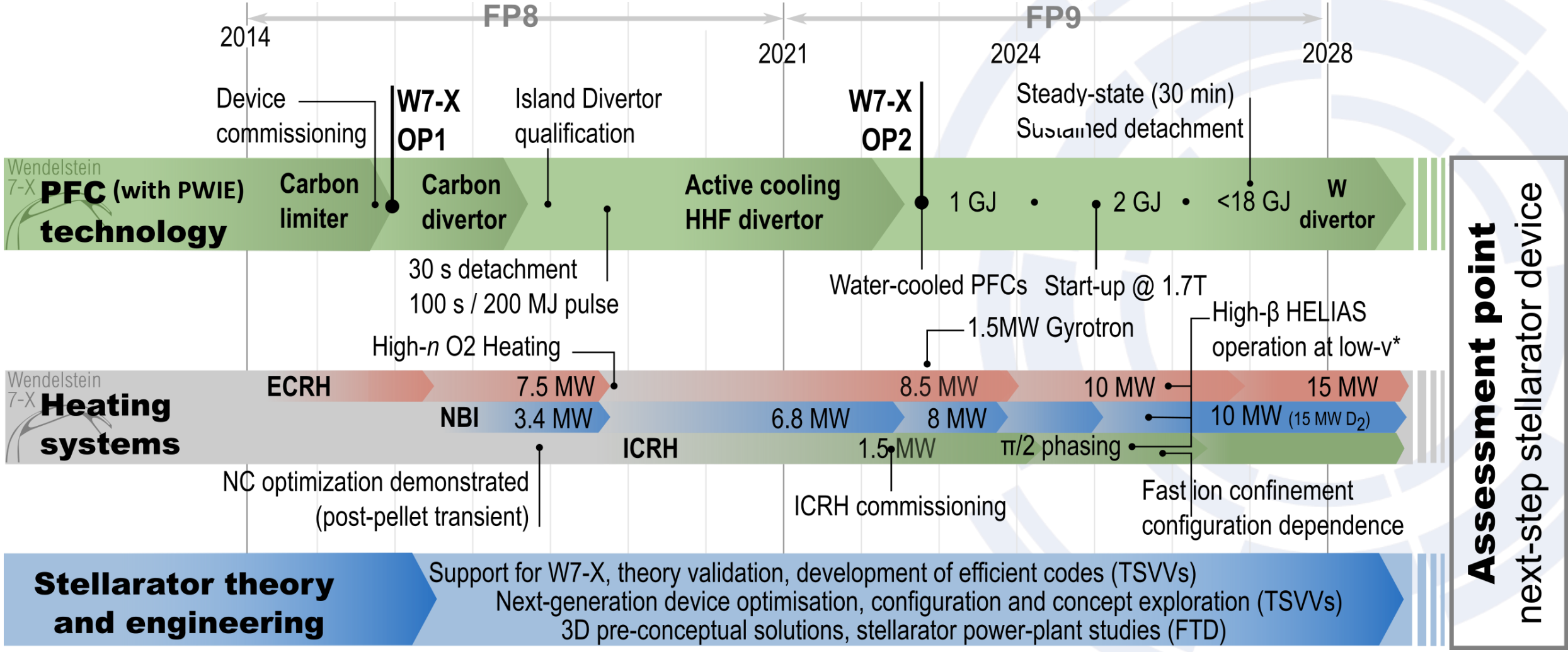
PSD Planning Meeting

WP STEL

M.Jakubowski (TFL), D.Carralero(DTFL), I.Calvo (DTFL), J.Haese(PSO), presented by C.P. Dhard

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.

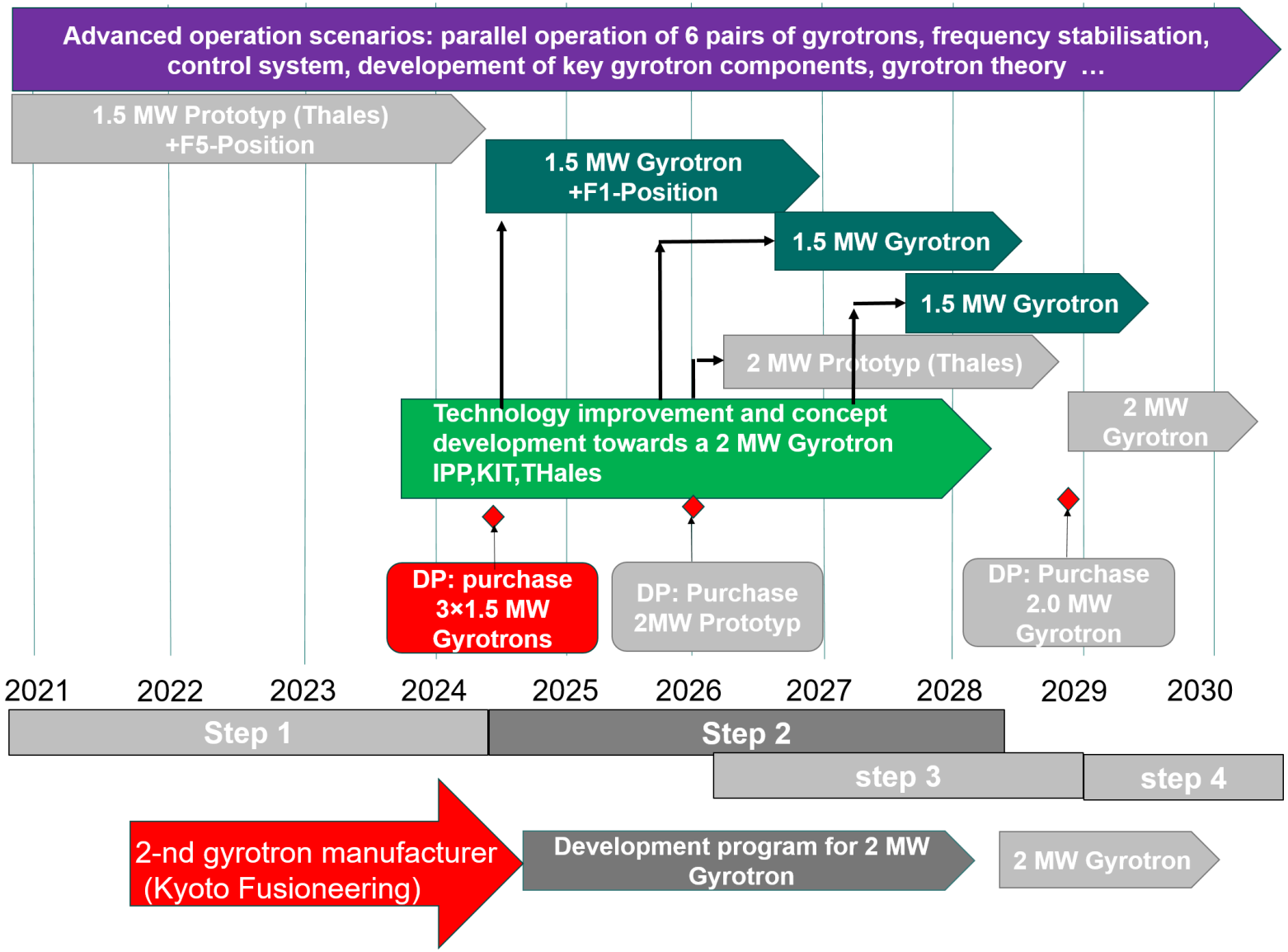
Reaching goals of W7-X within FP9



Gyrotron development – 10 MW for 30 minutes/ higher power in short pulse

- W7-X is increasing its input power.
  - 12 gyrotrons
    1.5MW Thales 2027, 2MW Kyoto Fusioneering 2028,…
  - 10 MW/30 minutes, ca. 12 MW for shorter pulses
  - Extending NBI input power from 8 MW to 12 MW

- This provides more PSOL power, and hopefully higher target loads (in carefully adjusted configurations).

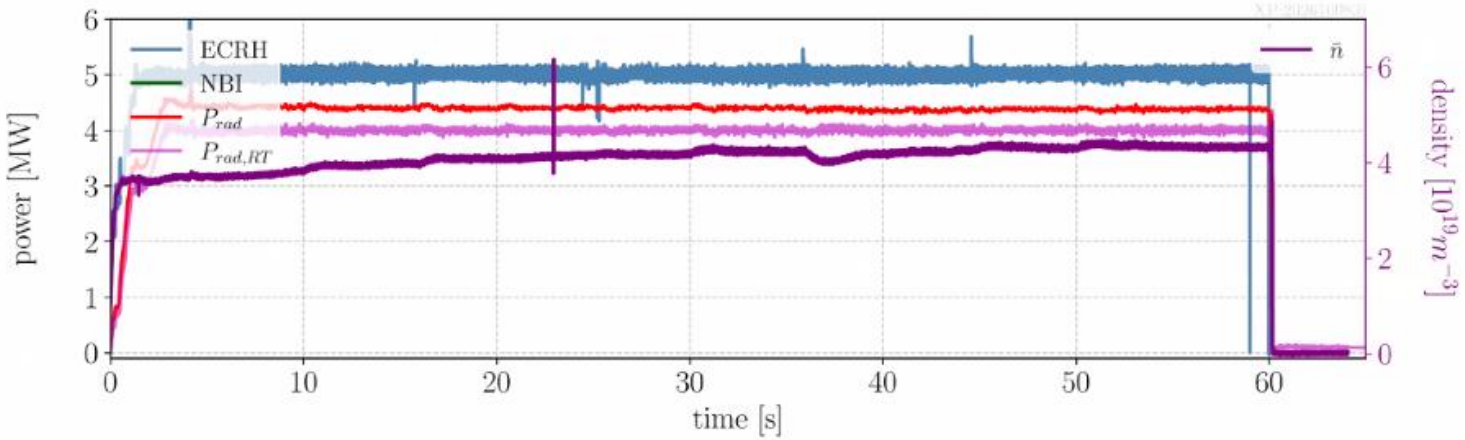


Grand Delivarables in 2026–2027

Grant Deliverable 1	Report on high confinement scenarios via plasma profile control and high-power scenarios at low magnetic field to reach reactor relevant collisionalities ($\nu^* < 0.1$) and high beta ($\langle\beta\rangle \geq 2.5\%$)
Grant Deliverable 2	Report on experimental assessment of modelling predictions for fast ion physics and turbulent transport
Grant Deliverable 3	**Report on long pulse scenarios with nτTi > 0.1e20 and plasma duration of up to 1000 s**

