MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Progress on PWI investigations in Wendelstein 7-X

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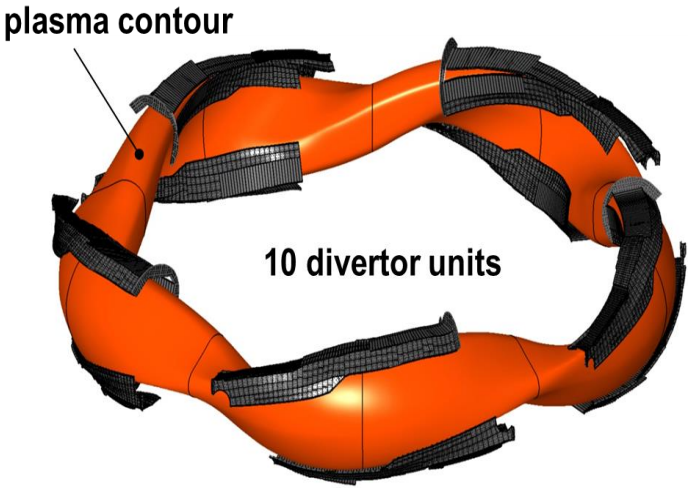
- The W7-X Team: Author list in O. Grulke et al., Nucl. Fusion 64 (2024) 112002.

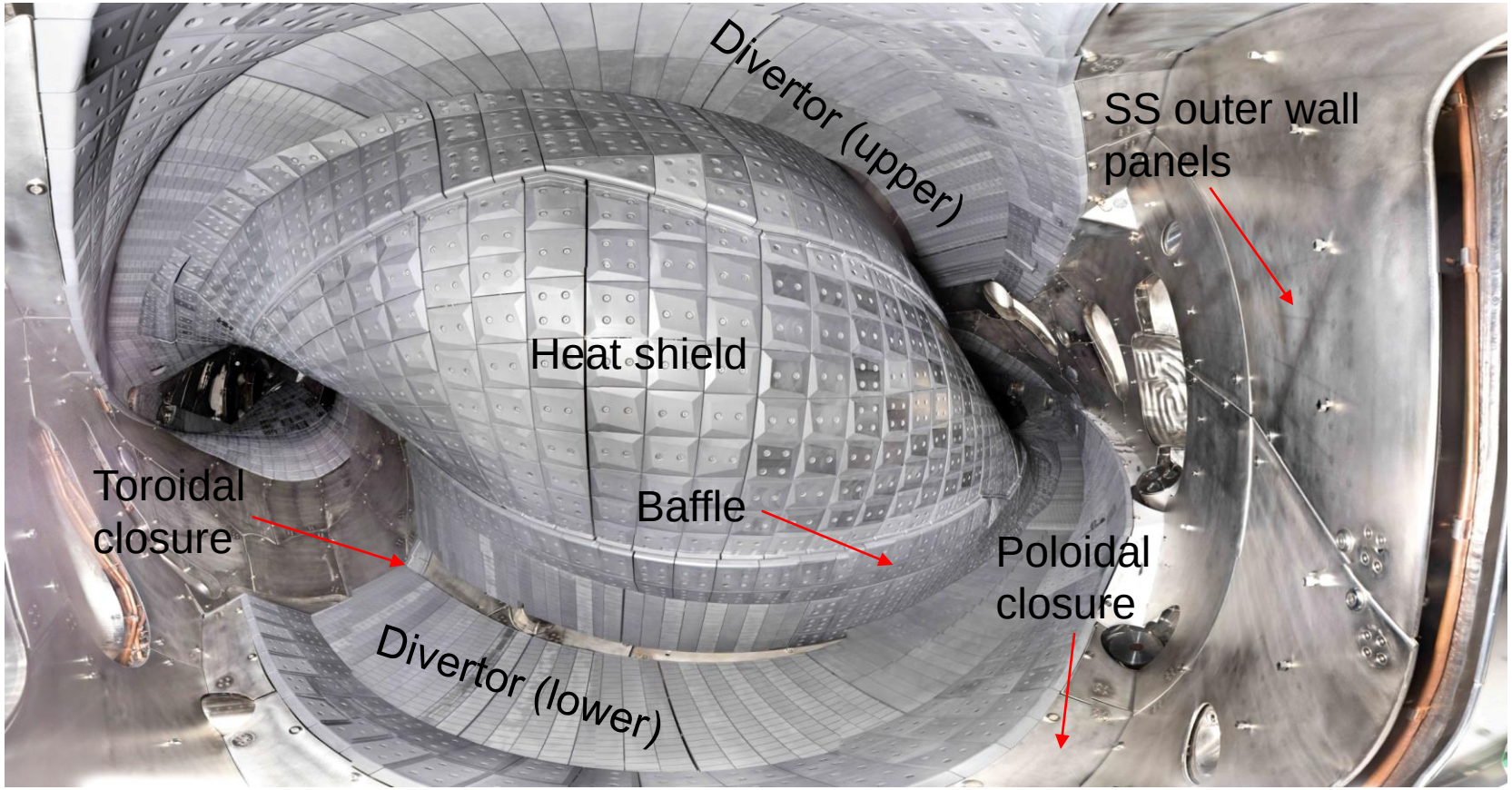
W7-X Plasma-facing components (PFCs)

