder, energy threshold)
- Strong deposition at remote areas above outer divertor and at top of the machine (upper X-point)
- Impact of main chamber source on core plasma pollution depends on screening efficiency
- Need for a benchmark experiment in full-W device with impurity seeding and semi-detached divertor

New/updated activities in 2025: Focus on boronisation and retention

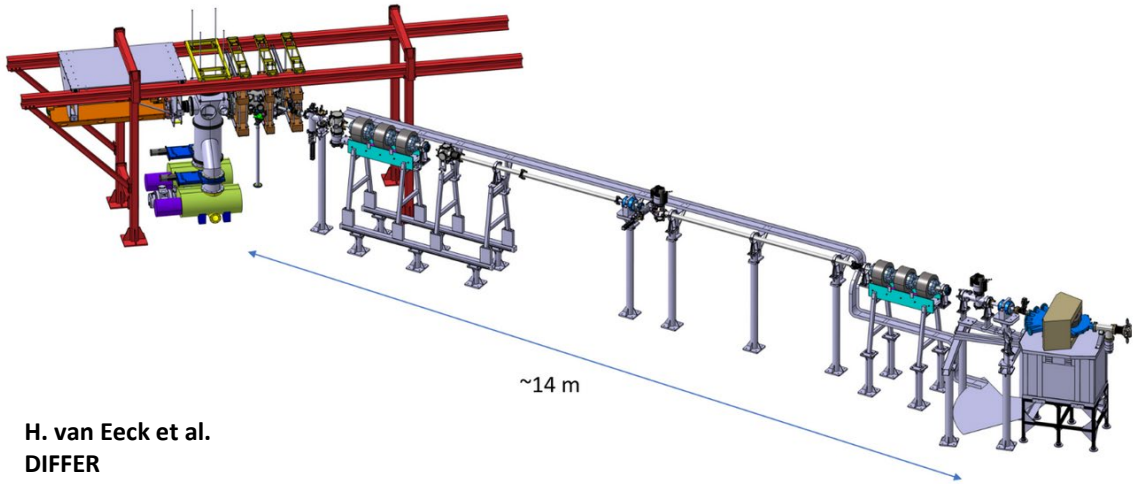
- SP C+ SP F : B layer database
  - Development artificial B layers for physics studies and comparison with tokamak samples
  - Matrix about fuel content: impact energy, temperature, material mixing, stability, fuel content, release as function of temperature
  - Use of TOMAS (upgrade), new facilities in IAP, and other abs to create variety of B layers with and without D content as reference
  - Magnetron-sputtering or laser-ablation-induced deposition used as replacement for boronization (later not possible in labs)
  - Transfer knowledge from Be to B => need for B database with D content in B layers for PWI modelling



Joint Meeting WPTE/PWI in Aix in September

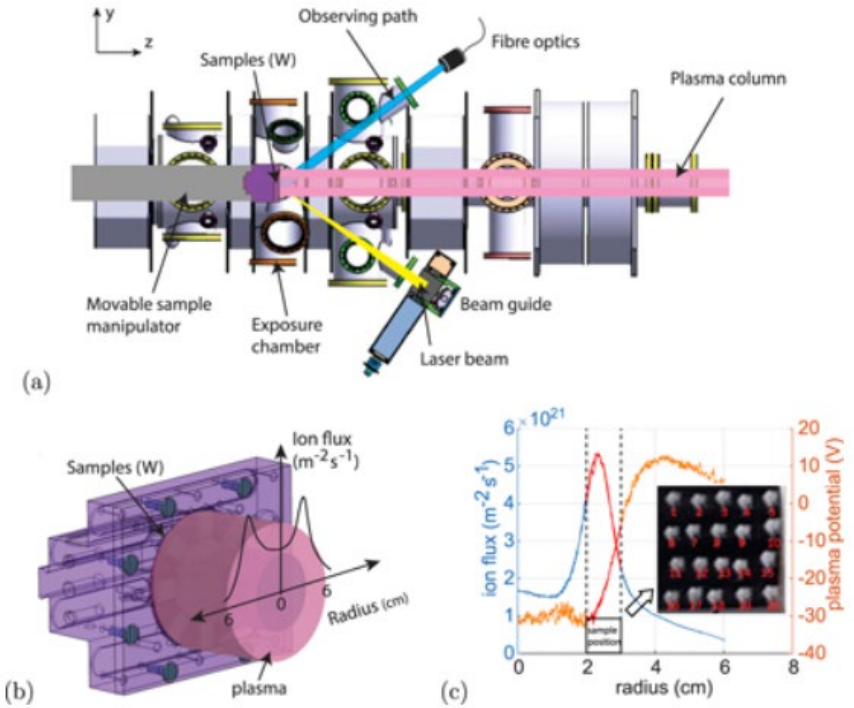
Boron-related in-situ/vacuo fuel retention and recovery studies