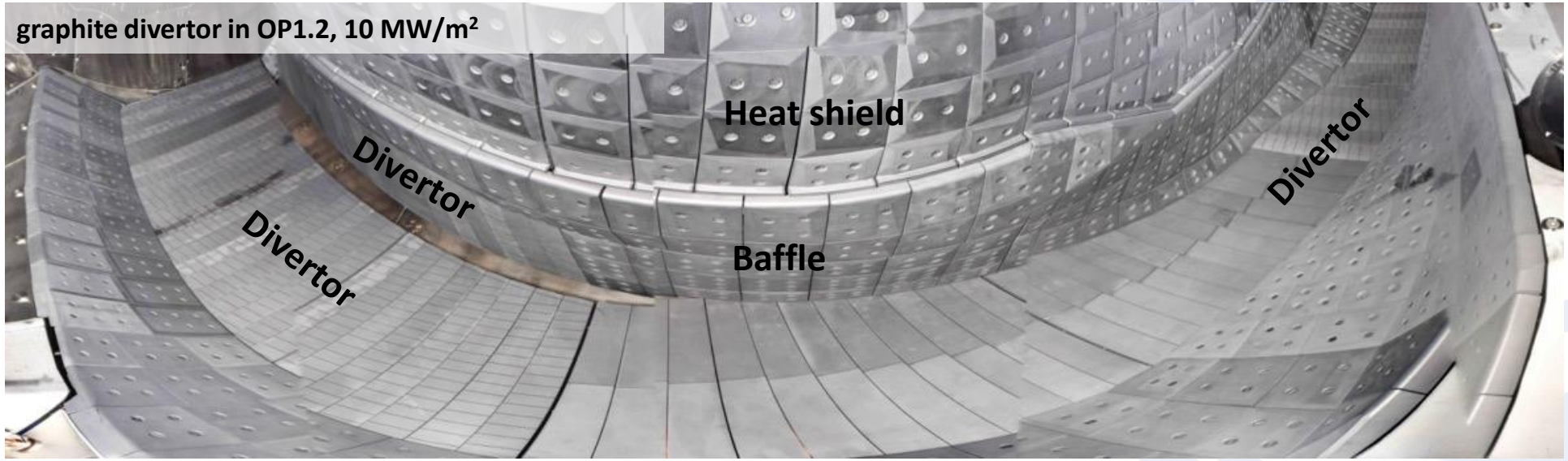
W7-X goal for OP2.4-2.6 is 6 GJ energy throughput (ongoing):

- 60s preparatory program went well
- best achievement: 155s discharge length (~780MJ)
- if gyrotron drop outs cannot be compensated by other gyrotrons (power stabilization), change to relative radiation feedback P_{rad}/P_{heat} important

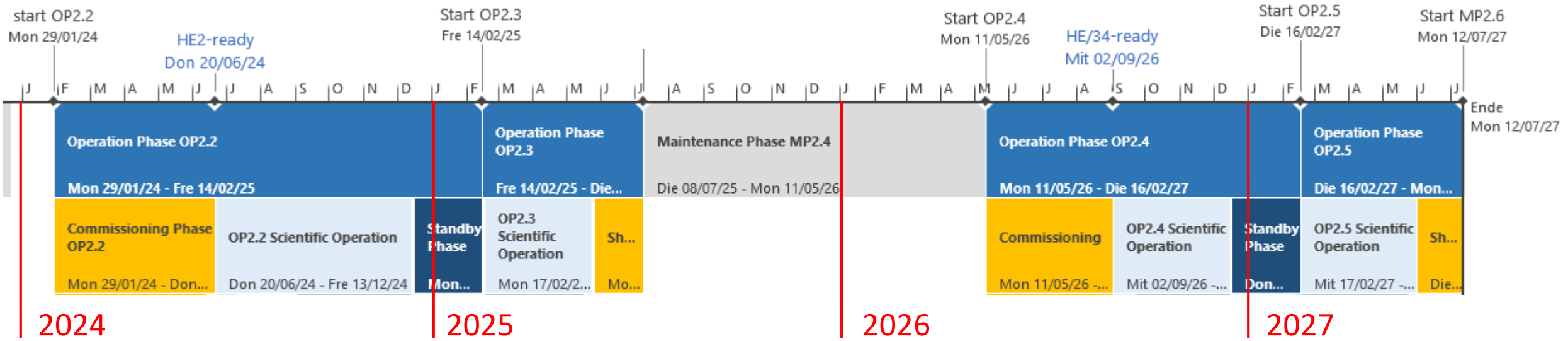


Towards steady-state compatible divertor

OP1.1	OP1.2	OP2	OP3
2015 / 2016 • 5 MW • 4 MJ • 6 sec	**2017 / 2018** • 8 MW • 200 MJ • 100 sec	**2022 - 2028** • 10 MW • 1GJ, →18 GJ • 30 minutes	**202x …** • Heating upgrades • 18 GJ • 30 minutes
Inertial cooling	Inertial cooling	Water-cooling of PFCs	carbon-free device



Operational planning until 2027



- Experimental campaigns are grouped together in pairs with standby phases in between
- Groups of experimental campaigns alternate with maintenance phases
- Diagnostic upgrades, heating systems upgrades, preparation of deuterium operation, conversion of plasma facing material from carbon to tungsten, eventually tungsten divertor

Research topics for experimental campaigns 2026/2027

Tag	Description
High performance conditions	Exploration of reduced turbulence/ high-performance scenarios in view of stationary plasma conditions with temperature-, density and impurity-profile control.
Heating scenarios	Exploration of heating scenarios using upgraded heating capabilities (ECRH, NBI, ICRH).
High beta scenario development	Development of high plasma beta scenario by low field operation.
Long-pulse operation and wall conditioning	**Development of integrated scenarios for long-pulse operation with PFC heat-load control, efficient particle exhaust and impurity screening; Development of wall conditioning procedures.**
Detachment	**Development of long and stationary divertor detachment scenarios with and without impurity seeding.**

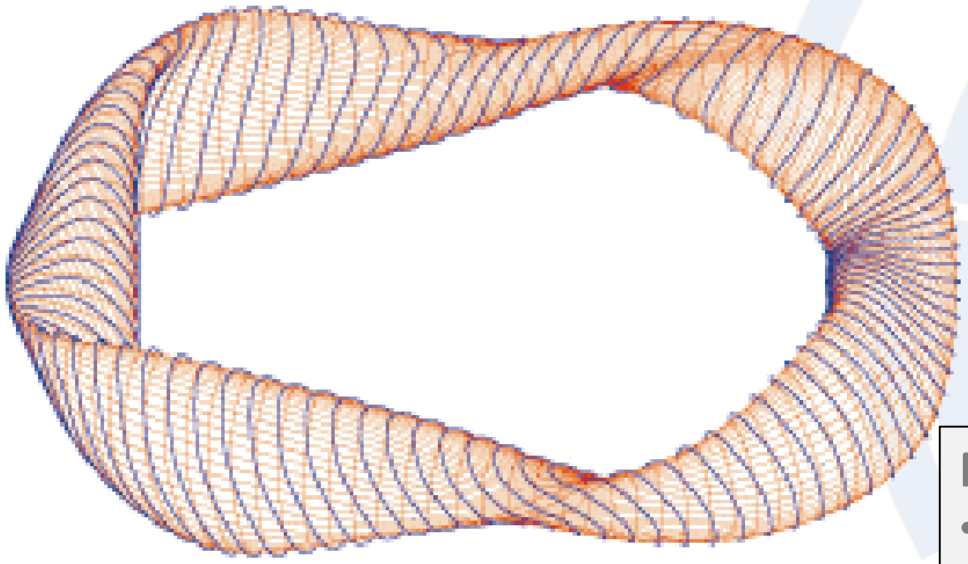
Research topics for experimental campaigns 2026/2027

Tag	Description
Tungsten PFCs (together with WP PWIE)	Exploration of scenarios compatible with carbon free operation and tungsten PFCs.
Documentation of physics basis	Physics basis (core, edge) and reference discharges.
Core physics studies	Completion of the core transport and stability physics basis in the extended operational space.
Edge physics studies	**Completion of the edge and SOL physics basis in the magnetic configuration space of W7-X.**

Gaps in six areas

Scenario integration
- **Plasma fuelling**
- Auxiliary heating
- Integrated scenarios

Plasma-wall interaction
- **Gross erosion, migration & core influx of tungsten**
- Closed divertor
- Strategy for wall-conditioning



