R&D issues linked to the full W wall in ITER

Joint WP TE and WP PWIE Technical Meeting on Plasma Wall Interactions in full W devices

Tom Wauters, ITER Science Division

17 September 2024

china eu india japan korea russia usa

Outline

- **Key aspects of the new ITER Baseline**

- R&D issues linked to the full W wall in ITER

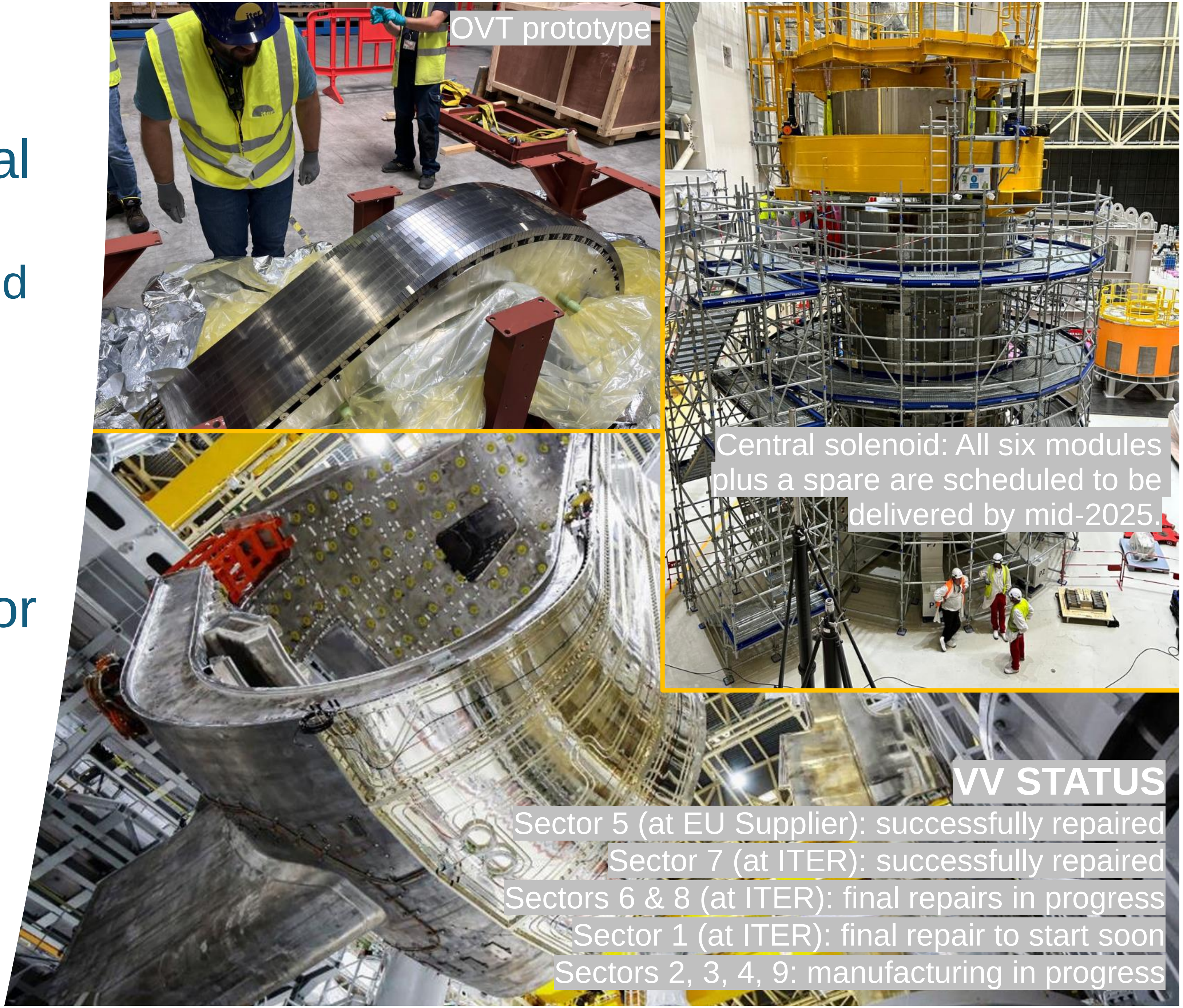
- Content based on
  - ➢ A. Loarte EPS 2024
  - ➢ R. Pitts PSI 2024
  - ➢ STAC-29 and 30 assessments
  - ➢ ITPA R&D priorities for ITER

ITER status

- Vacuum Vessel & Thermal Shield problems
  - Repairs partially completed
  - Re-think of strategy led to **new baseline**

- Most plant support systems are operational or in commissioning.

- All TF and PF coils are completed and at IO.