SP C + SP F + SP X (in-vacuo)
- Fuel retention and release properties of B layers exposed to fuel species and build with fuel
- Simulation related to fuel trapping and release
- Ion-damage W material studies



H. van Eeck et al.
DIFFER

SP C + SP F + SP X (in-operando)
- Fuel retention and release properties of B layers exposed to fuel species and build with fuel
- Simulation related to fuel trapping and release
- Recycling-studies on surface



In-situ deuterium content measurement by in-operando LIBS (PSI-2) or in-operando NRA (UPP) in 2025 foreseen without breaking vacuum and controlled B+D interaction

PCR Request Summary

- Facility costs increase and hardware increase: 140 k€ CC
  - Includes cost for TOMAS (40 days) with about 35 k€ in addition
  - Includes cost for GYM (30 days) with about 35 k€ in addition
  - Includes cost for ion beam facilities and new facilities to analyse samples with about 50 k€
  - Includes cost for additional materials (e.g. bor,, gas) beyond what is in stock (bought by FZJ as lead lab) ~ 20k€
- Mission cost increase: 100 k€ CC
  - No mission money from initial indicative budget left (additional cost for JET-LIBS transferred into 2025, additional cost meetings, end of 5-years-project essential) => 50 k€
  - Mission costs for extensive use of TOMAS exploitation by ERM-KMS team to FZJ => 30 k€
  - Mission costs for COMPASS support (was not in the PCR) => 20 k€ (including training)
- Human resource increase: 1ppy (in addition to the proposed shift of 1 ppy from 2024 to 2025)
  - Support in analysis and interpretation of boron retention analysis matrix and new sets of experiments and diagnostics
- Reuse of 2025 JULE-PSI budget for in-situ boron studies

Status PEX-FZJ Upgrades

- PEX-FZJ upgrades include JULE-PSI (plasma) and JUDITH-3 (e-beam) in the hot material laboratory (HML) in FZJ. Controlled area, licensed for activated and toxic materials.
- FREDIS with LID-QMS analysing JET tiles is installed in the HML.
- Main plan for JULE-PSI in PWIE when FP9 was set-up for 2024+:
  - Study of neutron-damaged materials for DEMO regarding properties, retention, power handling, erosion, etc.
  - Study of (damaged) Be materials for ITER – as the only facility running after closure of JET
  - Jule-PSI plasma operation with limited tritium amount possible
- JULE-PSI device is built and operates in Argon / Hydrogen in FZJ outside of the hot cell
  - Deuterium measurements this year with plasma characterisation foreseen
  - Analysis and simulation of the plasma started (SOLPS-ITER) + EIRENE (alone)
- JUDITH-3 constructed and operates outside of the hot cell
- Three required new hot cells are not yet installed due to substantial cost increase (Corona/Inflation/…)
- Construction in 2025 => Transfer of facilities in 2026 => Full operation in 2027.
- Grant deliverable withdrawn. No operation with activated or toxic materials in 2025 => Shift 2026/27

Status PEX-FZJ Upgrades II

- Situation changed with respect to start of FP9: ITER decision to abandon Be!
- Focus of PEX-FZJ Upgrades now purely on activated, neutron damaged materials, and tritium
  - Neutron-damaged materials from fission application for plasma exposure also delayed (WPMAT)
  - Studies with boron in principle possible, but PSI-2 and JUDITH-2 exist and are easier accessible (cheaper)
- Delay of hot cell has only moderate impact on the mid-term research program

