HELIAS key gaps meeting 24.06.2025

Plasma-wall interactions and PFCs

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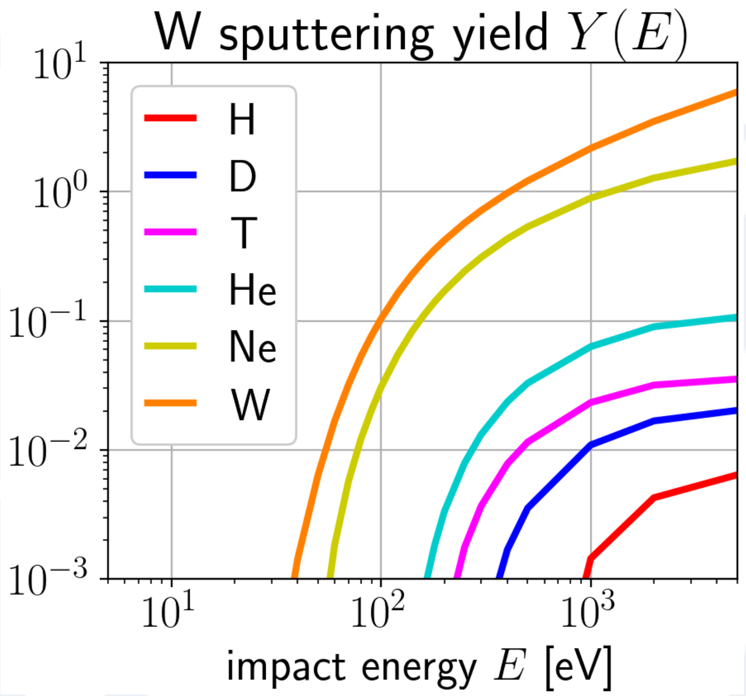
Introduction

- Important goals of PWI and PFC research:
  - maximize lifetime of PFCs w.r.t. erosion
  - minimize T retention, undesirable plasma impurities, dust
  - qualify PFCs and diagnostics
- Here: explicitly focus on W as the most promising plasma-facing material (no liquid metal divertor etc.)
- Main gap: all-metallic environment required to prove feasibility of carbon-free HELIAS reactor
  - **no suitable all-metallic stellarators available at the moment**
  - one considered option: W7-X all-metallic upgrade for OP 3 (>2032)
- Some PWI and PFC questions are not stellarator or HELIAS-specific
  - can be addressed by non-HELIAS stellarators, tokamaks, linear plasma devices, neutron irradiation facilities, ion beam experiments, high heat flux facilities, ...
  - important to point out alignment with EUROfusion tokamak DEMO activities

PWI.1: W gross erosion in reactor-relevant conditions

- Scope: Estimate W sources, considering:
  - divertor targets: erosion by seeding impurity ions (e.g. Ne) and W self-sputtering
  - baffles, heat shield, remote areas: erosion by energetic charge-exchange neutrals (D, T)
  - erosion by fast particle confinement loss
- Experimental techniques and devices:
  - W7-X: sample exposure using manipulators (MPM, MATEO) or embedded samples / tile replacement + W spectroscopy & post-mortem analysis; preferable in future: global W erosion in all-metallic stellarator
  - certain aspects can be covered by other devices: tokamaks, ion beams, linear plasma devices
- Codes/Models:
  - BCA codes e.g. SDTrimSP, MD codes, PIC codes, ERO/WallDYN+EMC3-EIRENE, ASCOT