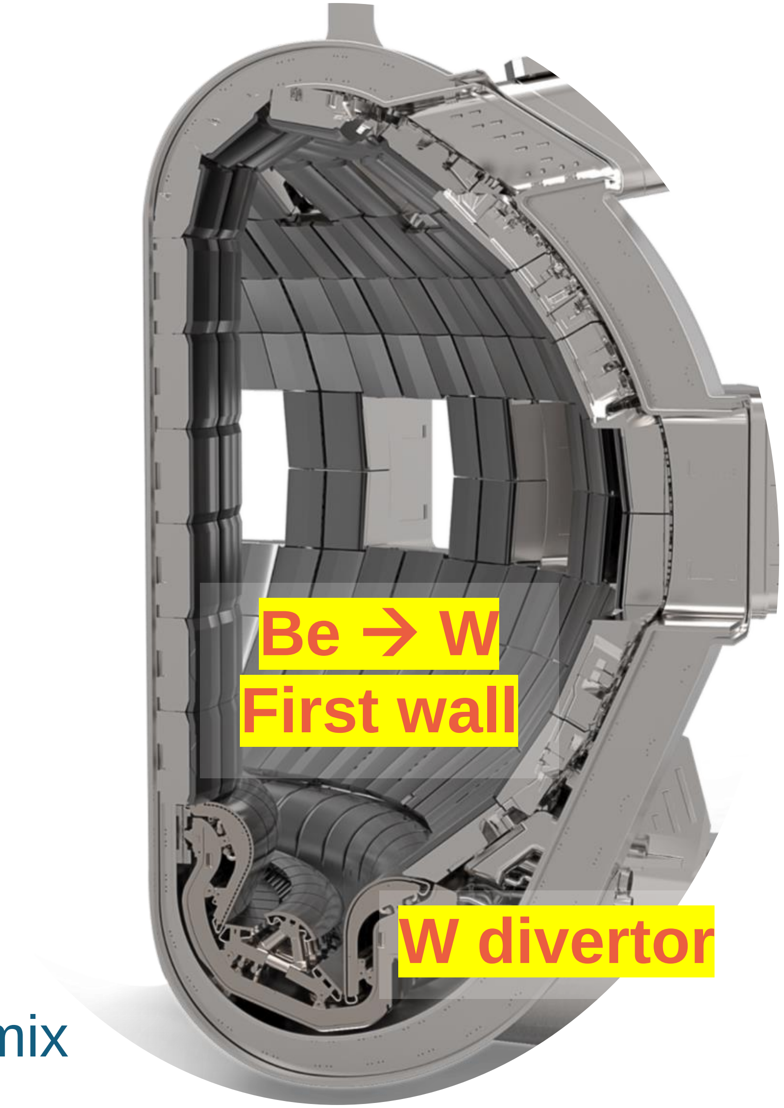


More details in https://www.iter.org/newsline/-/3818 and https://www.iter.org/newsline/-/3830

New Baseline rationale

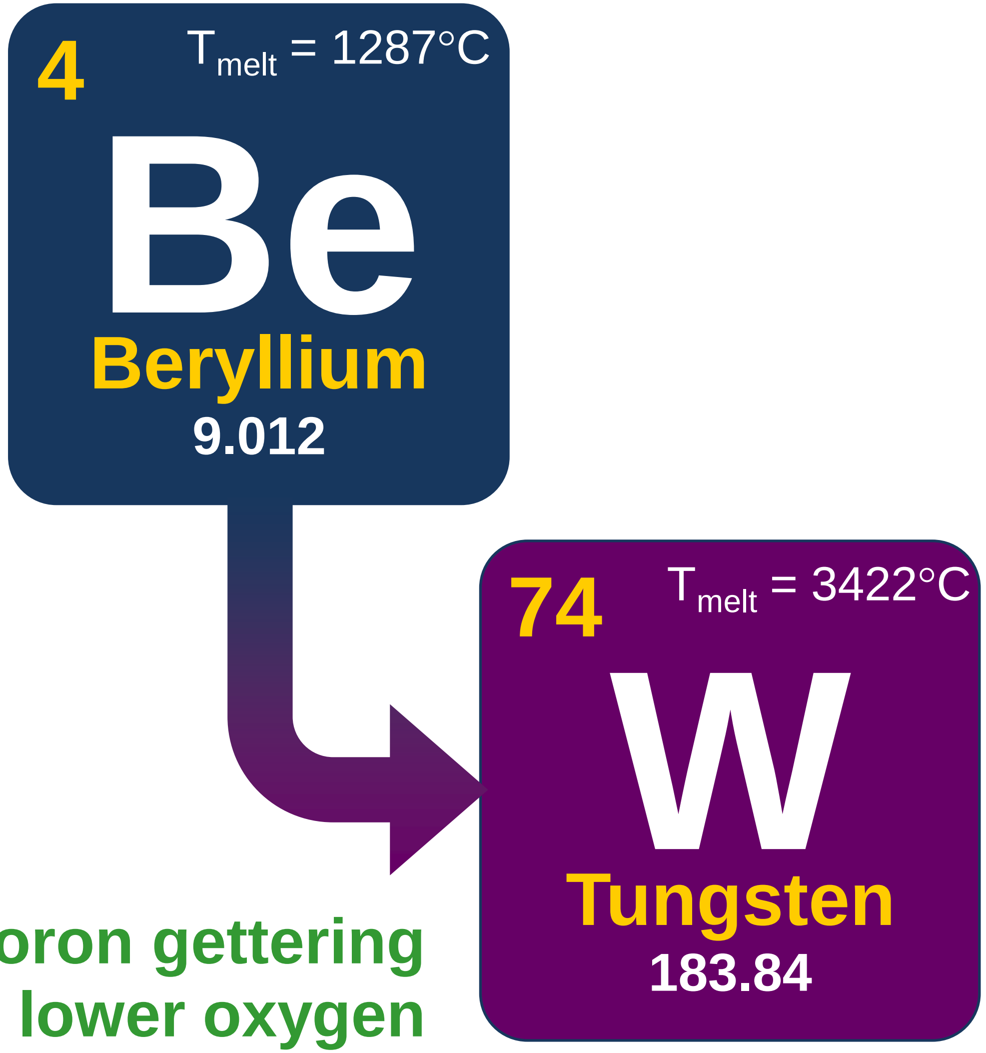
- Robust achievement of ITER Project goals, in view of past challenges (delays due to the Covid-19 Pandemic, technical challenges in completing first-of-a-kind components and in nuclear licensing)
- Realistic and reliable assembly – commissioning – operation
- Achievement of earliest start of the ITER Nuclear Phase (DD operation) and minimization of technical risks (SRO)
- Stepwise Safety Demonstration (DT-1 and DT-2 phases)

- Key elements of the new baseline:
  - First Wall: from Beryllium (Be) to Tungsten (W)
  - Increase in H&CD installed power and change of power mix
  - Boronization for risk mitigation to achieve Q = 10



Why change to a tungsten first wall?