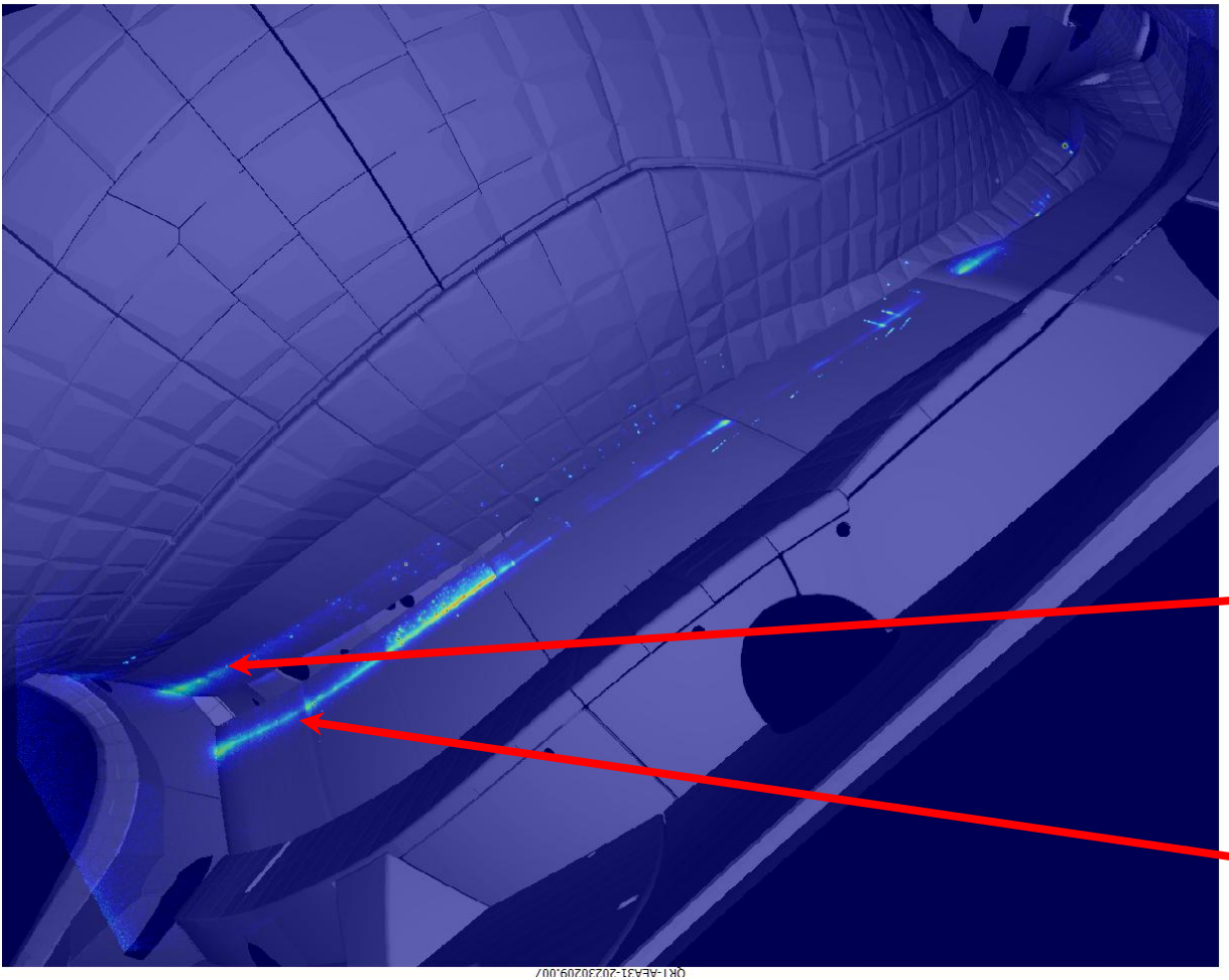
Fast particle confinement
- **Confinement (at high β)**
- Alfvén eigenmodes
- Prediction of wall losses
- Interplay with fast ions/turbulence/zonal flows

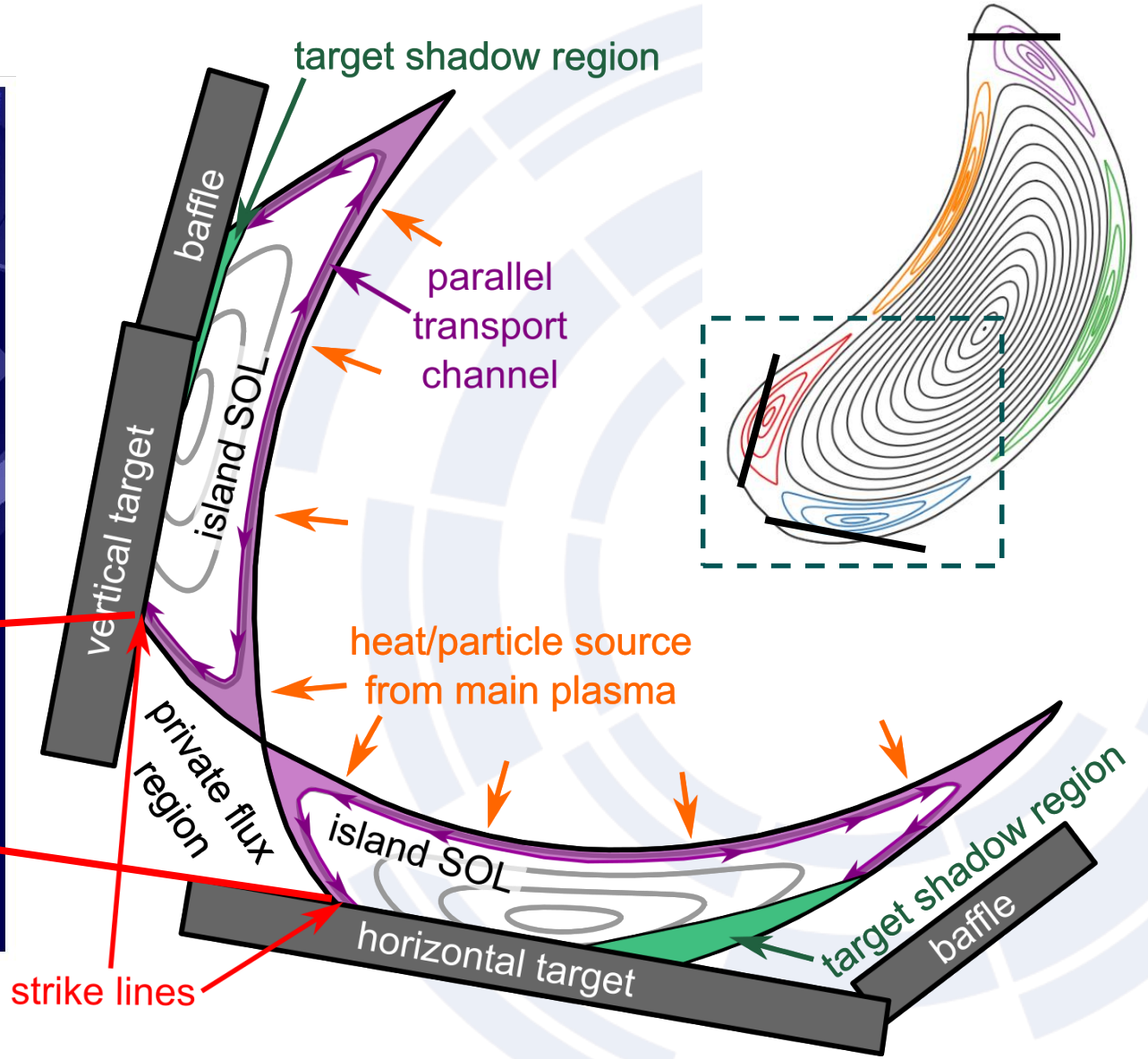
Heat and particle exhaust
- **Drift effects**
- Divertor closure
- Cross-field transport
- Core/edge compatibility
- Island/SOL geometry

MHD equilibrium and stability
- **Stability at high β**
- Current driven instabilities
- Divertor resilience

Core transport and confinement
- **Configuration dependence**
- Impurity transport
- Predictive modelling