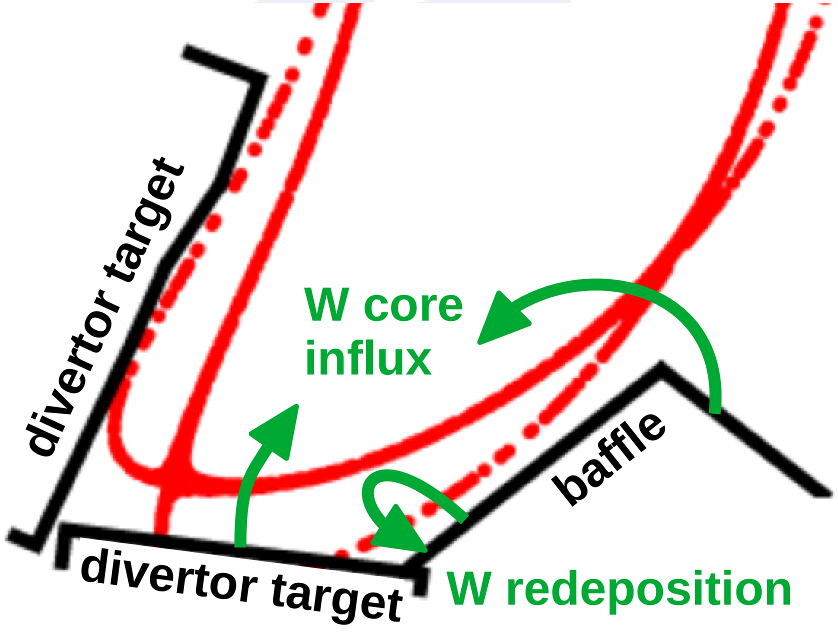


High priority due to importance of W PFC lifetime and core radiation

Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.1	2.5	2.5	3.0	8	High	Medium

PWI.2: W migration & core influx

- Scope:
  - asssess difference between gross and net erosion, considering prompt redeposition and transport mechanisms like drifts, friction, thermal forces
  - W divertor screening efficiency (influx to the confined plasma)
- Experimental techniques and devices:
  - W7-X (W samples, TESPEL, LBO -> VUV, SXR, bolometry, LIBS), all-metallic stellarator (-> global erosion)
- Codes/Models:
  - STRAHL, ERO, WallDYN, EMC3-EIRENE
  - *code development needed for self-consistent model combining main plasma & impurity transport with drifts and turbulence effects; lack of validated W atomic data (ADAS)*



Synergy with impurity transport in other HELIAS gaps

High priority due to importance of W PFC lifetime and core radiation; low alignment w/ tokamak DEMO

Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.2	3.0	3.0	2.5	8.5	High	Low

PWI.3: Wall conditioning and lifetime of boron layers on W PFCs

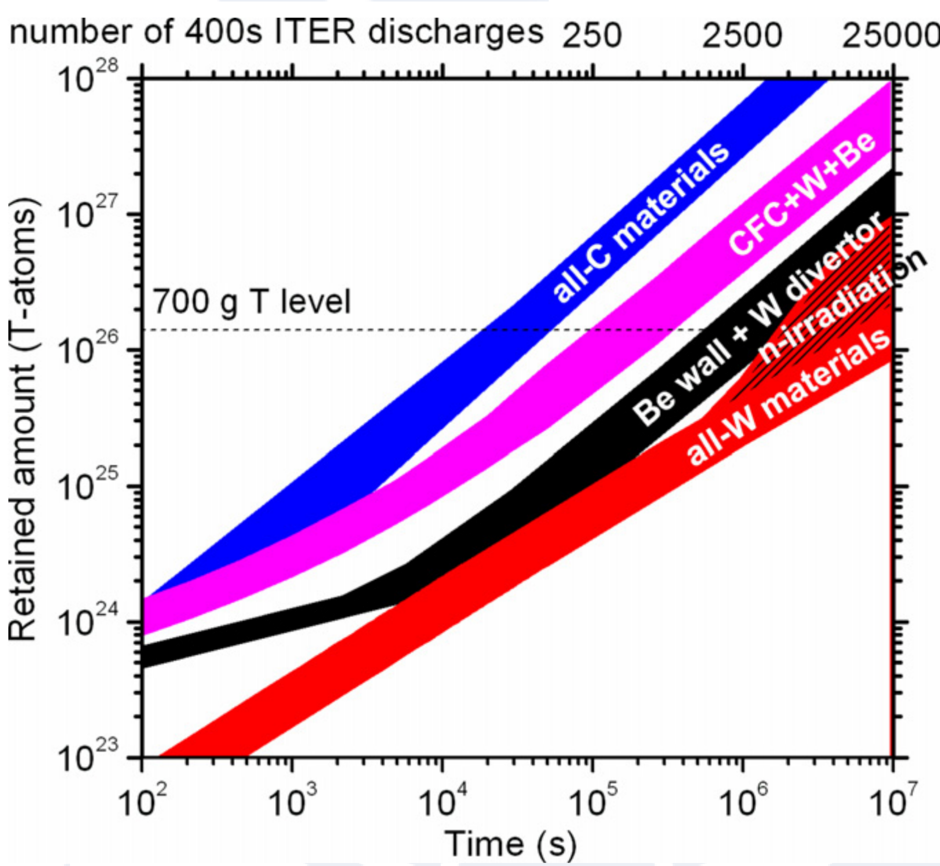
- Scope:
  - test boronisation on W components by GDC, ECWC, powder/pellet injection; optimize for homogeneous B layers and low-Z plasma (relevant especially during reactor start-up)
  - B layers: lifetime and redistribution
- Experimental techniques and devices:
  - W7-X: spectroscopy, post-mortem analysis of samples incl. manipulators (MPM, MATEO); all-metallic stellarator
  - certain aspects can be covered by lab experiments (e.g. TOMAS), tokamaks
- Codes/Models:
  - EMC3-EIRENE-(DIS), DUSTT, MIGRAINE, ERO, WallDYN
  - *GDC modelling as used for ITER (Wauters NME 2025)*