PFC areas:
Carbon: 108 m^2
Stainless steel: 71.4 m^2

All the PFCs are water cooled (OP2).



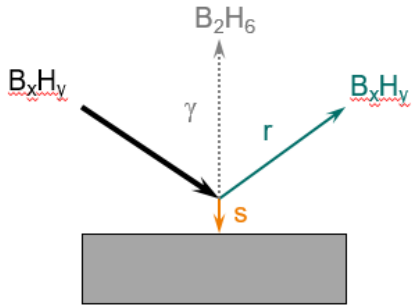
Panorama view (module 4)



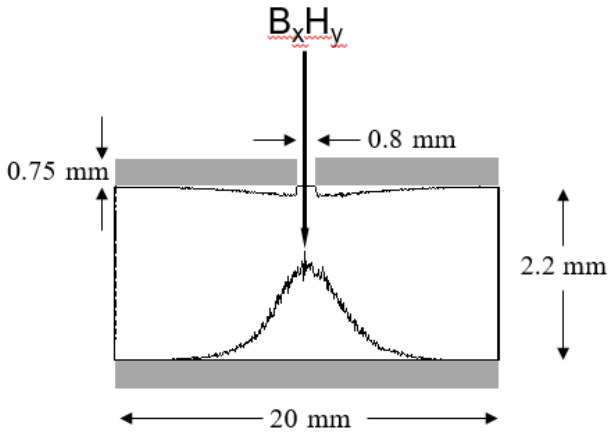
Divertor material: Fine grain graphite (FGG) for OP1.2 (Test divertor unit (TDU)), changed to carbon-fiber composite (CFC) for OP2 (High heat flux (HHF))

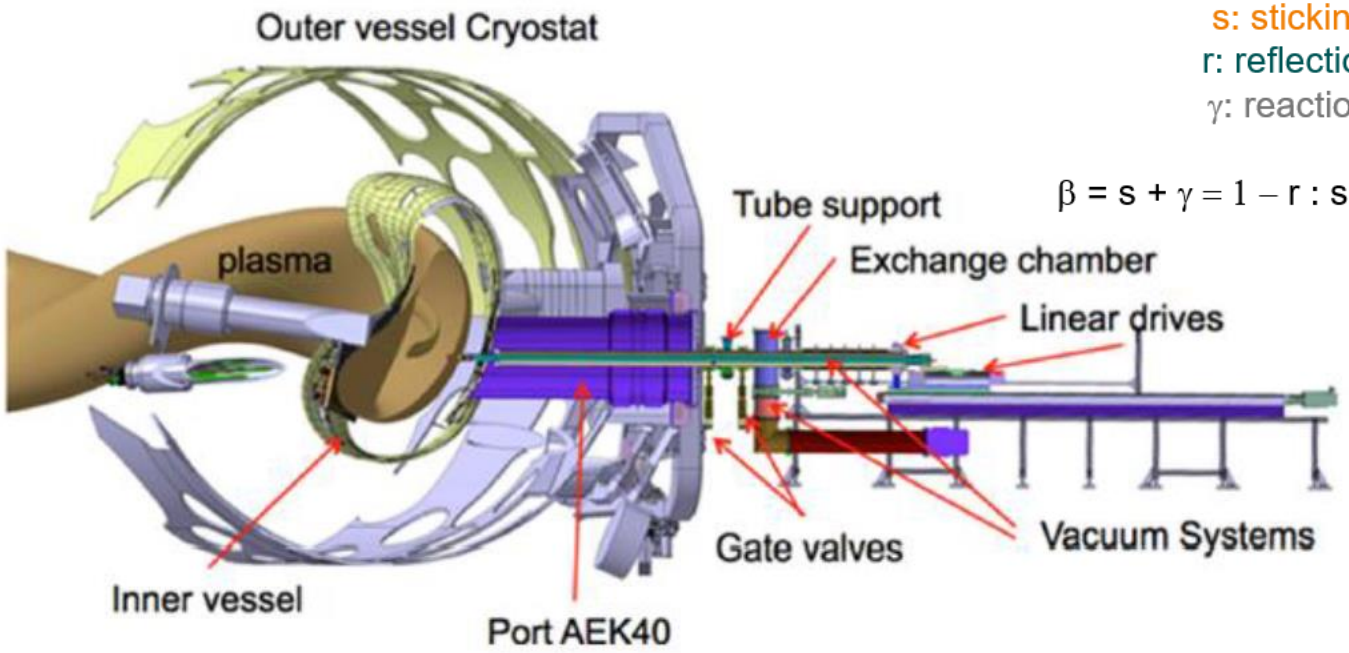
Boronization: Cavity probes exposure via Manipulator