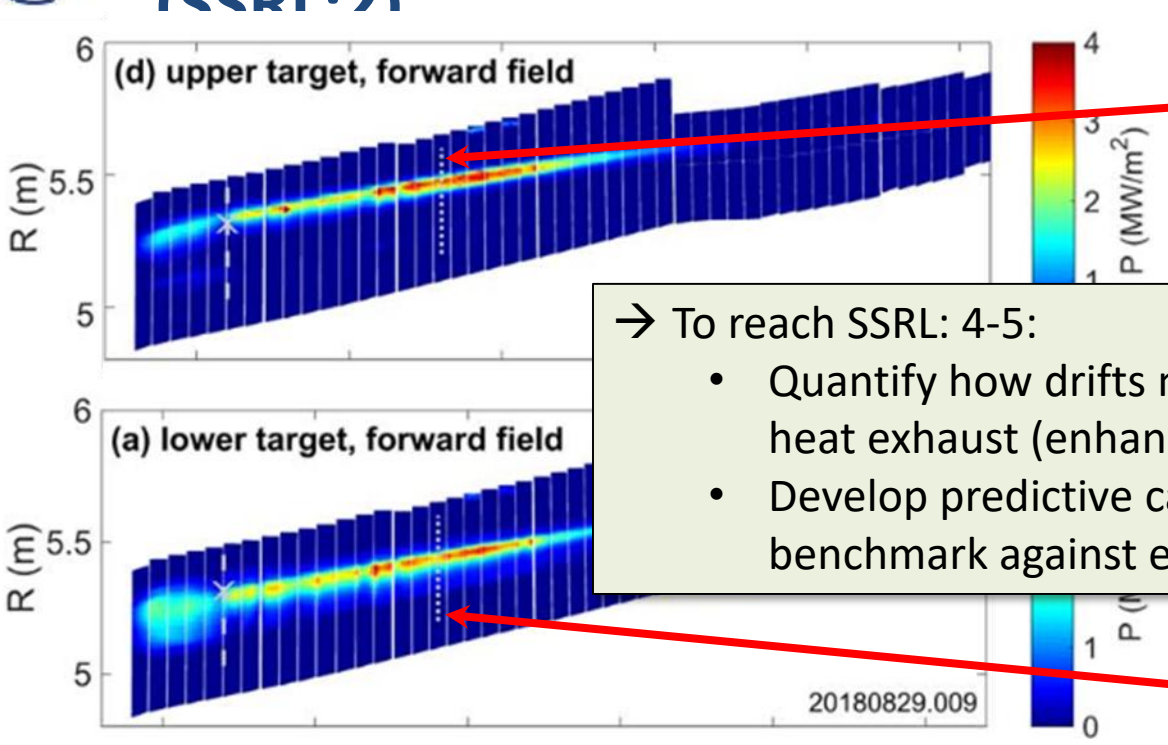
Island divertor

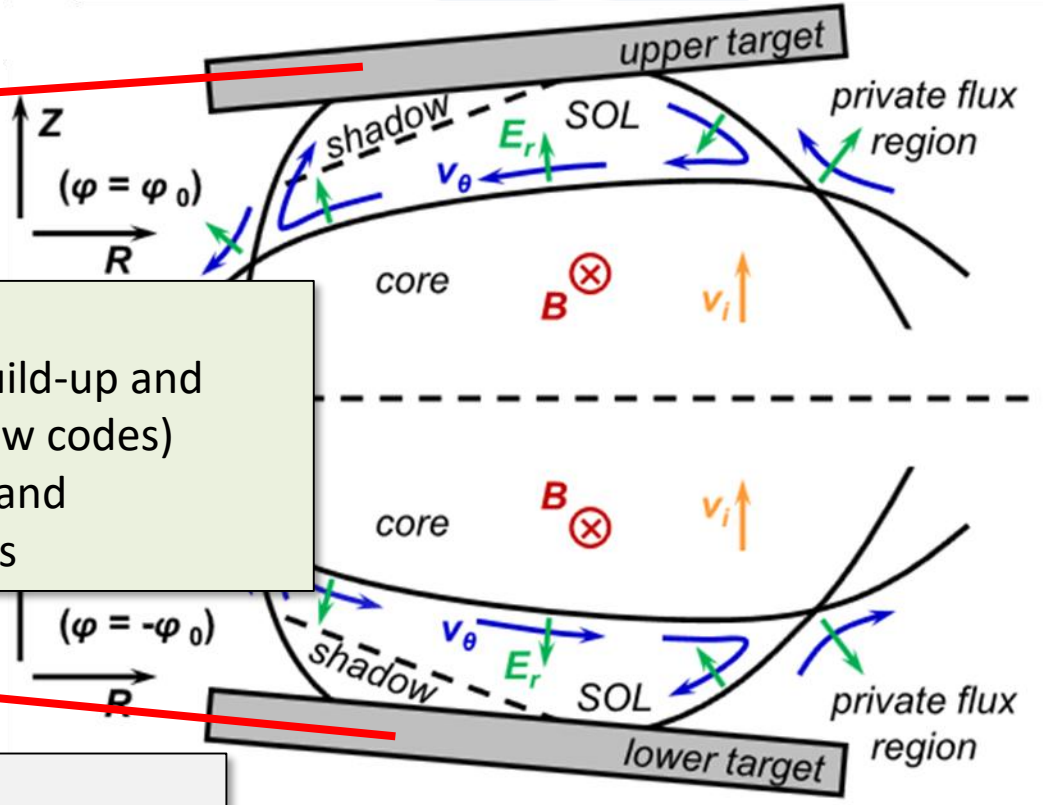




[Courtesy of M. Kriete]

Assess influence of plasma drifts on the island divertor (SSRL 2)





→ To reach SSRL: 4-5:

- Quantify how drifts modify build-up and heat exhaust (enhanced or new codes)
- Develop predictive capability and benchmark against experimets

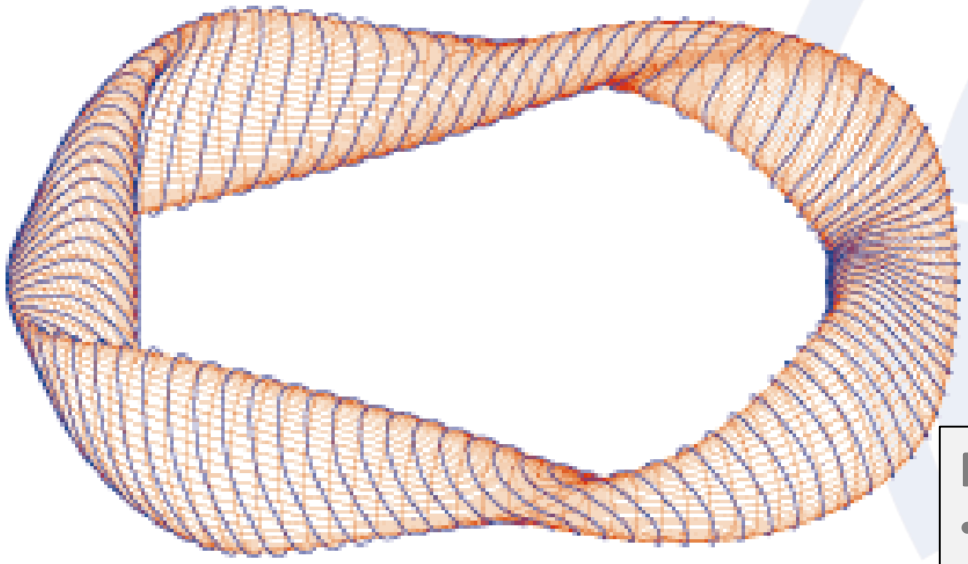
- Drifts are important transport mechanism at W7-X
- Asymmetry in heat and particle fluxes, very large v_{pol} ~1 – 10 km/s measured, while $v_{\parallel}$~50 km/s ($\Theta_{v\parallel}$~0.1 km/s)
- To date, there are no self-consistent tools available to study how drifts affect heat/particle transport.
- It is unclear, if this is W7-X specific (due to relatively low gradients in SOL), or is it also relevant for FOAK.

[K. Hammond, et al., PPCF **61** (2019) 125001
M. Kriete, et al., NF **63** (2023) 026022
Carsten Killer et al 2025 Nucl. Fusion 65 056026]

Gaps in six areas

Plasma-wall interaction
- **Gross erosion, migration & core influx of tungsten**
- Closed divertor
- Strategy for wall-conditioning

Scenario integration
- **Plasma fuelling**
- Auxiliary heating
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- **Confinement (at high β)**
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- Prediction of wall losses
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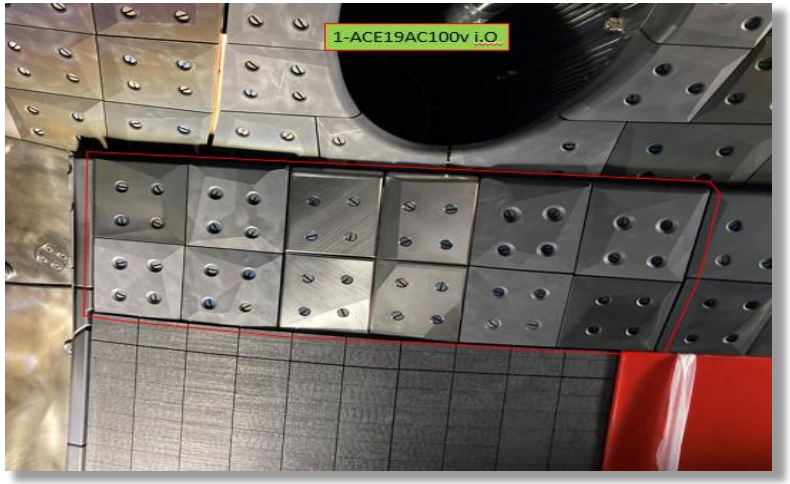
Heat and particle exhaust
- **Drift effects**
- Divertor closure
- Cross-field transport
- Core/edge compatibility
- Island/SOL geometry

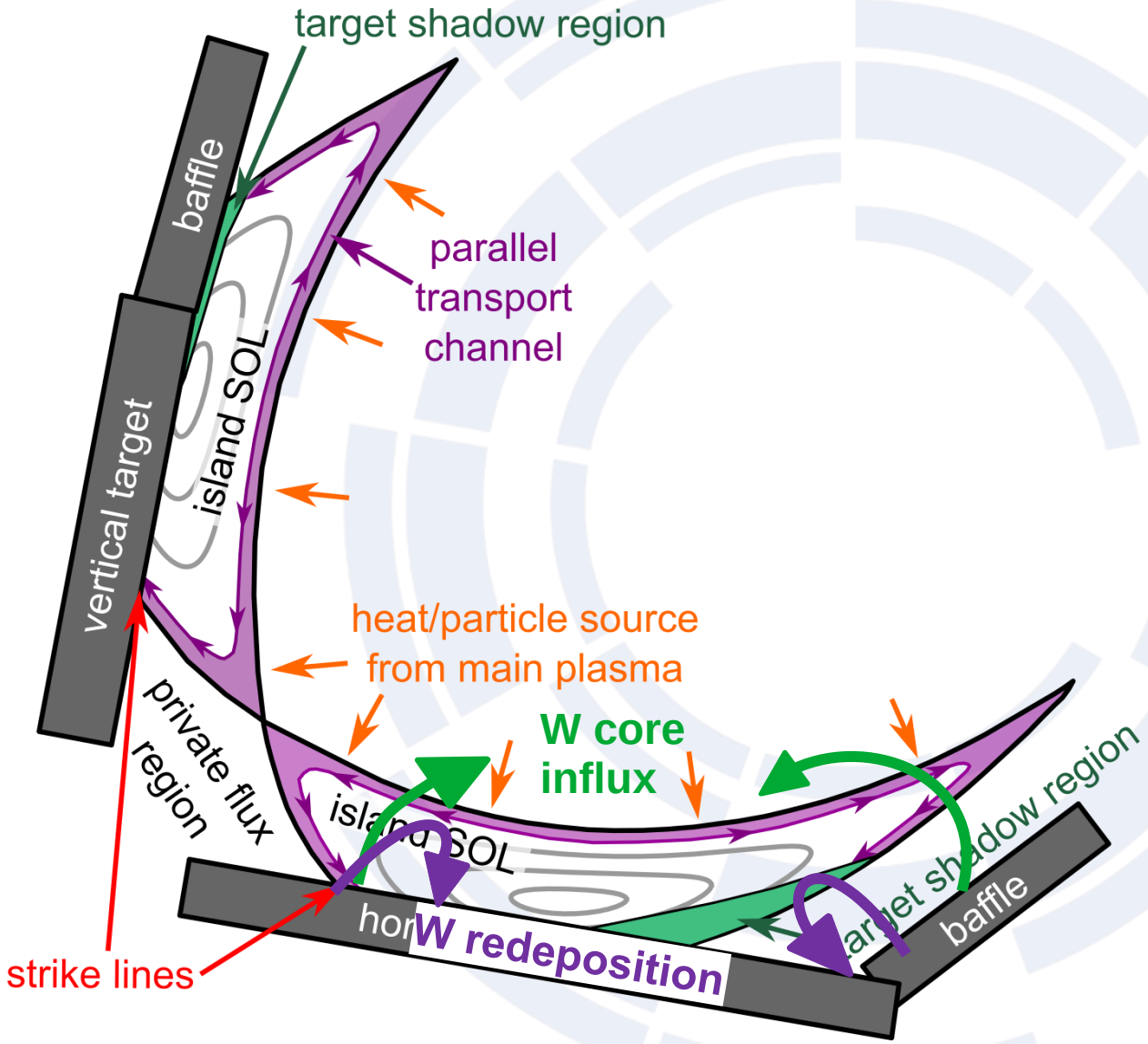
Core transport and confinement
- **Configuration dependence**
- Impurity transport
- Predictive modelling

MHD equilibrium and stability
- **Stability at high β**
- Current driven instabilities
- Divertor resilience

Assess gross erosion, migration & core influx of tungsten (SSRL: 2)

- Future reactor will operate most likely with all-metal first wall (tungsten).
- W7-X device (status 2026) : ca. 90 m² of carbon, ca. 80 m² steel, ca. 2 m² of tungsten; carbon is present in all plasma discharges as impurity
  [Naujoks, Nuc. Mat. Energy 25 (2020) 100821, Brezinsek, NF 62 (2022) 106006]
- Only partial alignment with tokamaks due to complex transport and exhaust in stellarators.