Medium priority: mostly relevant in start-up of reactor

Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.3	2.5	2.0	2.5	7.0	Medium	Medium

PWI.4: Tritium retention in W PFCs and cleaning

- Scope:
  - estimate short and long-term retention by implantation/co-deposition + diffusion, trapping, permeation => affects wall pumping, outgassing, fuelling and density control
  - assess fuel removal efficiency by different cleaning techniques incl. baking, cleaning discharges, GDC, ECWC => develop fuel retention mitigation and removal strategies
- Experimental techniques and devices:
  - all-metallic stellarator (H/D): RGA, LIDS, LIA-QMS, LIBS, passive spectroscopy, IR cameras
  - lab experiments (e.g. TDS)
- Codes/Models:
  - reaction-diffusion (macroscopic rate equation) codes e.g. FESTIM/TMAP/MHIMS; ab-initio DFT / MD, WallDYN, EIRENE, ERO
  - *need code development for combined retention & transport modelling (as e.g. SOLEDGE-MHIMS)*

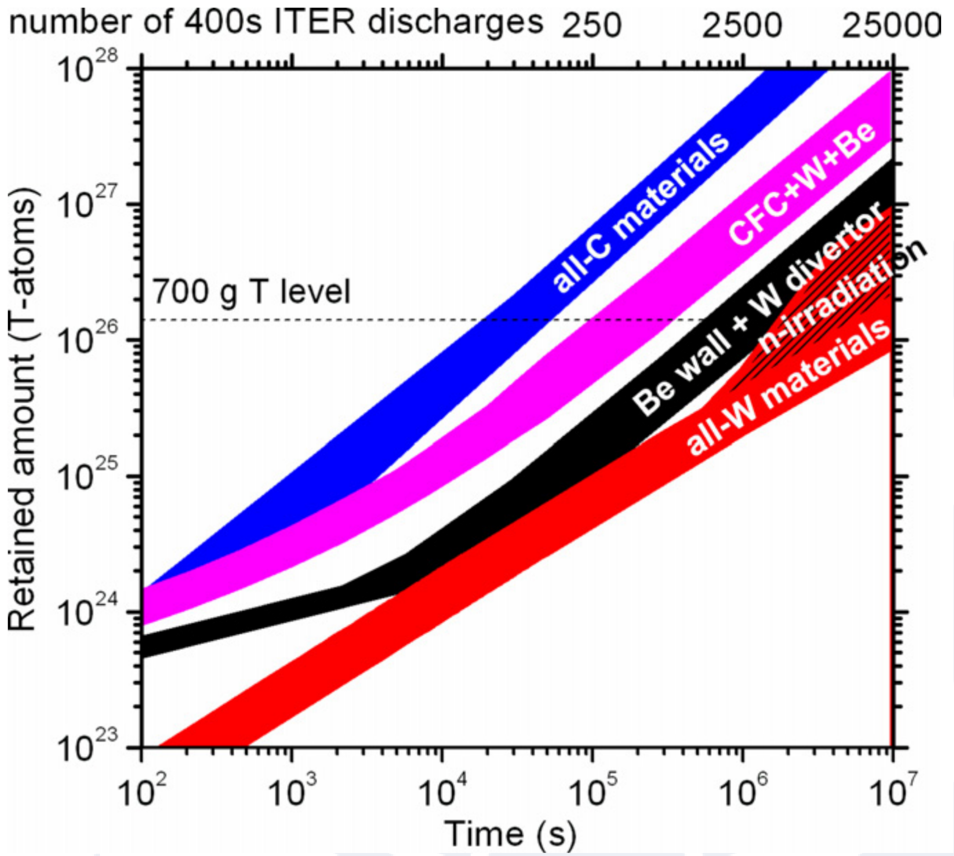


Medium priority due to high overlap with tokamak DEMO

Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.4	2.0	2.0	2.0	6.0	Medium	High

PWI.5: Effects of 14 MeV neutrons on materials

- Scope:
  - consider influence of neutron damage (dpa, transmutation) at DEMO-relevant fluence on retention, thermo-mechanical properties, diagnostics degradation
    - assess effect on other gaps
- Experimental techniques and devices:
  - neutron irradiation facilities (IFMIF-DONES, VNS, MYRRHA/MINERVA, ...), proton or W self-damage + lab experiments
- Codes/Models:
  - Monte-Carlo neutronics codes such as MCNP; MD