- Exposure in W7-X during boronisation on 21.10.2024
- Using Multi-Purpose Manipulator (MPM)
- 2 cavity samples exposed
- At position of inner wall



s: sticking coefficient
r: reflection coefficient
γ: reaction probability

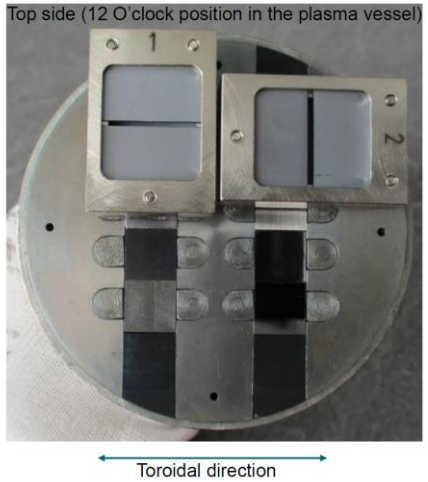




P. Drews, Nucl. Fusion 57 (2017) 126020

$\beta = s + \gamma = 1 - r$: surface loss probability

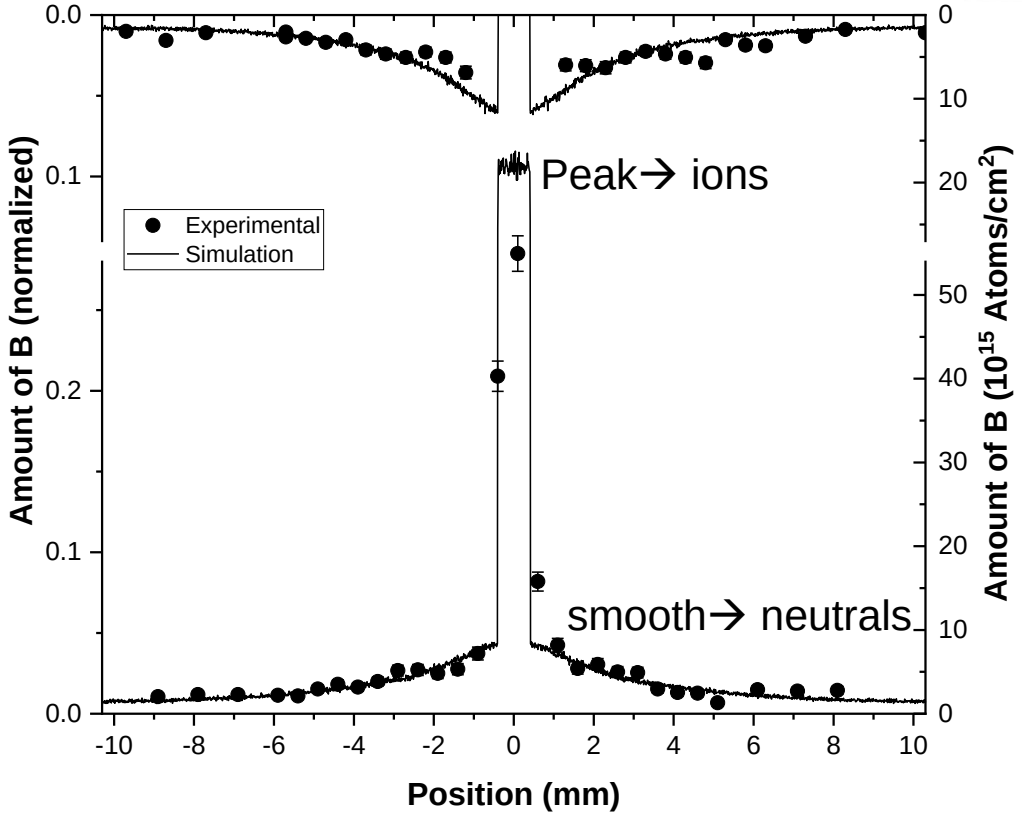
Cavity technique: $r \Rightarrow \beta$



Results: Cavity probes

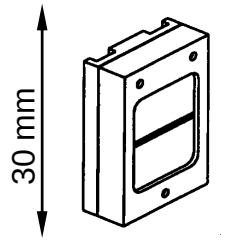
Horizontal view (Cavity 2)

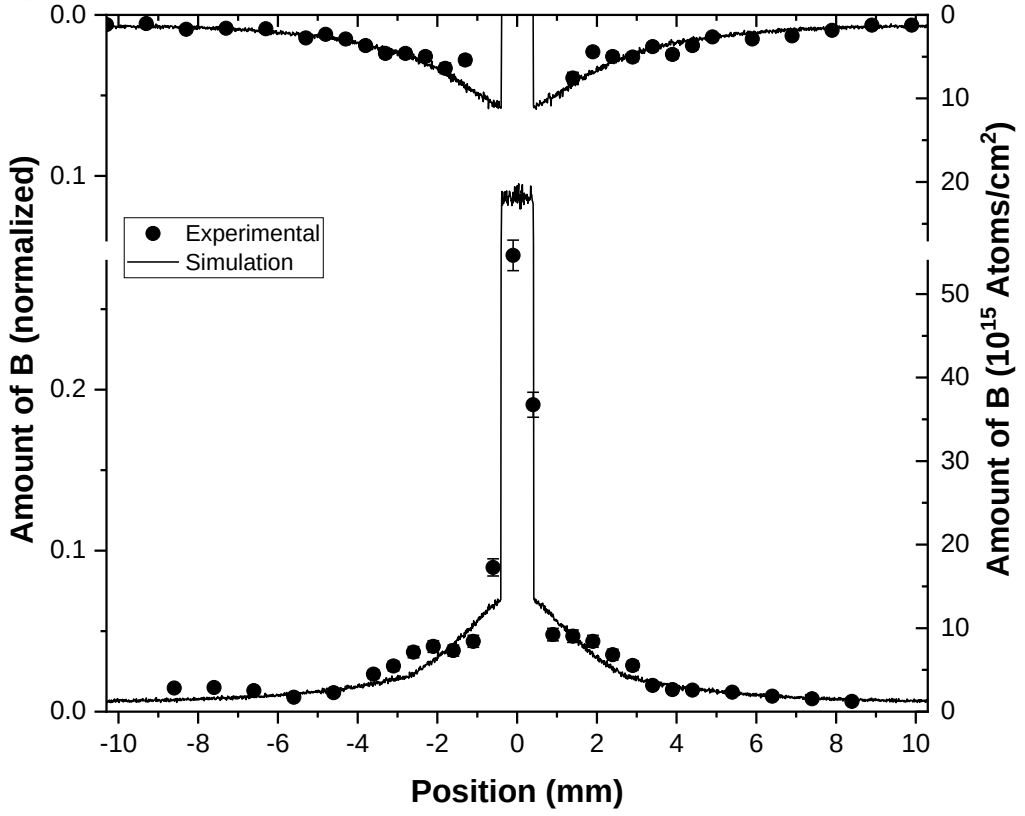
- Top/Bottom: β = 0.31±0.02 (stat.)
- Incident flux: 95% Ions + 5% Neutrals
- Best fit: β = 0.2 (Ions), ~1.0 (Neutrals)