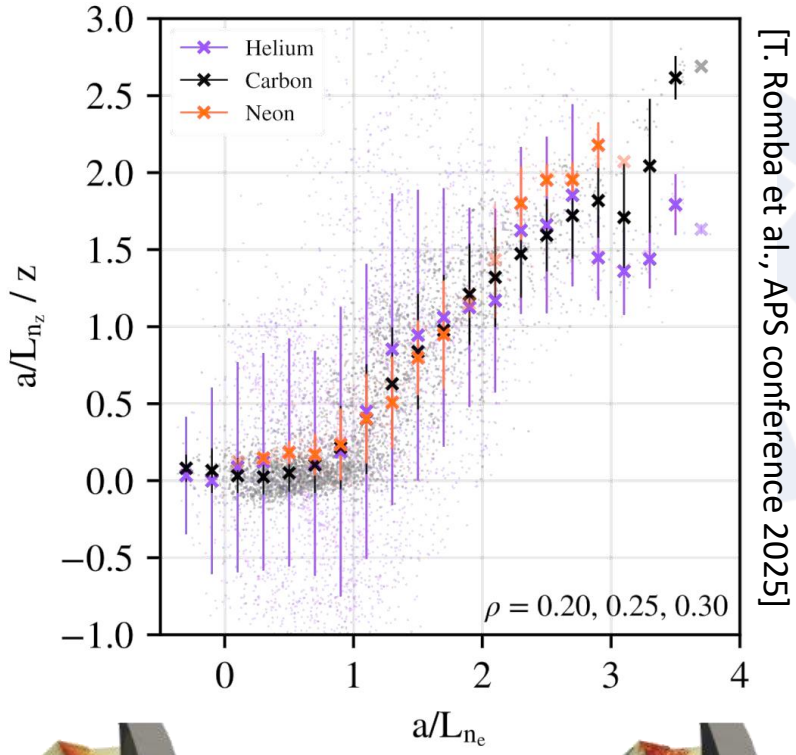


Assess gross erosion, migration & core influx of tungsten (SSRL: 2)

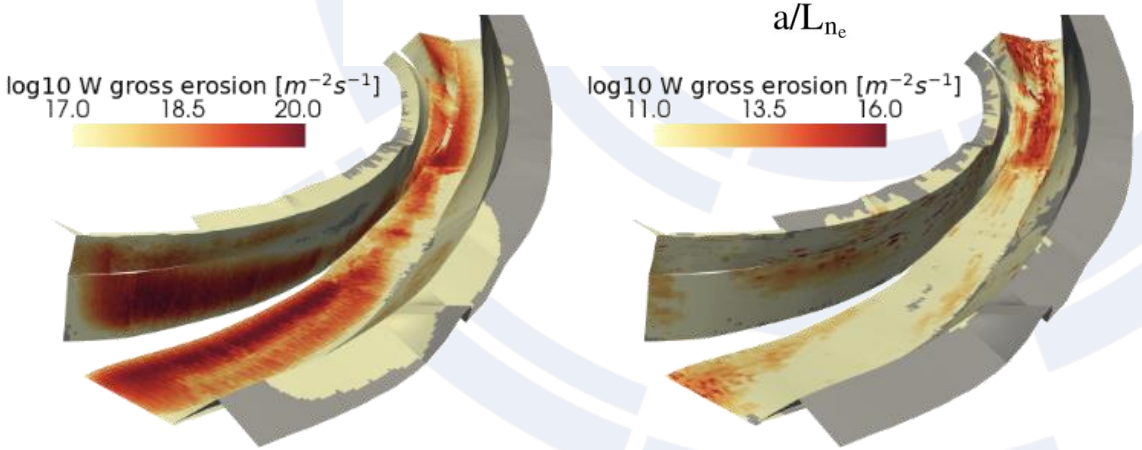
- Although W7-X typically operates with Zeff ~ 1.5 Impurity peaking scales linearly with Z → hints at core accumulation of tungsten in future.

- Estimating W sources (divertor targets, baffles)
  - → @W7X: Sample exposure using manipulators or tile replacement - W spectroscopy & post-mortem analysis
  - Code development needed for self-consistent model combining main plasma & impurity transport with drifts and turbulence effects.

- All-metal HELIAS stellarator crucial for reaching SSRL 5 and beyond.
  - For instance: validating of numerical predictions for migration of tungsten in full tungsten, close divertor ← Heat & particle exhaust gaps



[T. Romba et al., APS conference 2025]



[Romazanov et al., ISHW 2026]

Key Physics Gaps

- An ongoing activity on identifying key physics gaps towards stellarator reactor:
  https://tinyurl.com/HELIASgaps

- Important gap: tungsten divertor in a stellarator. Experiments at W7-X of limited value: sputtering in all-metal device will be different than in carbon (oxygen) dominated W7-X. How to bridge this gap?

- Import gap: Create a set of validated tools, which can aid design and exploitation of future, all-metal devices (Wendelstein Alpha, WISER). This includes numerical tools to model edge & divertor plasmas, as well as erosion, migration and re-deposition of material in 3D topology of the island divertor.

W7-X PWI activities: Ongoing

S.N.	Activities	WP PWIE	WP STEL	Other
A.	**Operation phase (OP)**		yes	
1.	Investigation of plasma with tungsten PFCs W-baffle, heat shield tiles 2.5 m^2		yes	
2.	Dedicated tungsten erosion, W-TESPEL, W-LBO for transport studies	yes	yes	yes
3.	Erosions induced by shifting islands closer to the baffles with impurity gas inj.	yes	yes	
4.	Exposure of material samples via Multi-Purpose Manipulator (near/far SOL)	yes		
5.	Material migration investigations by $^{13}CH_4$ / ^{15}N isotope injection	yes		
6.	Core/Edge spectroscopy measurements (Tungsten, Carbon, Boron, Oxygen…)	yes	yes	yes
B.	**Maintenance phase (MP)**		yes	
1.	Dust studies (generation, migration)	yes		
2.	Post-mortem analysis of retrieved tiles, targets ($^{13}CH_4$, ^{15}N …)	yes		
3.	In-situ layer thickness measurement on PFCs by Ellipsometry, Colorimetry		yes	yes
4.	In-situ investigation of arc-traces (generated during GDC, plasma operation)			yes
C.	**Simulations:** ERO2.0, WallDYN3D for the material migration, for predicting the behavior of an all-metal PFCs stellarator device, local W erosion	yes		

W7-X Wall conditioning activities: Ongoing

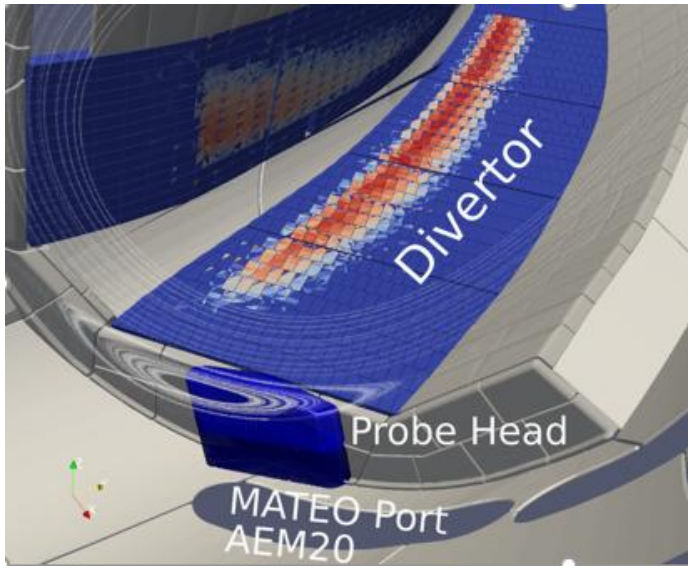
S.N.	Activities	WP PWIE	WP STEL	Other
A.	**Operation phase (OP)**		yes	
1.	Conduction of baking, glow-discharge conditioning, regular boronization		yes	
2.	Investigation of boronization by exposure of material samples via multi-purpose manipulator (MPM)	yes	yes	yes
3.	Measurements: Glow-discharge anodes, MPM-samples	yes	yes	
4.	Wall conditioning and plasma performance improvement by • Powder dropper (Boron, …) • Impurity pellet (TESPEL) injection (Boron, …), LBO (Boron, …) • Injection of B,… rod to the plasma edge		yes	yes
5.	Ion-cyclotron wall conditioning (ICWC), synergy with ECWC		yes	yes
B.	**Simulation of boronization**		yes	

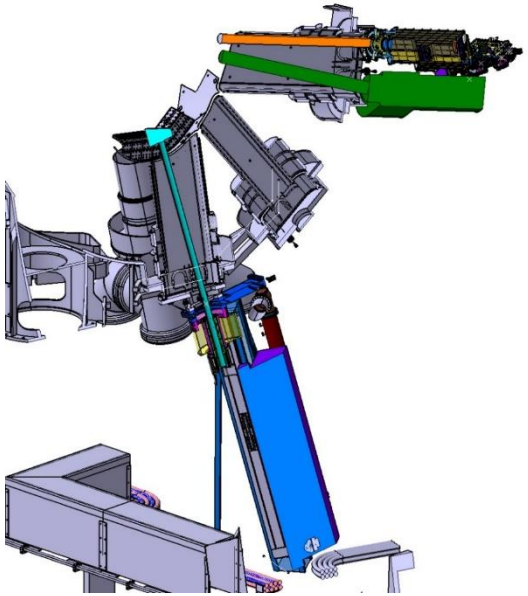
W7-X Exhaust activities: Ongoing

S.N.	Activities	WP PWIE	WP STEL	Other
A.	**Operation phase (OP)**		yes	
1.	Exhaust improvements by divertor Cryo-Vacuum Pumps (CVP)		yes	
2.	He pumping by Ar-frosting on CVP		yes	
3.	Exhaust improvements by • shifting the strike lines closer to the pumping gap • increasing the island size to plug the neutrals • optimizing the plasma parameters by heating power increase,… • exploring new magnetic configurations.		yes	
B.	**Maintenance phase (MP)**			
1.	Dust collection box for OP2.4		yes	
C.	**Simulations**		yes	
1.	2D/3D DIVGAS neutral gas modeling		yes	yes
2.	Multi-chamber modeling		yes	
3.	ANSYS ray-tracing model		yes	
4.	EMC3-EIRENE model		yes	yes