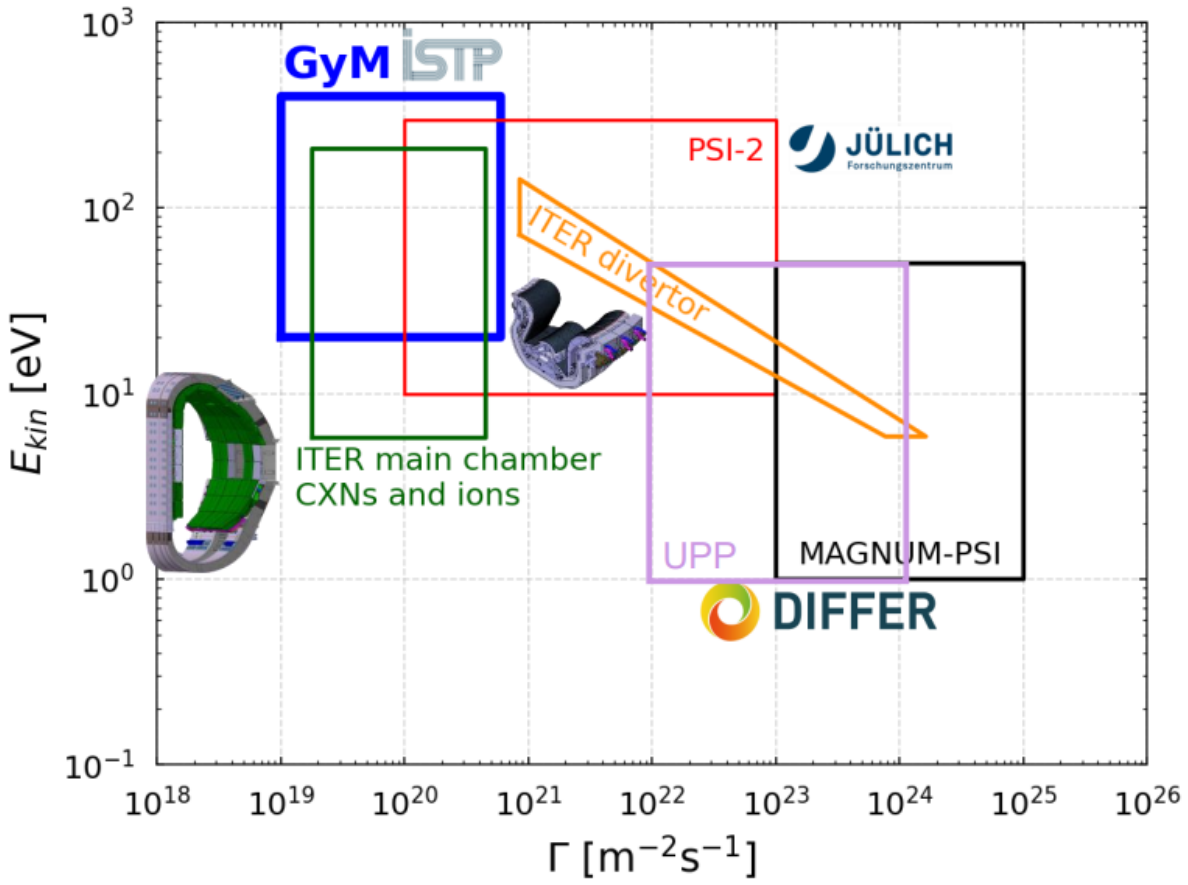
- Risk of not having PEX Upgrade in time in risk register tabulated:

  Use other linear plasma facilities if applicable for physics studies
  - No other facility for activated, neutron damaged materials, and tritium available => delay
  - Operation with Be not required anymore => need to study B => other facilities
- Note, operation of PSI-2 in the indicative plan for 2025 reduced to half of 2021

Risk Mitigation Proposal => Refocus on boron and WEST-related studies

Proposal to re-use indicative JULE-PSI budget [40 days] for other linear facilities (all 70% funding rate):