- Physics basis for tokamak operation with W walls is much stronger than it was at start of ITER construction
- Several issues with Be as PFC:
  - Erosion lifetime
  - Tritium retention in co-deposits
  - Low melting point → lower margin in I_p before potential “gap bridging” on FW panels (disruption current quench)
- Major benefit in assembly complexity and avoid costly later wall changeout
- BUT: lose low Z material facing the plasma and gettering properties of Be



+ Boron gettering to lower oxygen levels

New Baseline Phases and Research Plan

Now		~18 months	~26 months (start 2035)		~10 months
Engineering fabrication of system	Pre-SRO assembly	Integrated Commissioning I	Start of Research Operation (SRO	Post SRO Assembly	Integrated Commissioning II

Install:
- Actively cooled W divertor
- Blanket shield blocks
- Inertial W First Wall panels
- 40 MW ECH
- 10 MW ICH

- Commission PCS and Protection Systems to reduce risks in DT-1
- Hydrogen L-mode to 15 MA/5.3T
- Demonstrate H-mode DD plasmas
- First assessment of boronization, fuel retention/recovery, ICWC

- Final, actively cooled W First Wall
- NBI: 33 MW
- ECH: 40 → 60-67 MW
- ICH: 10 → 20 MW
- Final diagnostics set

DT-2, ~3 x 10^{27} neutrons

FPO-y	FPO-(…)	FPO-x
DT (Q=10), high duty ≥ 500 s Q ≥ 5, 1000, 3000 s		

DT-1 ~ 9 years, ~3 x 10^{25} neutrons

FPO-5	FPO-4	FPO-3	FPO-2	FPO-1
D, DT (Q=10) ≥500 s High duty, 250 MW, ≥300 s	D, DT (Q=10) 500 MW, ≥300 s	D, DT (Q=10) 500 MW, ~50 s	D, DT, 100 MW, ~50 s	H, H+T, D

https://www.iter.org/doc/www/content/com/Lists/ITER%20Technical%20Reports/Attachments/25/ITR-24-004-Baseline-ok.pdf

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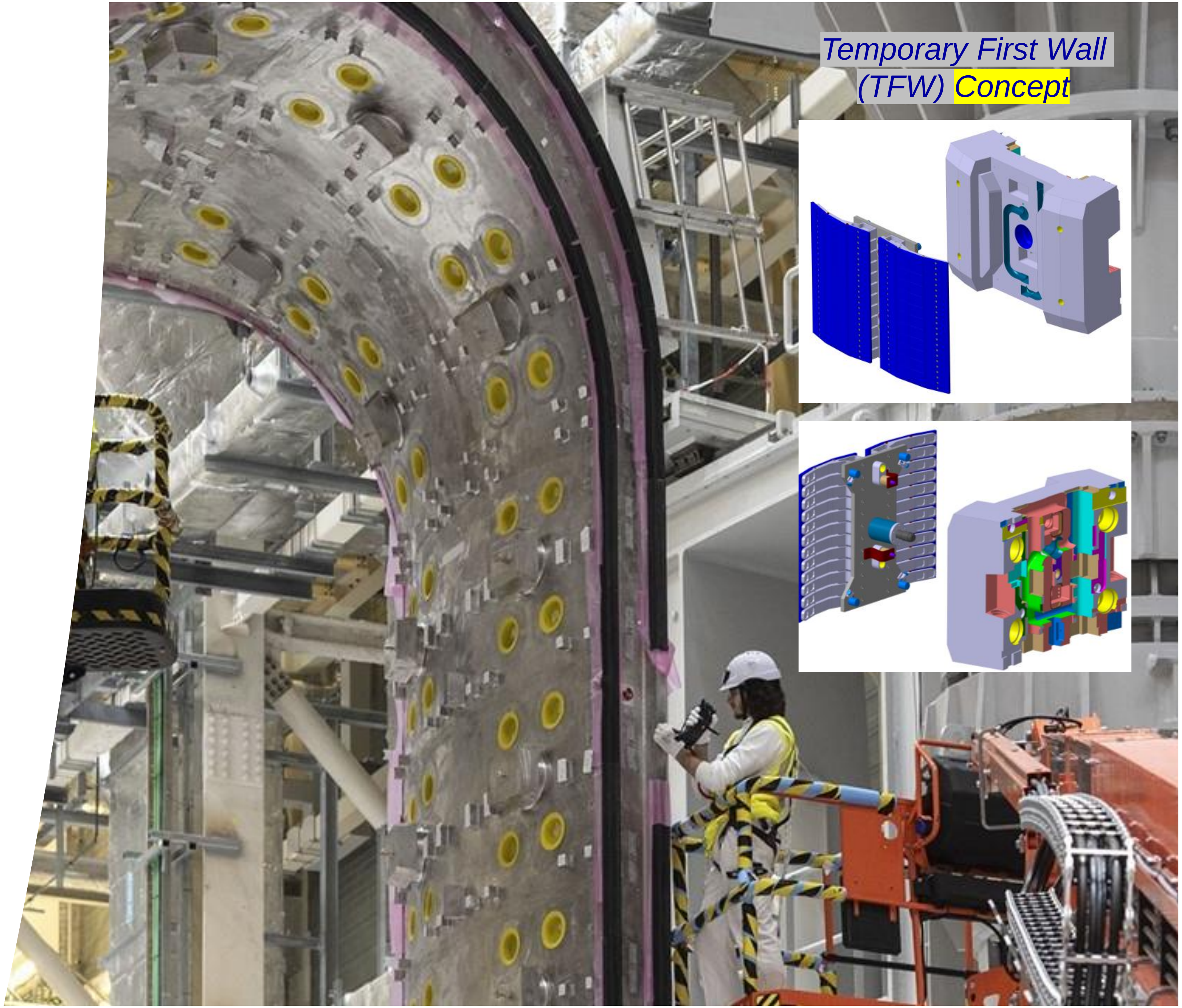


R&D needs for the new baseline

First consolidated version of the table of R&D needs for the new baseline

Ref.	System/ Issue	Required R&D	Category*	Required experimental facilities
A. R&D for design completion				
B. Implementation of the ITER Research Plan				
B.1. Disruption characterization, prediction and avoidance (for mitigation see Section 1)				
B.2. Stationary H-mode plasmas, ELMs, ELM control and impact on H-mode and power fluxes				
B.3. Characterization and control of stationary power fluxes				
B.4. Plasma-material/component interactions and consequences for ITER operation				
B.5. Start-up, Ohmic, L-mode scenario development				
B.6. Conditioning, boronization, fuel inventory control				
B.7. Basic scenario control and commissioning of control systems				
B.8. Transient phases of scenarios and control				
B.9. Complex scenario control during stationary phases				
B.10. Validation of scenario modelling and analysis tools				
B.11. Heating and Current Drive and fast particle physics				
B.12. Specific issues for long pulse/enhanced confinement scenarios				

The final priority list for the coming years to be addressed by ITPA will be commonly agreed by discussions this autumn