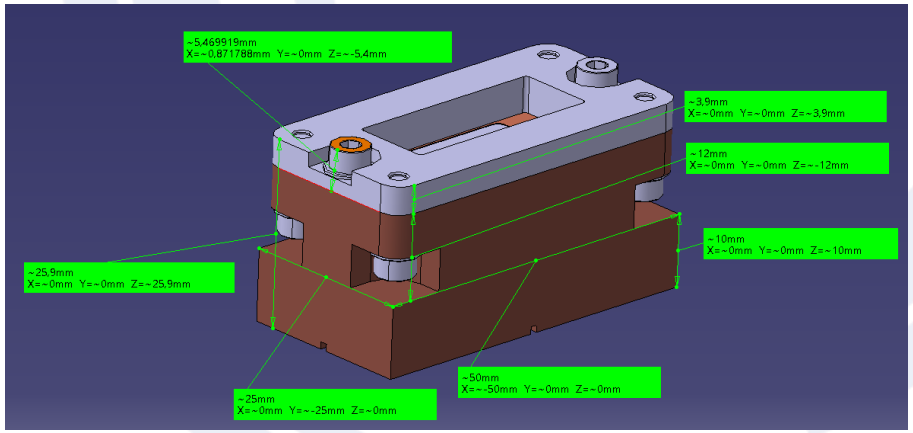
W7-X PWI/Wall conditioning/Exhaust activities: Future plans

S.N.	Activities	WP PWIE	WP STEL	Other
1.	New materials testing using divertor manipulator (MATEO: Manipulator for Target Exposure and Observation) system including LIBS system (expected for OP2.4)	yes	yes	
2.	Material probe head for the multi-purpose manipulator with Quartz crystal for erosion/deposition studies			





Source: D Höschen (FZ Jülich)



Source: CP Dhard, IPP_D_2KTGLR

Collaborations are welcome

PWI, wall-conditioning and exhaust investigations in W7-X stellarator

- Participation in the experiments by submitting the experimental proposals. EUROfusion call for the proposals are announced before beginning of each operation phase
- Exposure of materials to the plasma
- Analysis of retrieved tiles (ca. 10x10 cm^2), material samples (MPM)
- Analysis of dust samples
- Investigation of wall-conditioning methods
- Boronization studies: Exposure of material samples, cavity probes followed by analysis
- Simulations

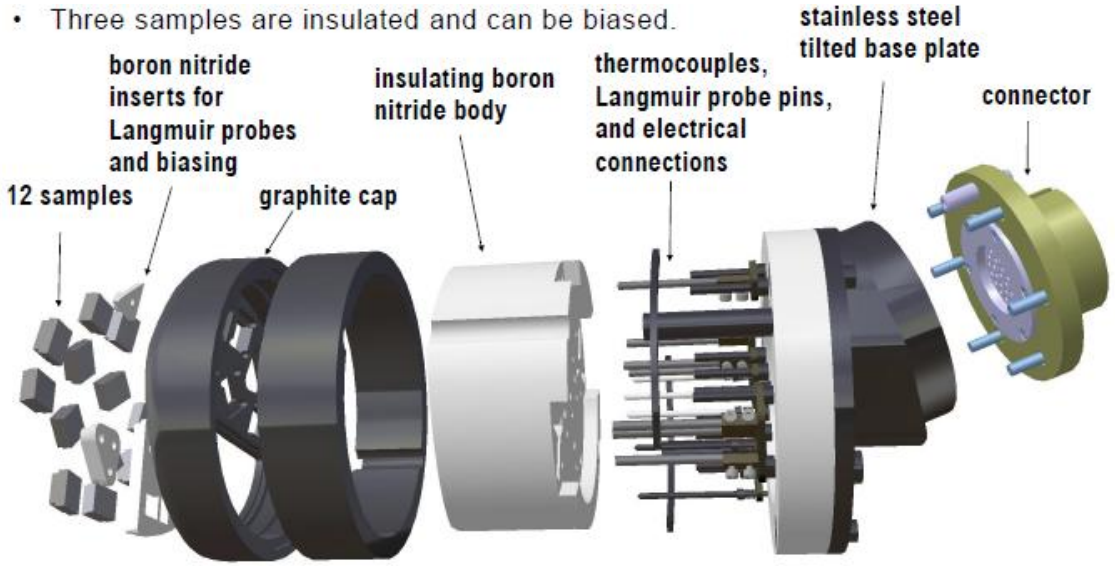
Contact: CP Dhard (chandra.Prakash.dhard@ipp.mpg.de)

Thank you very much for your kind attention

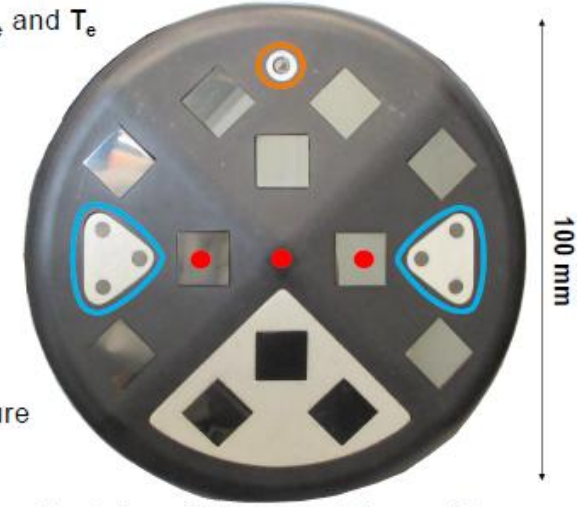
Backup slides

New set-up for layer thickness measurement: Ellipsometry

- Three samples are insulated and can be biased.

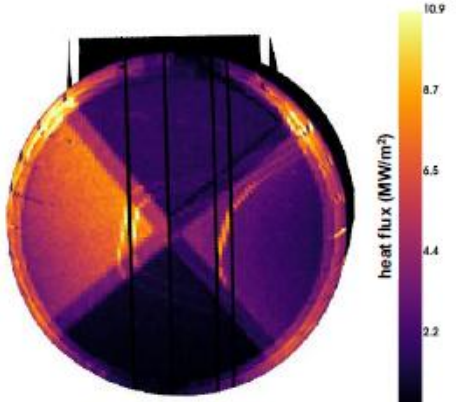


- Two sets of Langmuir triple probes → n_e and T_e
  - Flush mounted
  - Three pins with 3 mm diameter
  - No overlap on magnetic field lines
- Ball-pen probe (BPP) [1] → T_i
  - High temporal resolution
  - One pin with 2.5 mm diameter
- Thermocouples → temperature
  - Sample and probe head temperature
  - Three positions

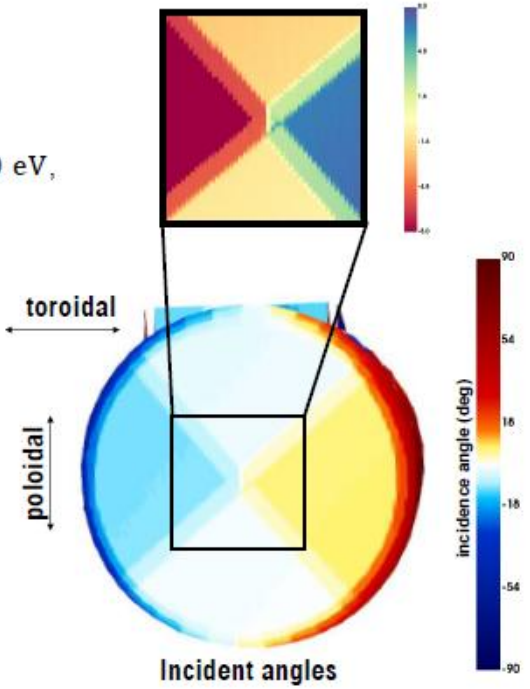


Front view with instrumentation markings

- Design simulated with EMC3-Lite [3].
- Position: 30 mm from last closed flux surface (LCFS).
- Settings: $n_e = 1 \cdot 10^{19}\ \mathrm{m}^{-3}$, $T_e = 100$ eV, $\chi = 3 \cdot 10^4 \frac{\mathrm{cm}^2}{s}$, $P_{SOL} = 1 \cdot 10^6$ W.