Vertical view (Cavity 1)

- Top/Bottom: β = 0.37±0.02 (stat.)
- Incident flux: 80% Ions + 20% Neutrals
- Best fit: β = 0.2 (Ions), ~1.0 (Neutrals)





Summary: Cavity probes

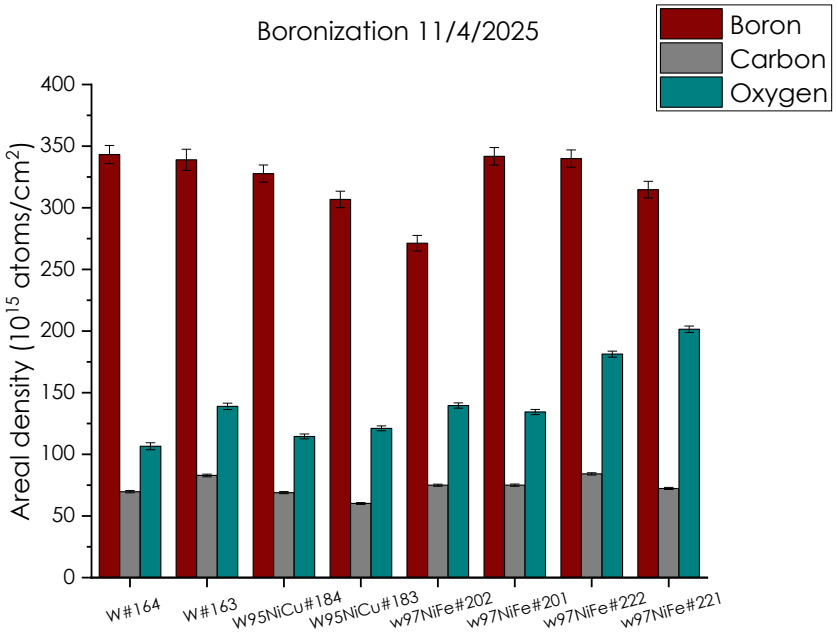
Surface loss probability β has been measured for boron radicals

- **During boronization in W7-X and ASDEX Upgrade**
- **Ions: β ≈ 0.2 Neutrals: β ≈ 1.0**
- **Open question: Which ion / radical species: B^+, BH^+, BH_2^+, … $B_2H_6^+$?**

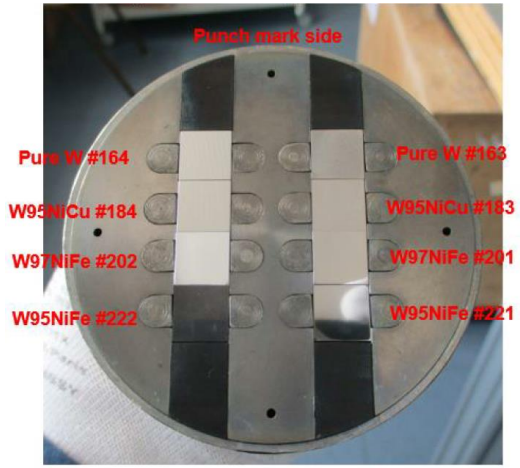
Presented at PFMC 2025, paper currently in refereeing process

Boronization: Samples exposed via Manipulator

Sample Name	OP2.2							
	Boron layer thickness		Carbon layer thickness			Oxygen layer thickness		
	average 10^{15} atoms/cm^2, nm	std. dev (%)	average 10^{15} atoms/cm^2	std. dev (%)	C/B	average 10^{15} atoms/cm^2	std. dev (%)	O/B
13.09.2024	93.2, 7.1	12.2	46.0	15.1	**0.49**	77.9	4.4	**0.8**
21.10.2024	80.2, 6.1	4.0	36.5	43.1	**0.35**	68.1	6.1	**0.8**
	OP2.3							
14.02.2025	152.6, 11.7	4.9	48.8	14.3	**0.32**	109.6	16.9	**0.72**
11.04.2025	323.0, 24.7	7.2	73.5	9.9	**0.23**	142.2	21.7	**0.44**