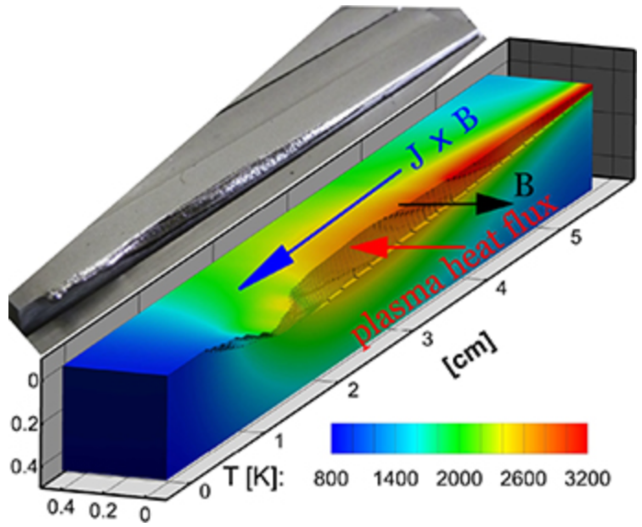


Medium priority due to high overlap with tokamak DEMO

Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.5	2.0	2.0	2.0	6.0	Medium	High

PWI.6: Dust, flaking, arcing, melting of W PFCs

- Scope:
  - estimate effects on PFC lifetime, W sources, T retention, environmental hazard of dust
  - effects of fast particles
- Experimental techniques and devices:
  - all-metallic stellarator: post-mortem analysis incl. photometry, fast cameras
  - certain aspects can be covered by tokamaks or other stellarators
- Codes/Models:
  - MEMOS, DUSTT, MIGRAINE



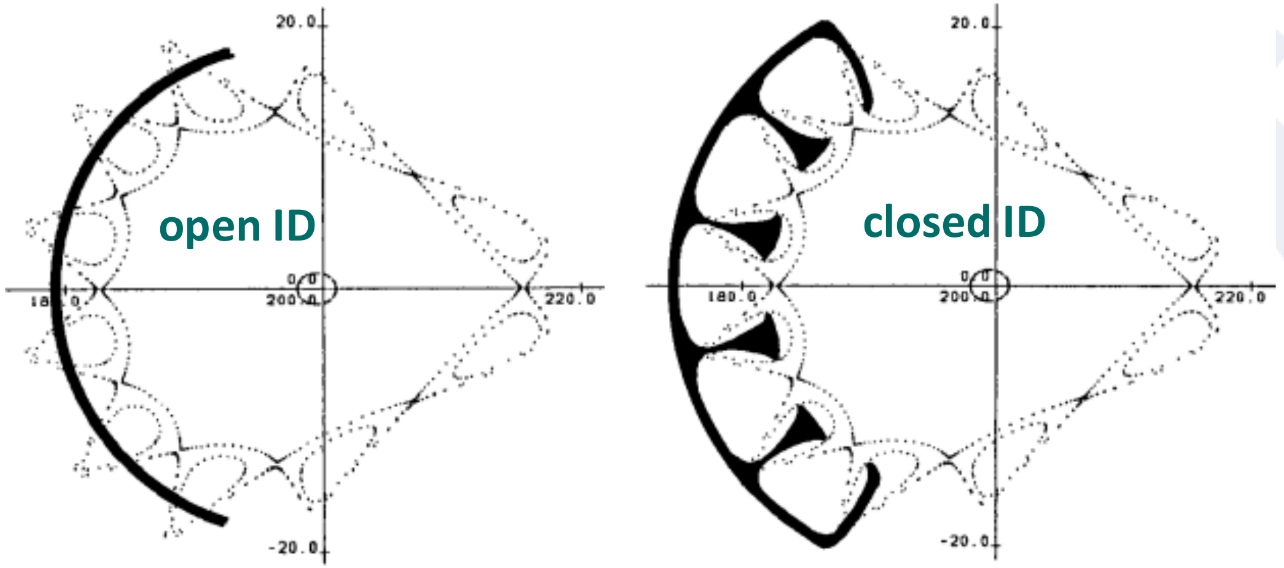
ELM-driven W lamella melt damage in JET divertor; MEMOS-U simulation

Medium priority as less transient events compared to tokamaks

Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.6	1.5	2.0	2.0	5.5	Medium	Low