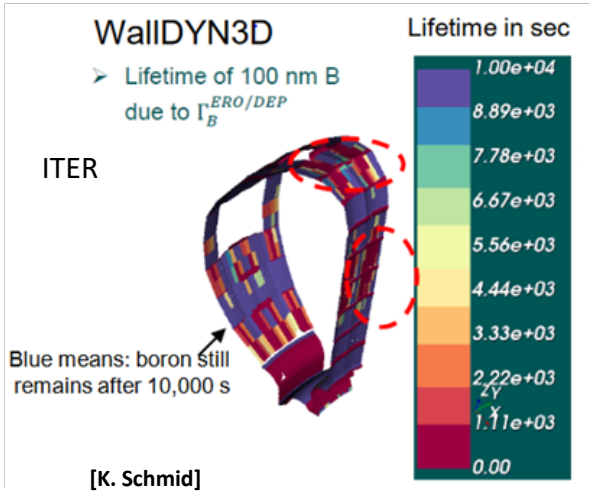
- Increase the experimental days in PSI-2 in 2025 to cover substantial studies on boron layers on boron PWI including in-situ LIBS for fuel retention and fuel removal [add ~45 days => 90 days]
- Increase budget of experimental days in UPP in 2025 to include substantial studies on boron PWI with in-operando NRA for fuel retention and removal from layers [add ~30 days => 40 days]
- Residual budget for additional MAGNUM days on existing subjects => priority WEST W simulation [add ~10 days => 50 days]
- Additional 100 k€ to be converted to mission under WPPWIE for 2025 (also 70% funding rate). Mission for experiments and associated analysis meetings



Scope: Work Package Plasma-Wall Interactions and Exhaust

Focus on ITER and DEMO materials, H and isotopes, He, seeding gases, and impurities

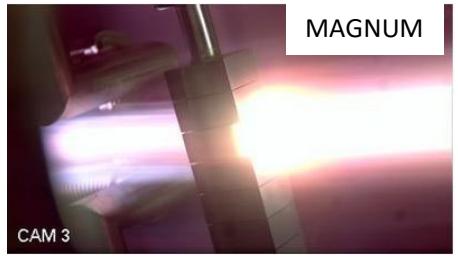
Goal: steady-state operation



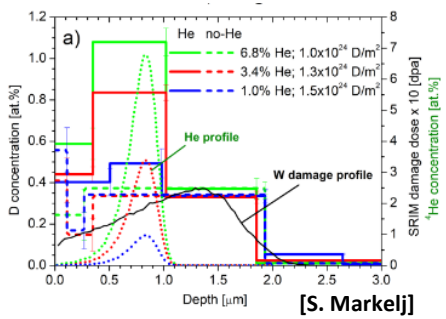
[K. Schmid]

3D erosion & deposition modelling
Tungsten, (Beryllium), Boron

Particle and heat flux
Tungsten + Deuterium



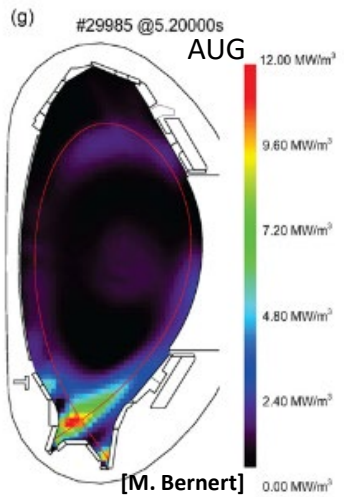
[T. Morgan]



[S. Markelj]

Fuel (**Tritium**) retention
Tungsten + Deuterium/Helium

Cold divetor operation
Tungsten + seed gas (Ne, Ar, Kr)

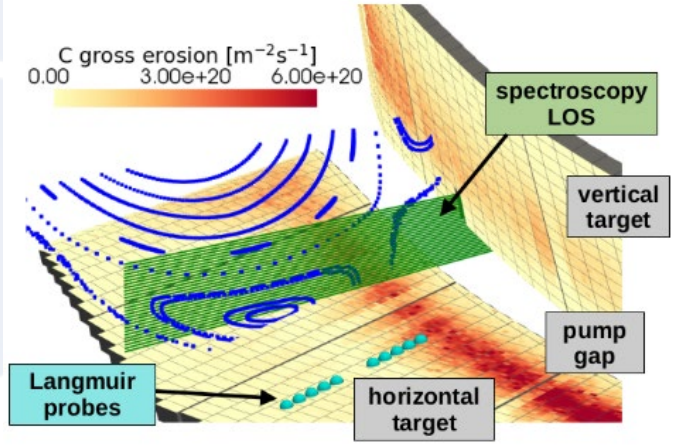


[M. Bernert]

Recombining plasmas in PSI-2 and MAGNUM-PSI

Support in WPTE exploitation
In AUG, WEST and JET in PWIE area with metallic PFCs

Support in WPW7X exploitation operating with Graphite towards Tungsten PFCs



[J. Romazanov]

Material qualification and synergistic effects of W and advanced W materials

PWI diagnostic development

Tokamak Experiments + Plasma boundary modelling + Global PWI modelling + Local PWI modelling