Category 1. The outcome of R&D can have major impact on system design or on the IRP (e.g. modifying the overall experimental strategy in each phase or the objectives of the phases themselves);

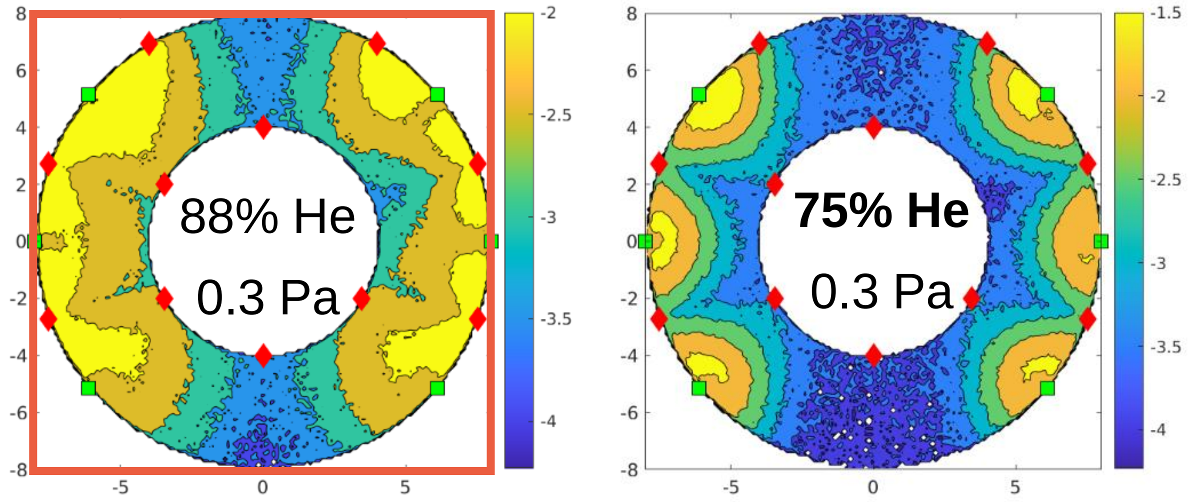
Category 2. The outcome of R&D is expected to have medium impact on system design or on the IRP (e.g. modifying significant details of the experimental strategy to achieve objectives in each phase);

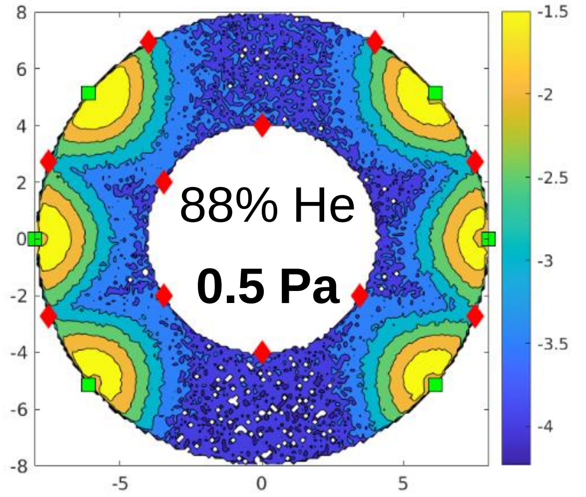
Category 3. The outcome of R&D is expected to optimize details of the IRP experimental strategy to achieve objectives in each phase by providing relevant experience.

Glow discharge boronization

- ITER will install a diborane GDC boronization system for control of impurity influxes
- Physics basis for system design:
  - Monte Carlo tracing of diborane molecules in glow plasma until ionization or dissociation, accounting for elastic collisions with neutrals
  - → # anodes increased from 7 to 11 (but not all available at SRO)
  - → Toroidally/poloidally (incl HFS) distributed injection points
- R&D required
  - ➢ Validate boronization modeling in tokamaks
  - ➢ Assess the need for layer uniformity to assist campaign restart / maintain low O content

Reaction counts of B_2H_6 in eq. plane (log scale)





B_2H_6 injected at ♦, anodes located at ■

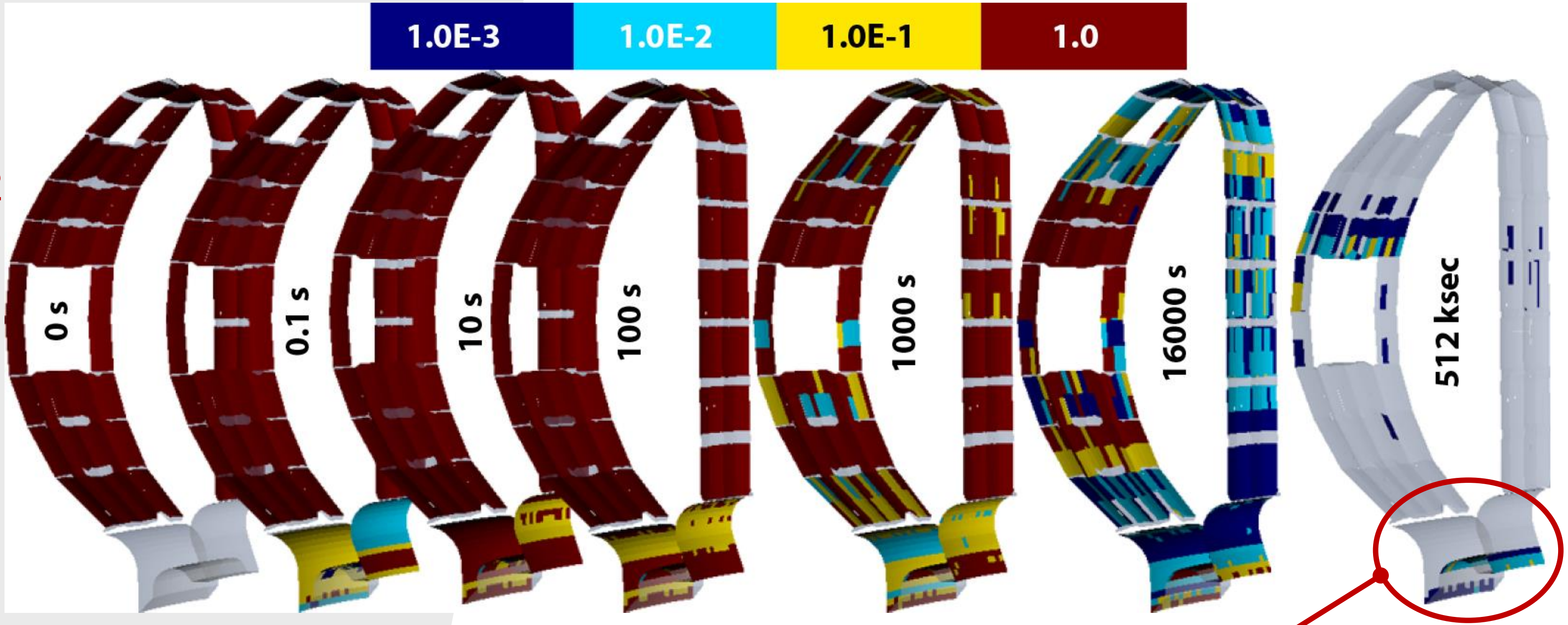
Best uniformity at
- ➢ 0.3 Pa with realistic 88%He / 12%H_2 gas mix achieved by feeding 5% diborane in He
- ➢ Uniform anode distribution
- ➢ Uniform gas injection distribution
- ➢ HFS gas injection