- No correlation between material and the boron layer thickness observed
- No correlation between surface roughness (polished – unpolished) and the boron layer thickness observed
- Thicker boron layers present lower C/B and O/B ratios. They do not scale proportionally
- Higher carbon concentrations than previously reported
- Boronization OP2.3: 11/4/2025 produced significantly thicker boron layers

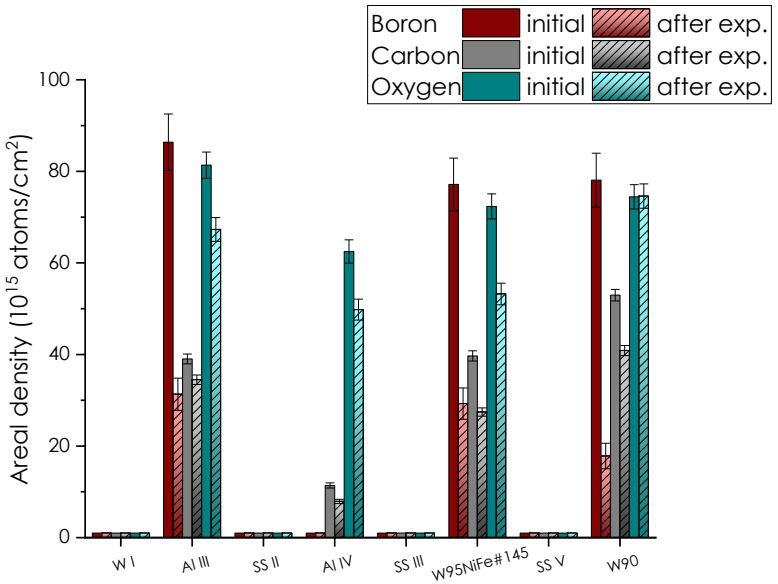


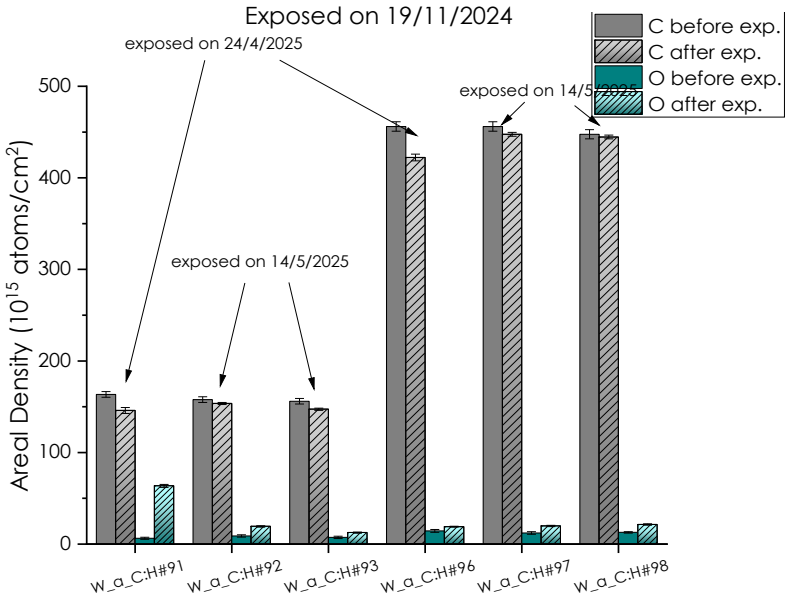
MPM Probe head FZJ-MAT1

Plasma exposure of the samples via Manipulator: CX-neutrals

Name	Exposures					
	Boron		Carbon		Oxygen	
	Av. loss	Std. dev.	Av. loss	Std. dev.	Av. loss	Std. dev.
	10^{15} atoms/cm^2	(%)	10^{15} atoms/cm^2	(%)	10^{15} atoms/cm^2	(%)
OP2.2 19/11/2024	54	6.8	8	8.1	11	11.4
OP2.3 24/4/2025	-	-	26	30.2	-	-
OP2.3 14/5/2025	-	-	6	41.5	+7	21.4
	He GDC					
21/2/2025	59	14.4	5	-	14	-