PWI.7: PWI qualification of closed island divertor with W targets

- Scope:
  - confirm desirable W erosion & screening (see gaps 1-2) in closed island divertor with improved baffling
- Experimental techniques and devices:
  - all-metallic stellarator with closed divertor (e.g. W7-X after OP-3 upgrade)
- Codes/Models:
  - FLT, WallDYN, ERO, EMC3-EIRENE



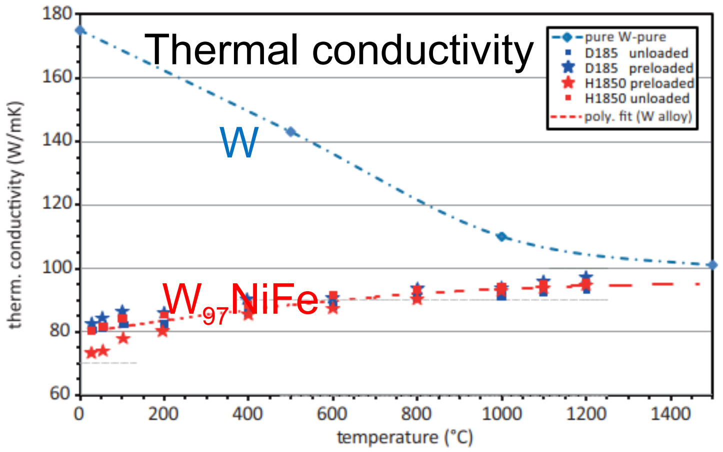
Synergy with "Heat and particle exhaust" group

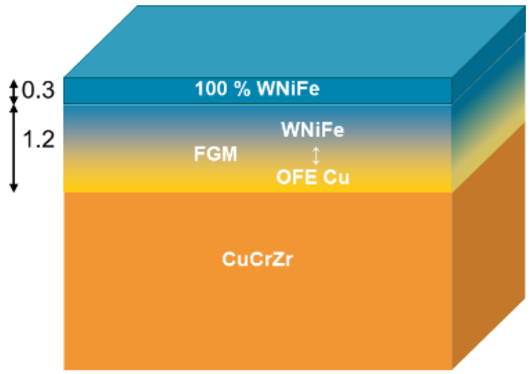
High priority to enable construction of all-metallic stellarator

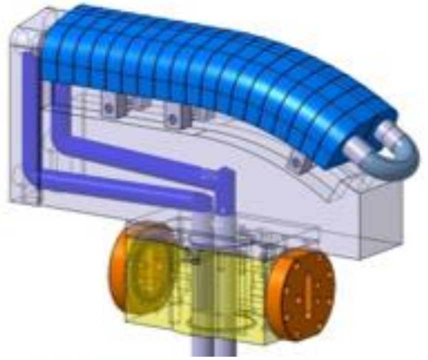
Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.7	2.5	2.5	3.0	8.0	High	Low

PWI.8: Qualification of reactor-compatible W-based materials and components

- Scope:
  - design transition from plasma-facing material (W) to heat sink material (e.g. Cu)
  - assess W composites (e.g. W/Ni/Fe alloys) in place of pure W
- Experimental techniques and devices:
  - W7-X (MPM, MATEO); all-metallic stellarator
  - certain aspects can be covered by tokamaks, other experiments (e.g. GLADIS)
- Codes/Models:
  - FEM, FLT, BCA+MD, ERO, WallDYN







sample exposure using MATEO

Synergy with WP-DIV

High priority to enable construction of all-metallic stellarator

Gap ID	Relevance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.8	2.5	2.5	3.0	8.0	High	High

Summary

Gap ID	Description	Rele-vance	Urgency	Effort required	Total Score	Priority	Alignment w/ tokamak DEMO
PWI.1	**W gross erosion in reactor-relevant conditions**	2.5	2.5	3.0	8.0	**High**	Medium
PWI.2	**W migration & core influx**	3.0	3.0	2.5	8.5	**High**	Low
PWI.3	Wall conditioning and lifetime of boron layers on W PFCs	2.5	2.0	2.5	7.0	Medium	Medium
PWI.4	Tritium retention in W PFCs and cleaning	2.0	2.0	2.0	6.0	Medium	High
PWI.5	Effects of 14 MeV neutrons on materials	2.0	2.0	2.0	6.0	Medium	High
PWI.6	Dust, flaking, arcing, melting of W PFCs	1.5	2.0	2.0	5.5	Medium	Low
PWI.7	**PWI qualification of closed island divertor with W targets**	2.5	2.5	3.0	8.0	**High**	Low
PWI.8	**Qualification of reactor-compatible W-based materials and components**	2.5	2.5	3.0	8.0	**High**	High