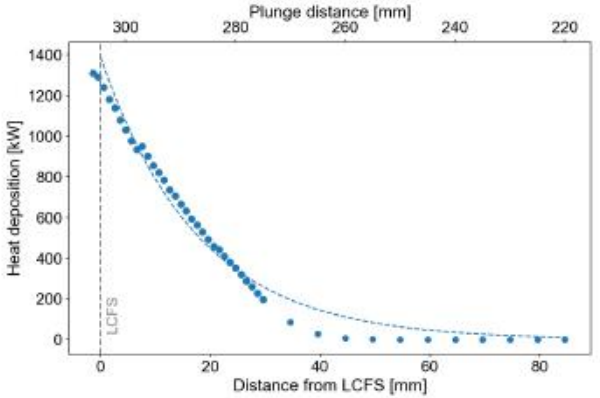


Deposited heat flux



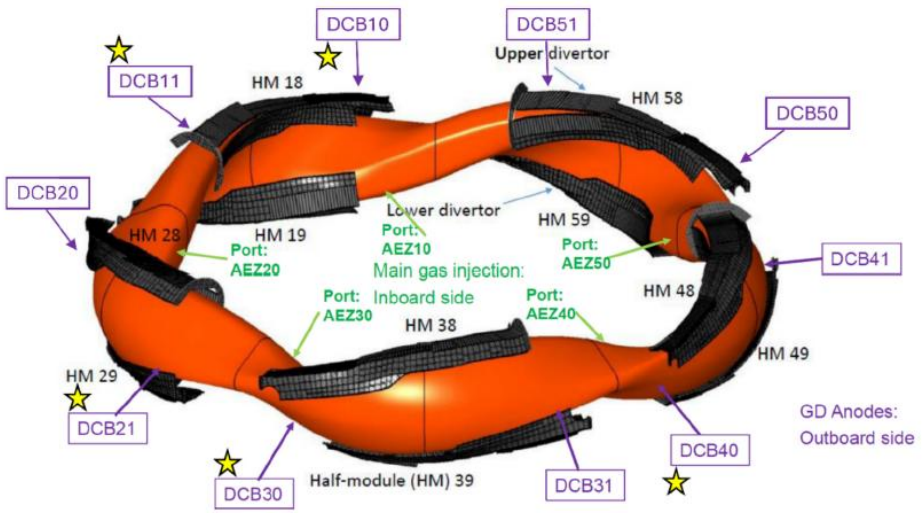
Incident angles

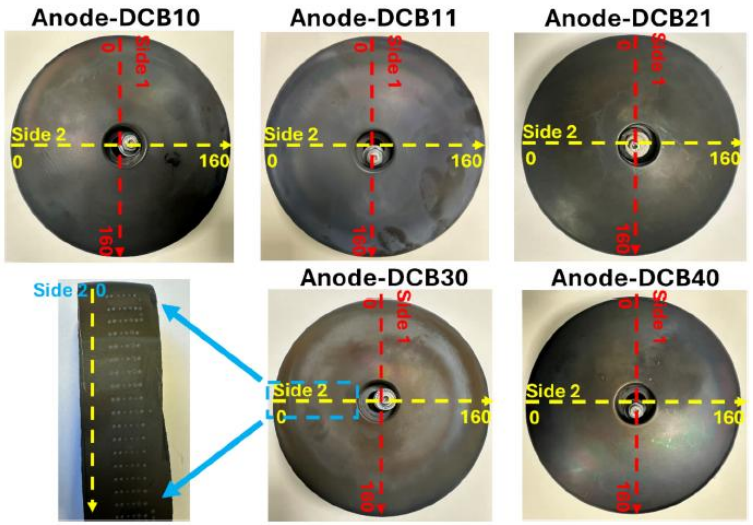
- **Incident angles** around $\pm(7-10)°$ at the left and right facing sides.
- **Deposited heat flux**:
  - Highest close to LCFS
  - Rim receives too high loads → Increase distance to LCFS
- Simulations repeatable for selected positions.

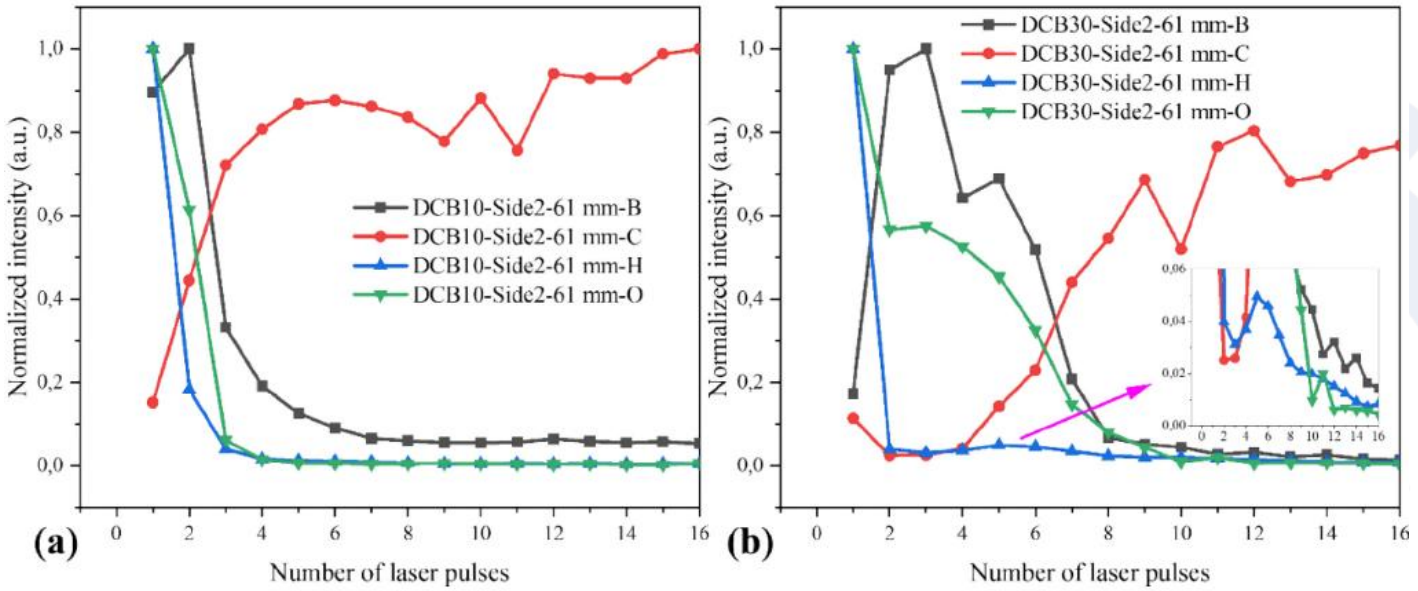


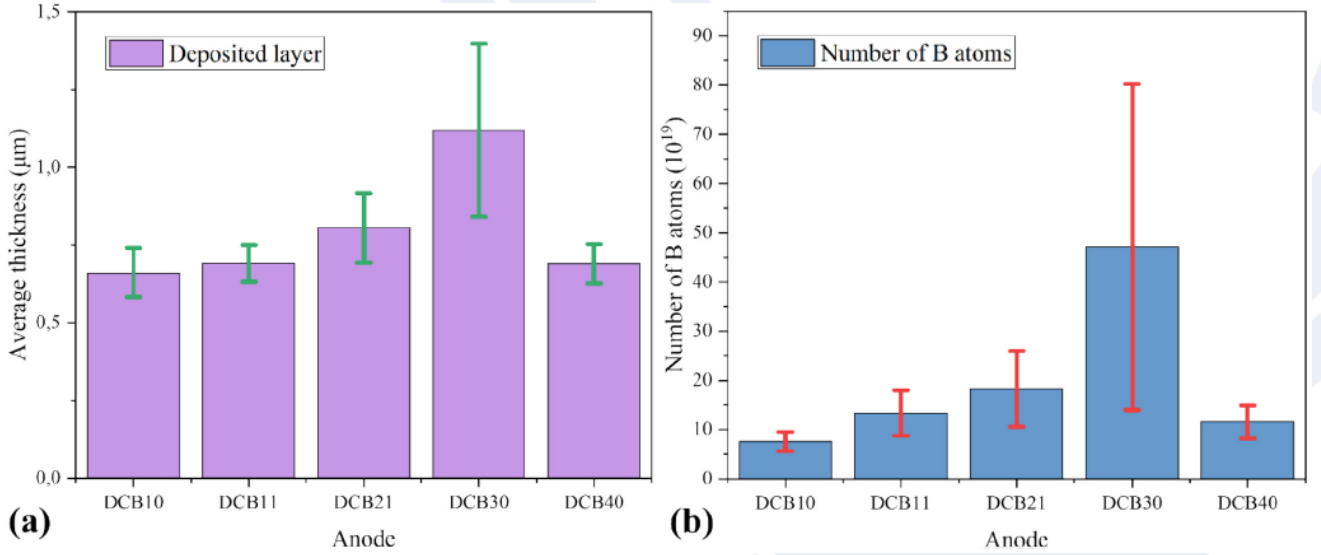
Source: L. Dittrich et al, Fusion Eng. Des. (2026) submitted, presented in SOFT 2026.