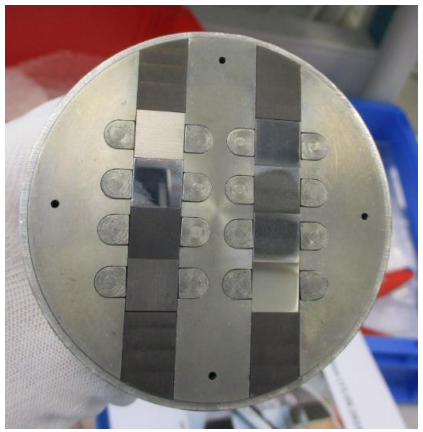
- Boron erosion rates significantly higher than the corresponding carbon and oxygen ones
- Average layer loss similar between plasma exposure and He-GDC for boronized samples
- A-C:H samples increased their oxygen concentrations after exposure
- Relatively low erosion of carbon





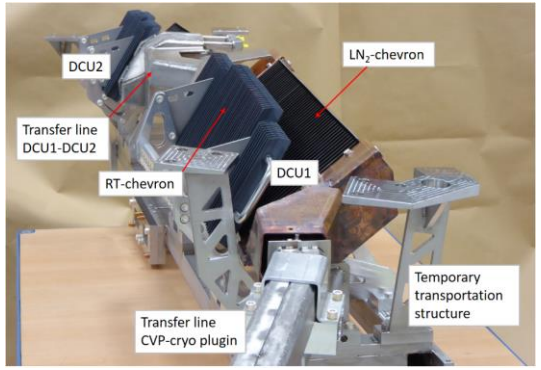
PWI activities: PFCs retrieved after OP2.2+OP2.3

Activities / Topics	Collaborators (with IPP-HGW)
1. Erosion, deposition, fuel retention investigations	
a. Post-mortem analysis: Retrieved first wall baffle, heat shield tiles (31 tiles), TZM screws (550 pcs.) and other components	AMU, FZJ, IPP-GAR, NIFS, WIT
b. White-light ellipsometry: First wall components	IPP-HGW
c. Colorimetry (optical (RGB) reflection) measurements: First wall, poloidal closure, pumping gap panels, divertor surfaces	NIFS
d. Arc-traces investigations: whole plasma-facing components (PFCs)	IPP-GAR, UTsu, UTok
e. Dust / loosely bound layers: Collected dust probes (loose layers) (112 pcs.)	IPP-GAR, RBI, WIT, U-Uppsala, FZJ
2. Wall conditioning (Glow discharge Boronization)	
a. Optimization of discharge: Investigation on GD anodes (10 pcs.)	FZJ, IPP-GAR
b. Characterization of deposited layer: Sample exposures via manipulator	FZJ, IPP-GAR

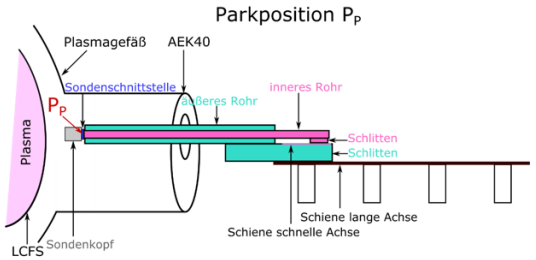


PWI activities: Overview

Activities / Topics	Collaborators (together with IPP-HGW)
3. Exhaust studies	
a. Divertor Cryo-vacuum pump: Performance optimization	KIT, NIFS
b. Neutral gas simulations: In the sub-divertor region	KIT
4. Experiments with tungsten PFCs (W-transport, accumulation, erosion/ deposition), 13C, 15N isotope injections	
a. Tungsten PFCs: Baffles, heat shield	IPP-HGW, UW
b. Tungsten samples from Multi-purpose manipulator	FZJ, IPP-GAR, NIFS
c. 13C and 15N isotopes injection from the manipulator	FZJ, IPP-HGW
5. Simulations (Carbon / tungsten PFCs)	
a. EMC3-EIRENE	IPP-HGW, UW
b. ERO2.0	FZJ
c. WallDYN3D	IPP-GAR
d. DIVGAS	KIT



Ref.: G. Ehrke



Ref.: C. Killer

Collaborators are welcome to propose the experiments for the PWI studies in W7-X for the next dual plasma campaign OP2.4+OP2.5 starting in second half of 2026.

Call for proposals will be announced through EUROfusion.

For any prior discussions, you may contact me, chandra.prakash.dhard@ipp.mpg.de

Thank you very much for your kind attention !