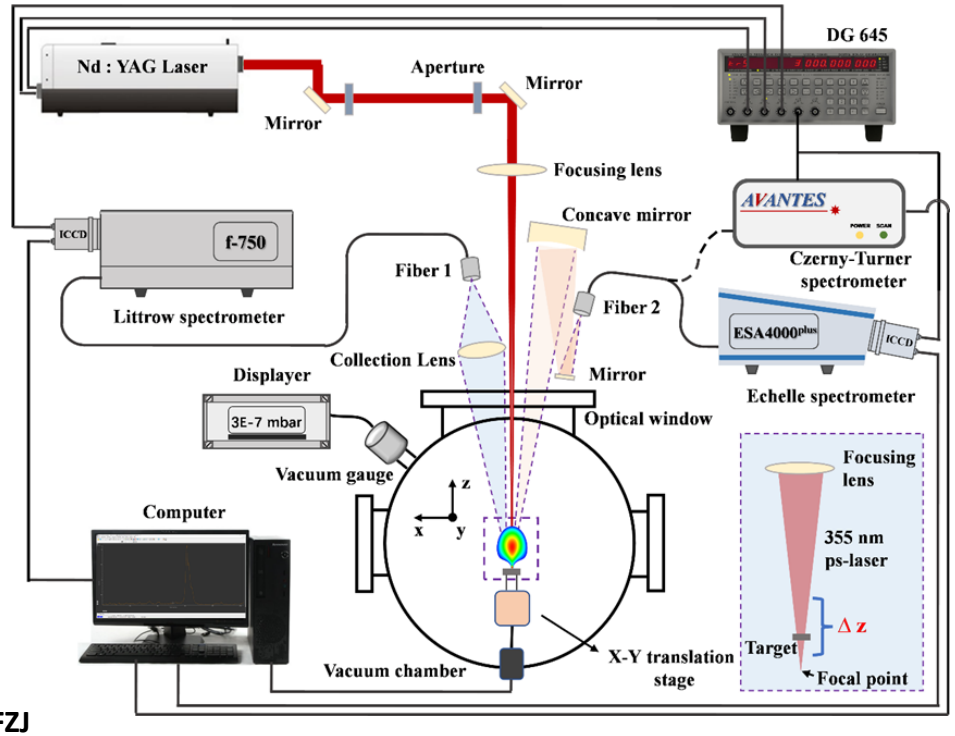
Laboratory experiments + PWI modelling

→ ITER, DEMO predictions

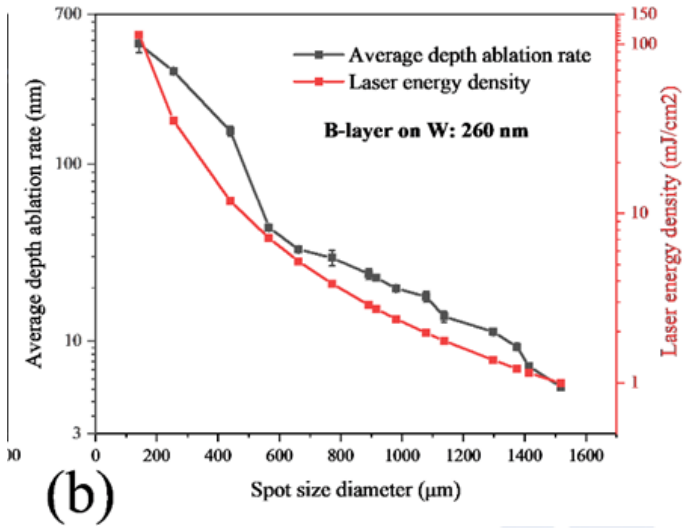
Examples: Development of LIBS to measure thin B layers (>5 nm) in 2024

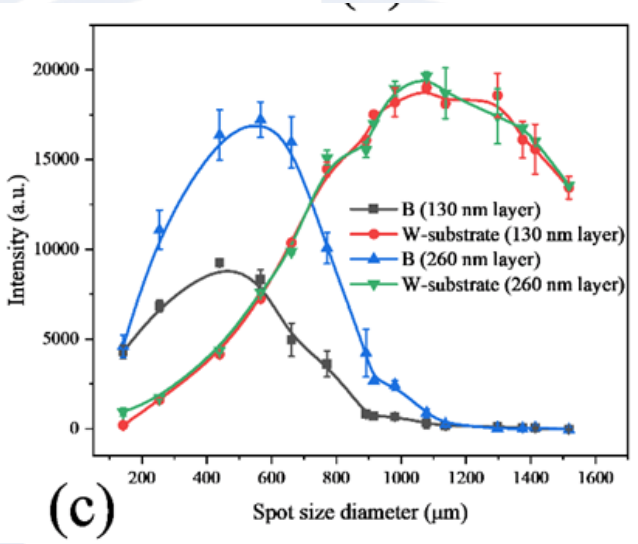
SP X:

- Qualification of LIBS on thin B-layers
- Qualification of LID-QMS on B-layers with fuel



FZJ





H. Wu et al. submitted to NME

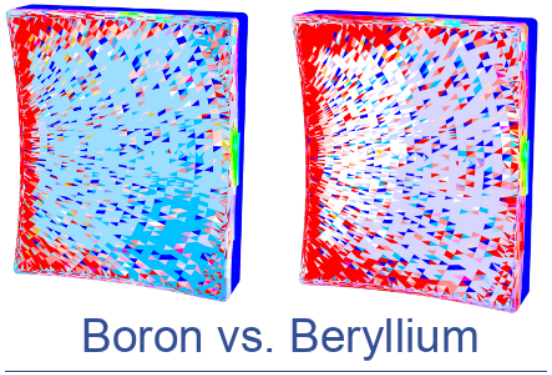
- ps-LIBS technique optimized to measure thin B layers on W substrate
- Thin deposits can be studied considering thin layer effects (reflection)
- Tests on artificial boron layers from magnetron sputtering (130/260 nm)
- Successful test on boron layer samples from Wendelstein7-X pure boronization exposure with deposits below 10nm on W samples
- Limitations due to B and W line overlapping
- Parallel recording of O, H, C and other impurities possible

=> Diagnostic tool for fast in-situ or ex-situ studies of boron layers

Examples/needs: Simulations about B erosion, transport, deposition

SP D:
- Modelling of toroidal devices w/wo boronization, W and B sources and migration
- Global fuel retention simulations
- Production of atomic and molecular data with B

ITER first Mo mirror:
B vs. Be depostion



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- Simulations strongly linked with IO activities/tasks
- Example to compare: Be vs. B in ERO2.0
- Impact of boronization on mirrors => linked to mirror studies under WPPWIE
- Boron chemistry not considered => data calculations

- JET with Be used as reference for Be and fuel retention studies with ERO2.0 and WallDYN-3D => C30C reference experiment
- In-situ spectroscopy, gas balance, and post-mortem analysis used to benchmark those codes => ITER predictions for Be/W ITER

- Predictive modelling of full-W ITER with B done under IO lead

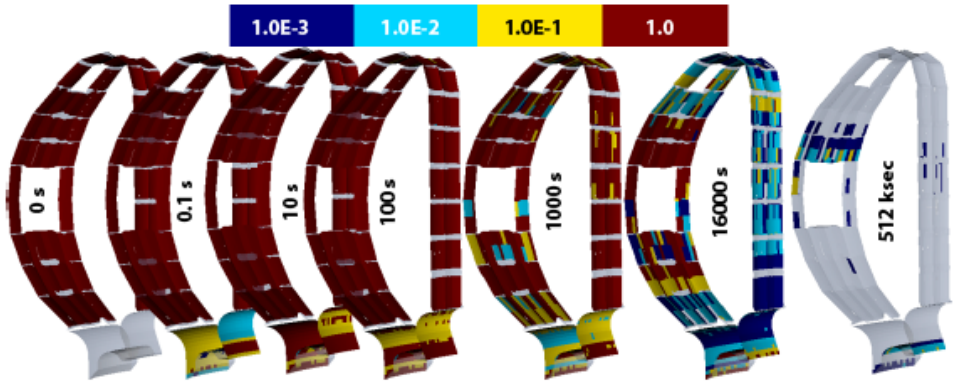

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Figure 13: Qualitative time evolution of the B surface concentration starting with a 100 nm B layer on the main chamber wall during a total of 512×10^3 s of steady state plasma exposure for OSM case 00g.