Boron layer lifetime?

K. Schmid PSI 2024, ISFN

- How long might the gettering properties of the boron layer last → how often might ITER need to boronize?
  - ➤ Both erosion and oxygen uptake capacity indicates MAX frequency of once per 2 weeks

- WallDYN3D with EMC3-Eirene plasma background
  - Trace B & W migration in 3D shaped wall
  - Case of “hot stagnant” far SOL
  - Initial 100 nm thick boron coating
  - Account for surface composition dynamics

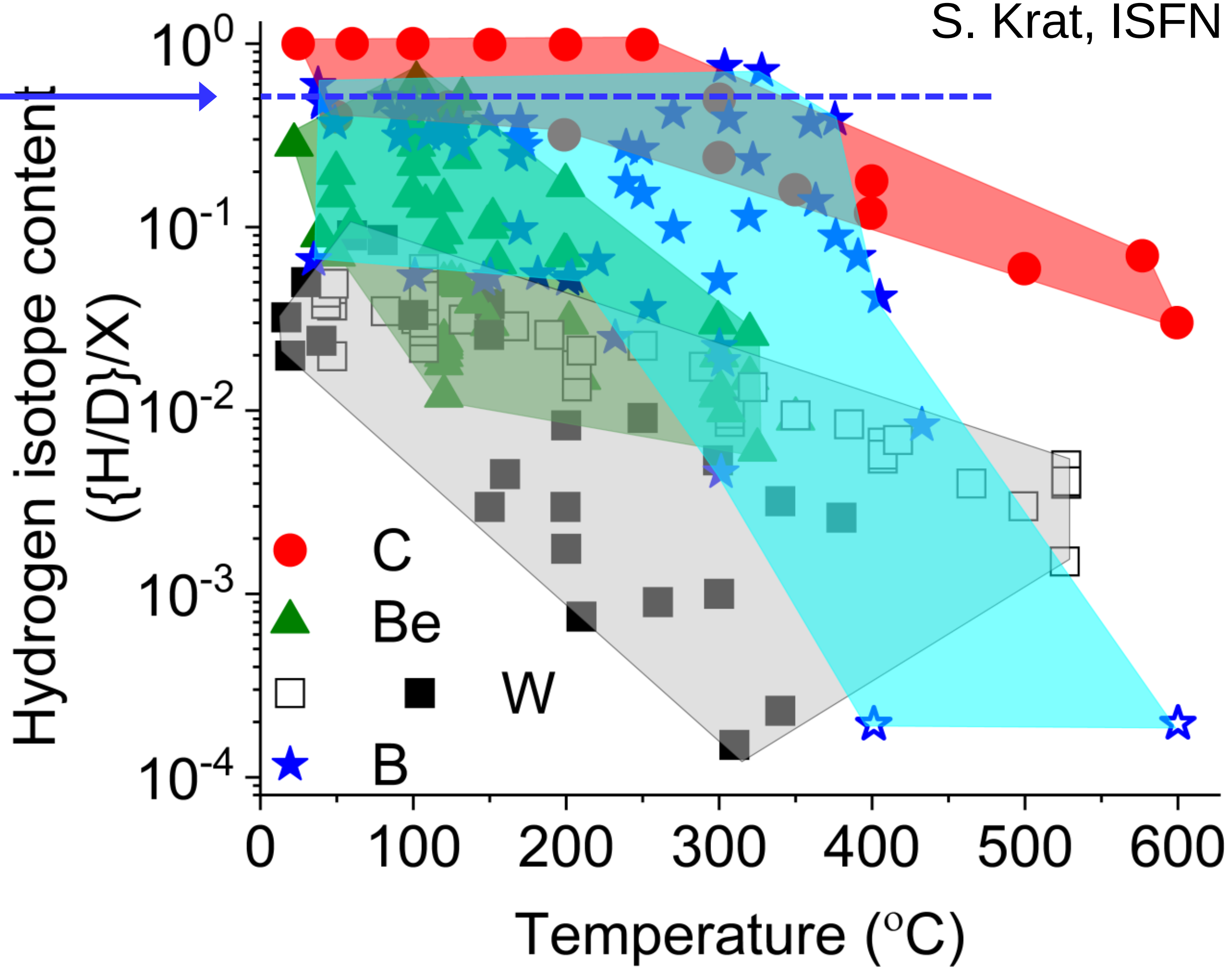


Plasma wetted areas deplete rapidly (~1000 s) → deposition at divertor baffles → re-erosion → most boron ends up below inner divertor target → potential dust source

Gettering lifetime maybe several 10^4 seconds

H retention in deposits/dust

- Very little data on fuel storage capacity in boron layers:
  - Deposited with diborane
  - Following erosion and migration
- Review of laboratory data:
  - 0.5 H/B assumption in ITER inventory estimate is conservative
- Tokamak layers:
  - Alcator C-mod with boronization: ~0.1 H/B inboard to outer div. [1]
  - ASDEX Upgrade with powder dropper: <0.1 H/B at outer div. & ~0.2 H/B at midplane limiters [2]
- Dust:
  - Content + production mechanisms?