W7-X Wall conditioning: Measurements on glow-discharge anodes



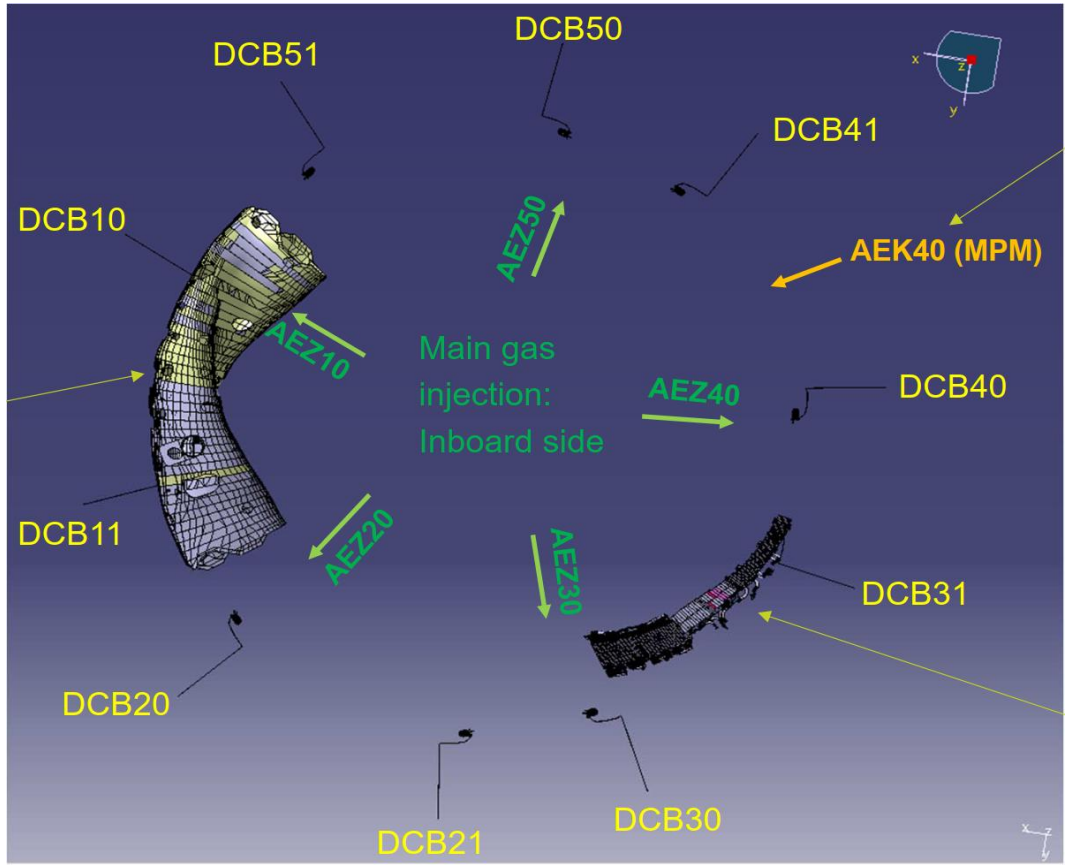


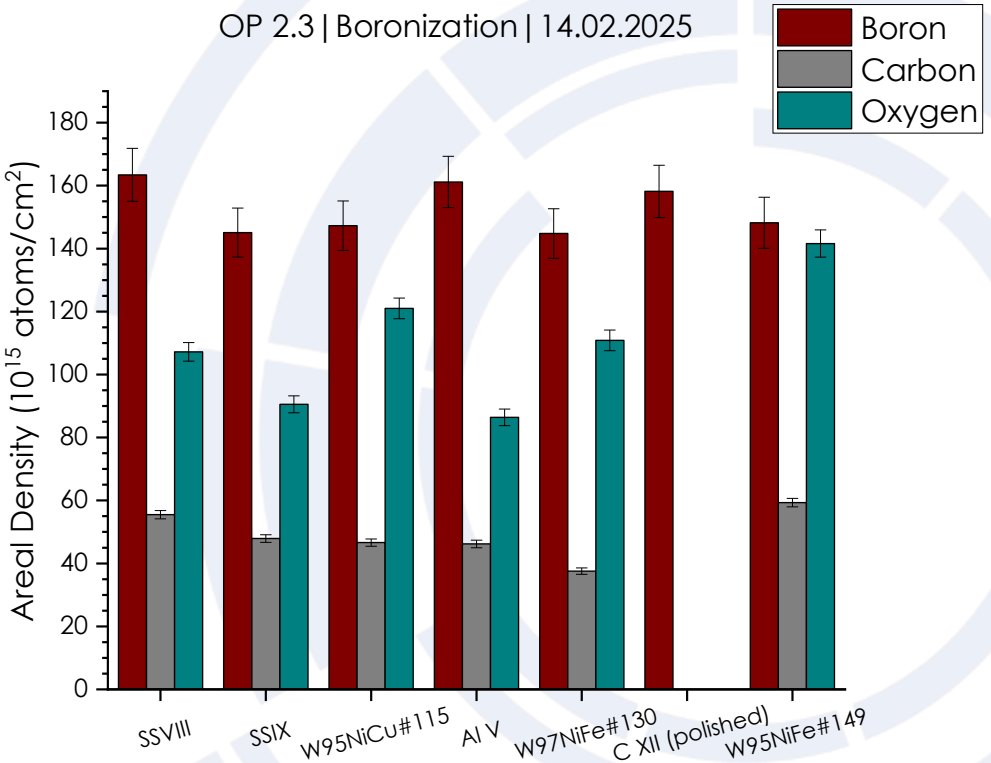




Source: H. Wu et al, Nucl. Mater. Energy 49 (2026) 102239

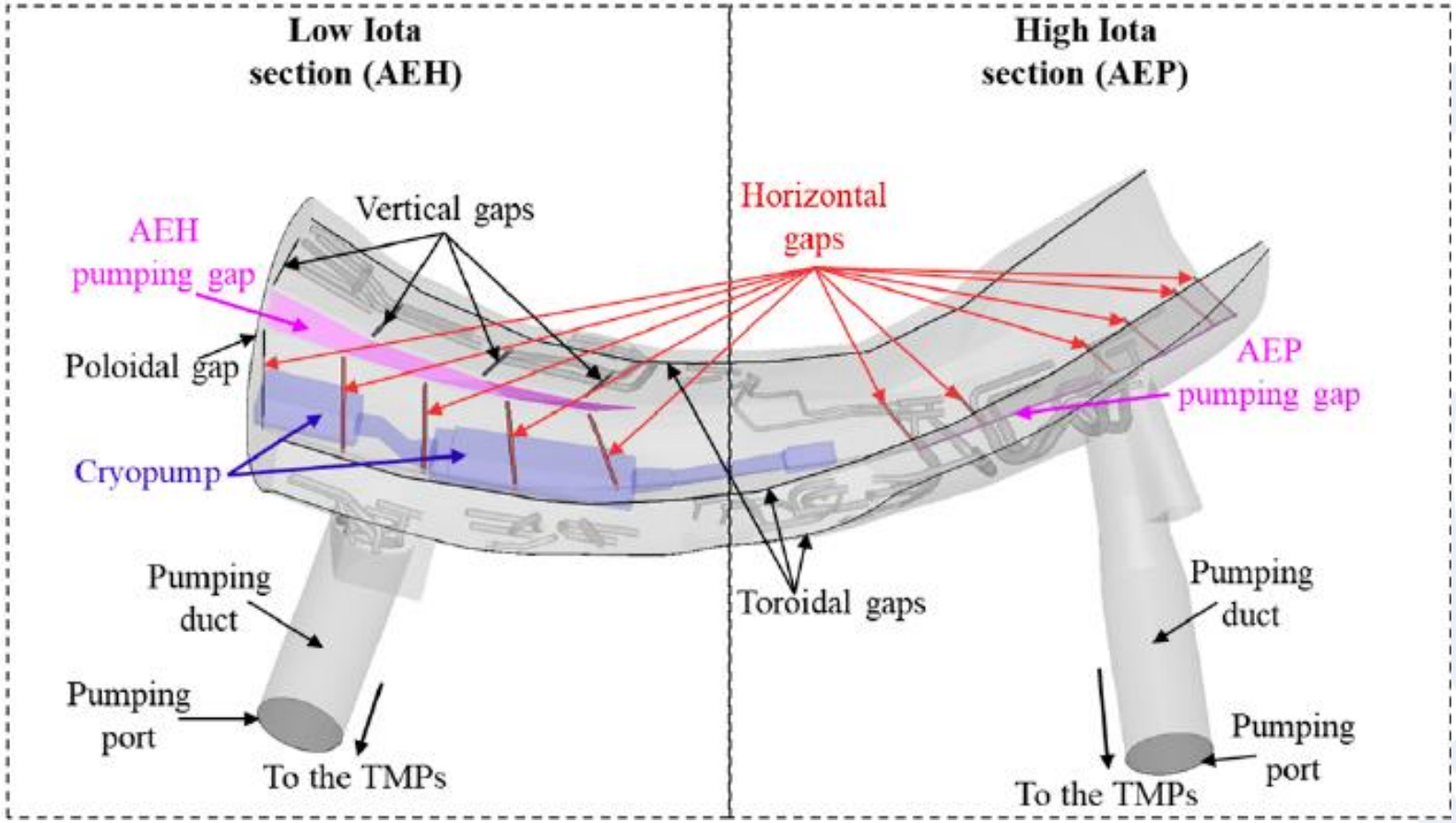
W7-X Wall conditioning: Measurements on material samples

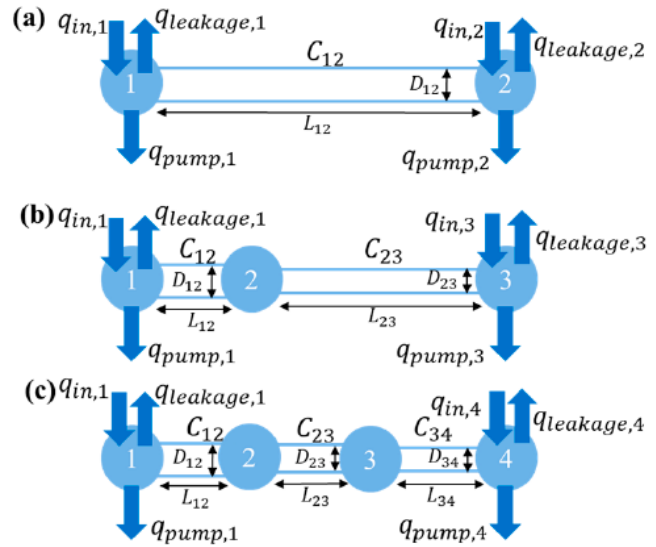


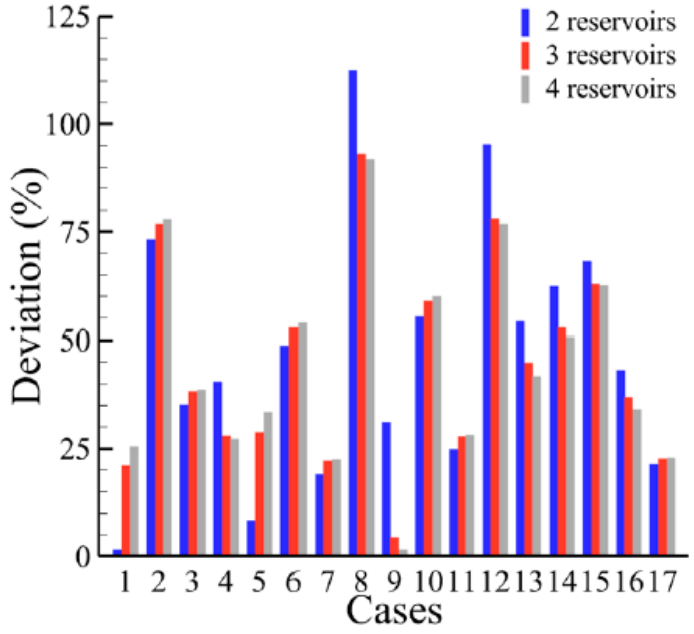


Source: F. Maragkos et al, Nucl. Mater. Energy (2026) under review

W7-X Particle exhaust activities: Simplified conductance model







Source: F. Litovoli et al, Computation 14 (2026) 24