- Benchmark experiment in full-W device after ITER-like boronization (100nm), in-situ characterisation and sample removal is missing.
- Next step: predictive modelling for AUG or WEST with the same codes
- Wish from WPPWIE: dedicated campaign on those devices post-bronisation over a significant period to assess global B pattern (~100 s)

WPPWIE 2025 Activities (Tasks) List

ID	Title
SP A.1	Synergistic Load Studies of Plasma-Facing Materials for ITER & DEMO
SP A.2	High Particle Fluence Exposures of Plasma-Facing Components for ITER
SP A.3	Advanced Materials under thermo-mechanical and plasma loads
SP A.4	High Temperature performance of Armour Materials: Recrystallization and Melting
SP A.5	COMPASS-U – Materials Assessment
SP B.1	Physics of erosion and deposition
SP B.2	Material migration in toroidal devices
SP B.3	Characterization of plasma-exposed materials
SP B.4	Reference coatings for ITER and DEMO
SP B.5	Production of metallic dust in toroidal devices
SP B.6	B-deposition on diagnostic mirrors
SP C.1	Transport of Hydrogen through the first wall of fusion devices
SP C.2	T retention Release from B layers
SP C.3	Influence of He, high-flux D and impurities on Hydrogen retention and transport
SP C.4	Influence of n-damage on Hydrogen retention and transport
SP C.5	T-permeation experiments in 316L

WPPWIE 2025 Activities (Tasks) List

ID	Title
SP D.1	Plasma Boundary Modelling
SP D.2	Production of Atomic/Molecular and Surface Data
SP D.3	Impurity Migration Modelling
SP D.4	Neutral Particles Modelling
SP D.5	COMPASS-U
SP E.1	LIBS at JET
SP E.2	Comparison of hydrogenic retention quantification by different techniques and fuel removal assessment
SP E.3	Post-mortem analysis of PFC and other objects in JET
SP F.1	Coordination
SP F.2	Boronisation
SP F.3	TOMAS
SP X.1	Atomic and molecular processes in attached/detached plasma
SP X.2	Optimization of laser-based surface analysis diagnostics
AIP.1	AIP: LIBS data-processing with Deep Neural Networks and Convolutional Neural Networks for chemical composition quantification in the wall of the next step-fusion reactors
AIP.2	AIP: AI-augmented SOL modelling for capturing impact of filaments on transport and PWI in mean field codes simulations
PEX	PEX commissioning of hot cells and test facilities

PCR July 2024 - reprise

WP	PCR proposal description	2024 [k€ CC]	means of expenditure	2025 [k€ CC]	means of expenditure	Implement 2024/2025
PWIE1	Support in the analysis of the impact of boronization on the new ITER re- baseline (O getter, fuel retention and removal, lifetime, properties) and associated A&M data calculations / modelling (SP B, SP C, SP D, SP X, SP F)	100	21PM 11.5k€ mission 15k€ use of facilities	100	21PM 11.5k€ mission 15k€ use of facilities	**Fraction done! SPF HR open**
PWIE2	Analysis of JET tiles including some extracted post DT tiles (2025) and JET RH LIBS analysis completion [Note containers call done after first PCR in April – not yet allocated]			200	46PM 23k€ mission	**2024 na 2025 prep**
PWIE3	SPA: Experiments and modelling of W recrystallisation and impact on power handling and retention. Support for W samples and OG&S (different SPs)	50	9.5 PM 25k€ HW	50	9.5 PM 25k€ HW	**2024 in 2025 prep**
PWIE4	SPB: dust studies for DEMO with W (and B dust)	75	16 PM 25 k€ use of facility	75	16 PM 25 k€ use of facility	**2024 in 2025 prep**
PWIE5	Charaterisation of ITER/DEMO Mo mirrors exposed to B flux [Note mirrors also in PCR April – allocated and used]			77	20 k€ HW, 15.5PM 2 k€ Mission 10k€ use of facilities	**2024 in 2025 prep**
PWIE6	SPC: increase ressources for permeation / retention studies with real T (T-lab in USPPL) incl facility costs	29	7.5PM	70	18PM	**2024 in 2024 prep**
PWIE7	Support to COMPASS-U PFCs selection, qualification and W source estimation.	200	50 k€ use of HHFF 25 k€ use of an. facilities 25 k€ use of plasma facilities, 38.5PM	200	50 k€ use of HHFF 25 k€ use of an. facilities 25 k€ use of plasma facilities, 38.5PM	**2024 in 2025 prep**

Proposal: PWIE1 => 12 PM unallocated to shift into 2025 for (delayed) boronisation activities => Call for a person and activites