[1] Krieger NME **34** (2023) 101374
[2] Wampler JNM **266-269** (1999) 217

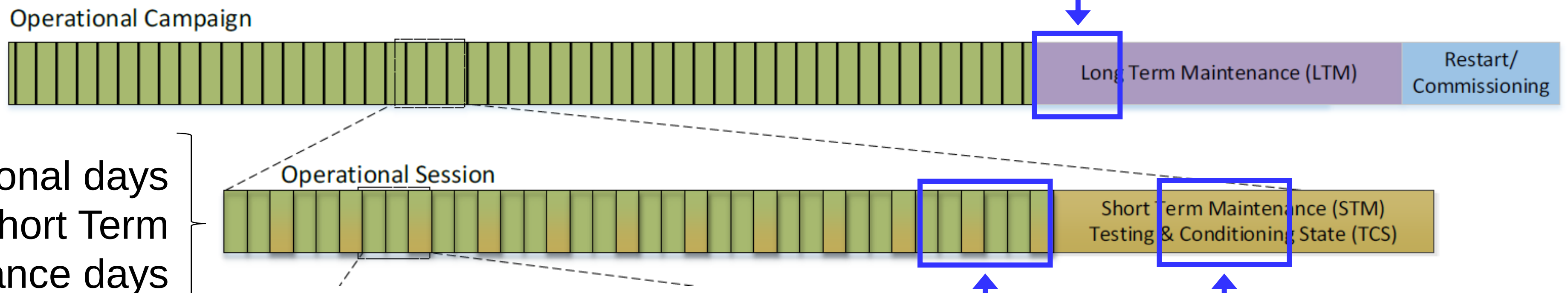
Need to demonstrate the ITER fuel removal strategy

- Conservative estimate of T retention in a full-W ITER based on experimental time provisionally allocated in the DT-1 Research Plan
  - Retention in B layers: 381 gT
  - Retention by W co-deposition: 3.9 gT
  - implantation in W: 24 gT

Case where no T removal schemes are applied

- T inventory management aims at <u>70-80% inventory reduction</u>
  - 15% of DT-1 FPO campaign time allocated to T removal

B_T off: GDC and baking @ 240°C



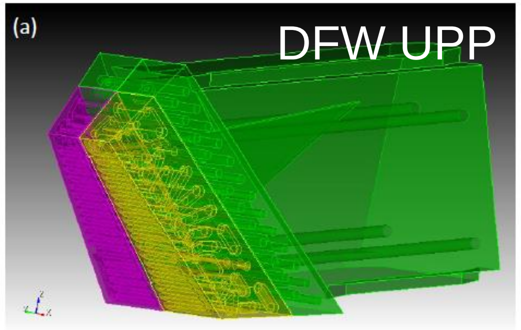
10-12 operational days and 2-4 Short Term Maintenance days

Dedicated time for T clean-up before STM / i.e. before boronization: RISP, ICWC, ECWC, …

B_T off: GDC boronization @ 70°C

- Based on JET DTE-2 : Raised Inner Strike Point (RISP) + Ion Cyclotron Wall Conditioning (ICWC)

Permeation

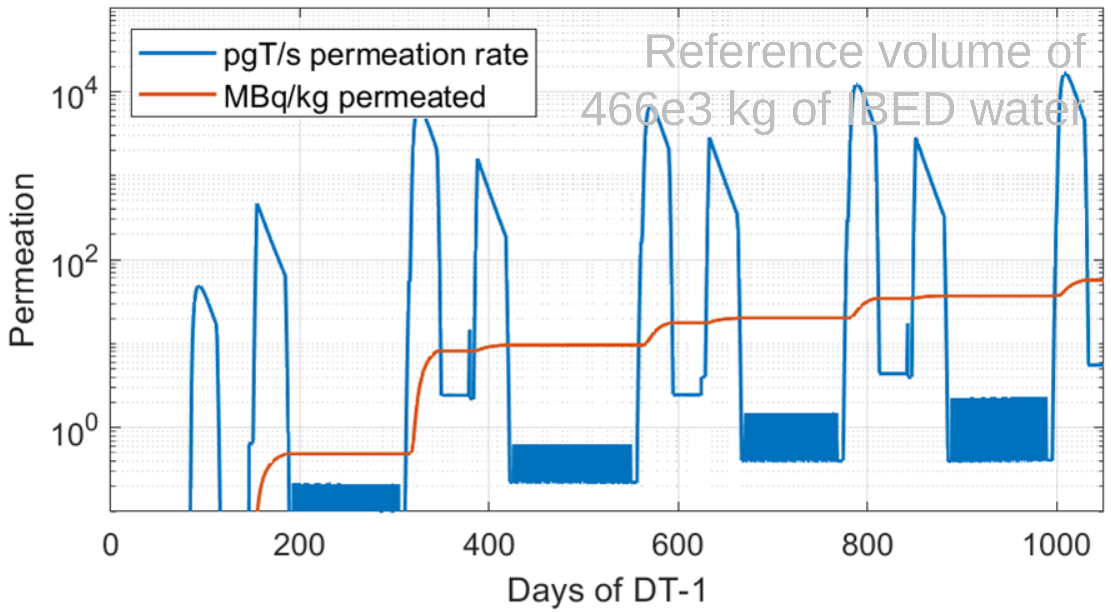


- ❑ Depending on material parameters, permeation through stainless steel 316L surfaces (of the diagnostic first wall) can be significant
  - ➢ TMAP7 analysis for 5 FPO campaigns of DT-1
  - ➢ 1 month baking at 240ºC before/after campaigns
  - ➢ Intermediate CXN flux: 2 10^{19} (D+T)/m²/s

Table 2: Tritium migration parameters for 316L steel used in this study

Parameters	"KAERI" parameters	Mean parameters	"Penzhorn" parameters
Diffusivity (D, m²/s)	$3.00 * 10^{-6} * e^{-\frac{0.63}{k*T}}$	$1.45 * 10^{-6} * e^{-\frac{0.59}{k*T}}$	$8.00 * 10^{-7} * e^{-\frac{0.56}{k*T}}$
Recombination (Kr, m⁴/s)	$3.80 * 10^{-24} * e^{-\frac{0.7}{k*T}}$	$1.75 * 10^{-24} * e^{-\frac{0.594}{k*T}}$	$2.16 * 10^{-24} * e^{-\frac{0.58}{k*T}}$
Trap concentration (at%)	0.08*2.5		
Trap energy (eV)	0.7		

↓ 141 mgT ↓ 74 mgT

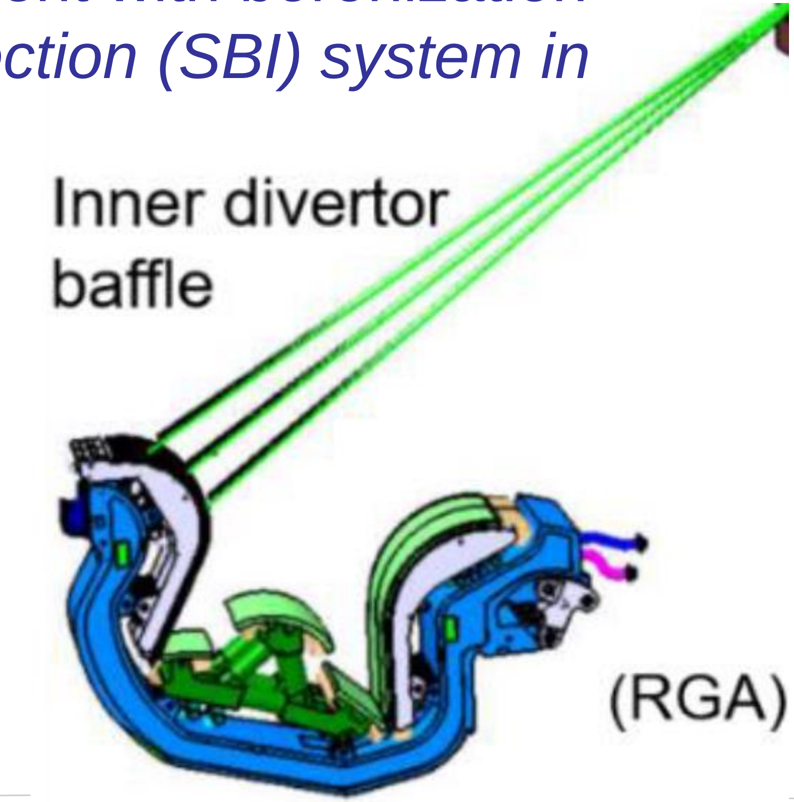


- ❑ Need for plasma-driven permeation studies in ITER-like conditions to better understand risk and constrain models
- ❑ Assess the potential of material coatings to reduce permeation (W, B)

Diagnostics / systems

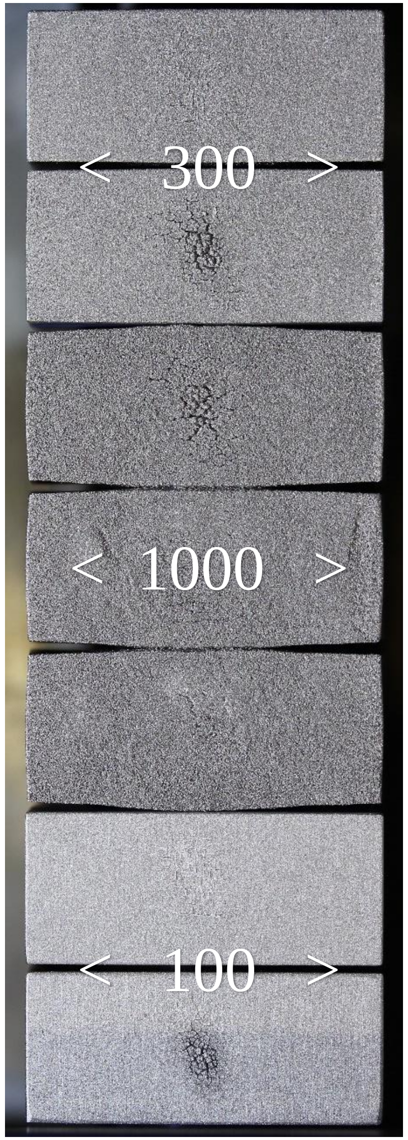
- Laser Induced Desorption for in-situ T retention measurement
- Demonstrate LIBS as quantitative measurement for T retention in Boron co-deposits
- Input to the active surface design of the first charge exchange samples
- Performance of diagnostic mirrors in full metal environment with boronization
- *Explore the viability and efficacy of a solid boron (B) injection (SBI) system in mitigating the risks to Q=10*

- Spectroscopy: assess experimentally observable lines (Te/ne) for use in ITER (no Be)
  - Divertor ionization front / Ti measurements
  - W influx/erosion
  - CXRS with W and B
- Demonstration of reflection-robust IR temperature measurements of plasma-facing components in metallic environment



X. Jiang et al., PSI (2024)

PFC surface modification / lifetime

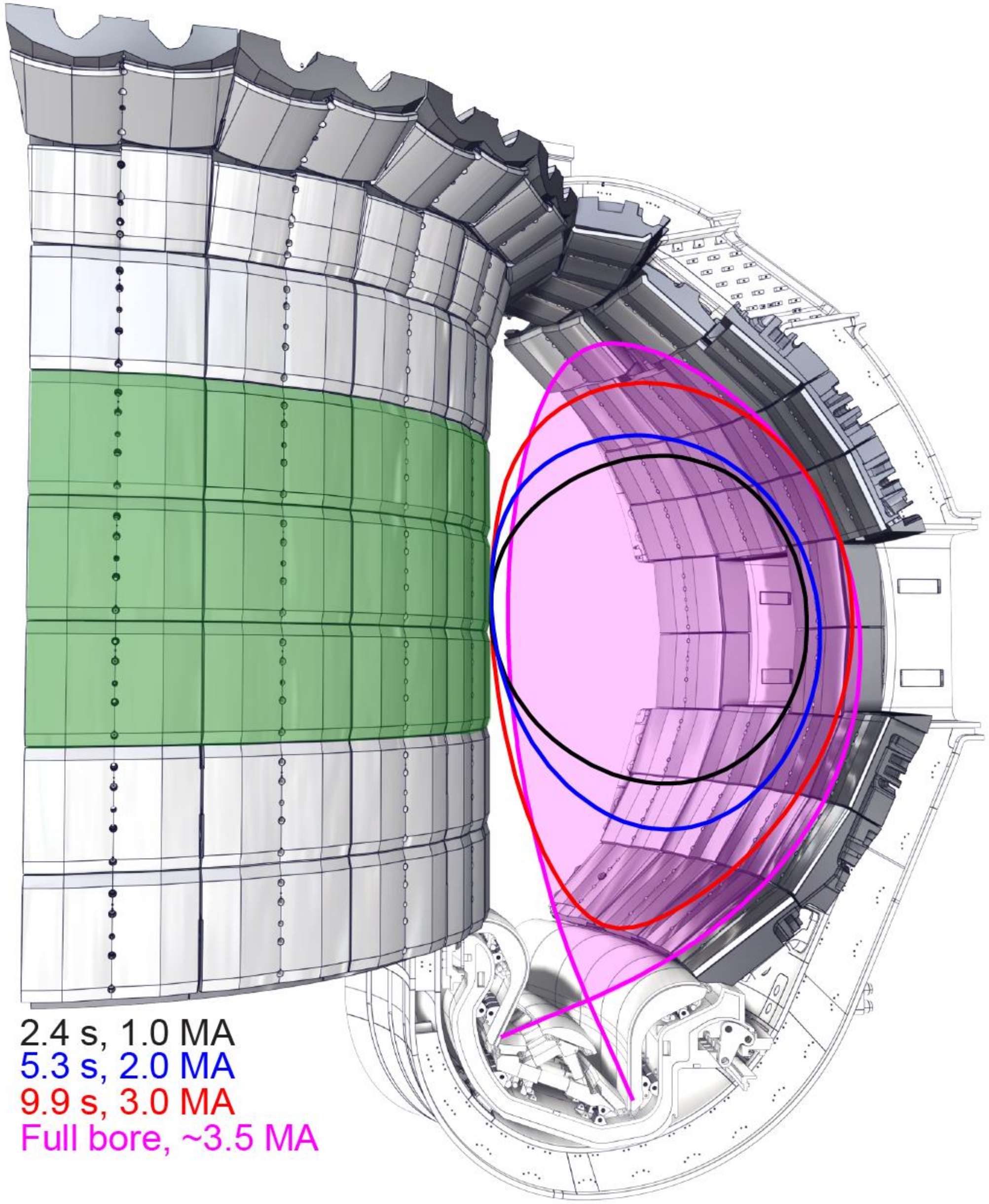


- ➢Assess W surface modification by high plasma fluence exposure and implications for tokamak operation: ITER-like fluences (and power fluxes, if possible)
- ➢Determine the consequences for the W divertor material properties of sustained operation above the recrystallization temperature and assess possible synergistic effects with plasma exposure
- ➢Determine power fluxes to castellated structures (divertor and first wall) in stationary plasmas and during ELMs over a range of conditions and identify dominant physics processes
- ➢Experimentally determine the tolerable level of surface damage/edge damage of W PFC on tokamak operation (from H-mode confinement deterioration to increased disruptivity due to uncontrolled W influxes in stationary conditions or following ELMs)

Cycling loading of pre-damaged W MB PFU to 20MW/m^2 in JUDITH 2

Limiter start-up on W – role of boronization?

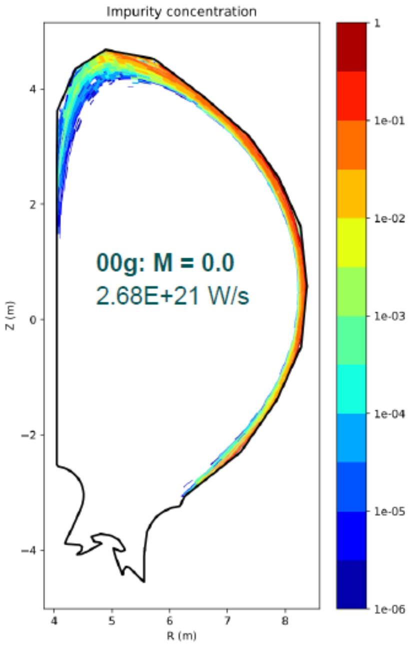
- Like many tokamaks, ITER plasmas will start up on the central column
- Switch from Be → W can have strong potential impact ($P_{RAD,W} >> P_{RAD,Be}$)
- Limiter phase is rather long (~10 s) on ITER cf. current devices
- New SOLPS-ITER, DINA and JINTRAC modelling shows self-regulating f_{rad} ~ 0.7÷0.9, independent of heating distribution or core transport
- Preliminary results from EAST confirm self-regulated sputtering and importance of central ECH

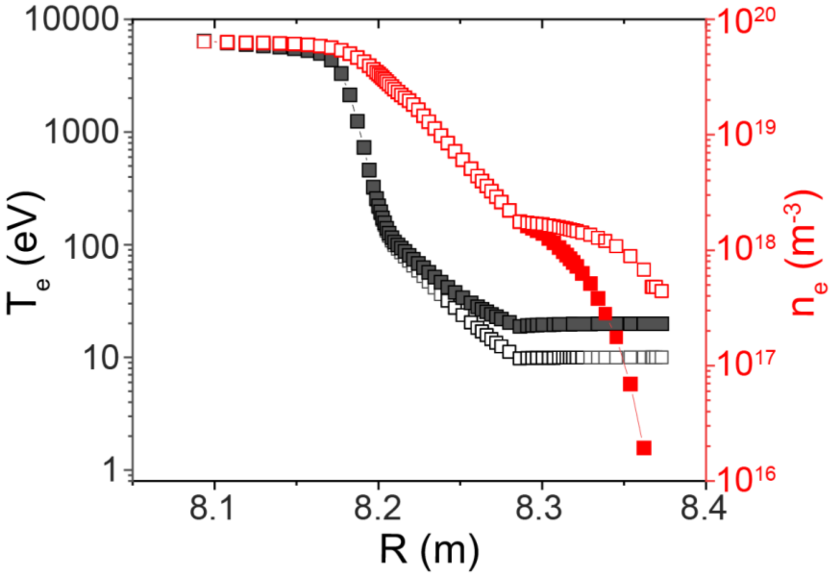


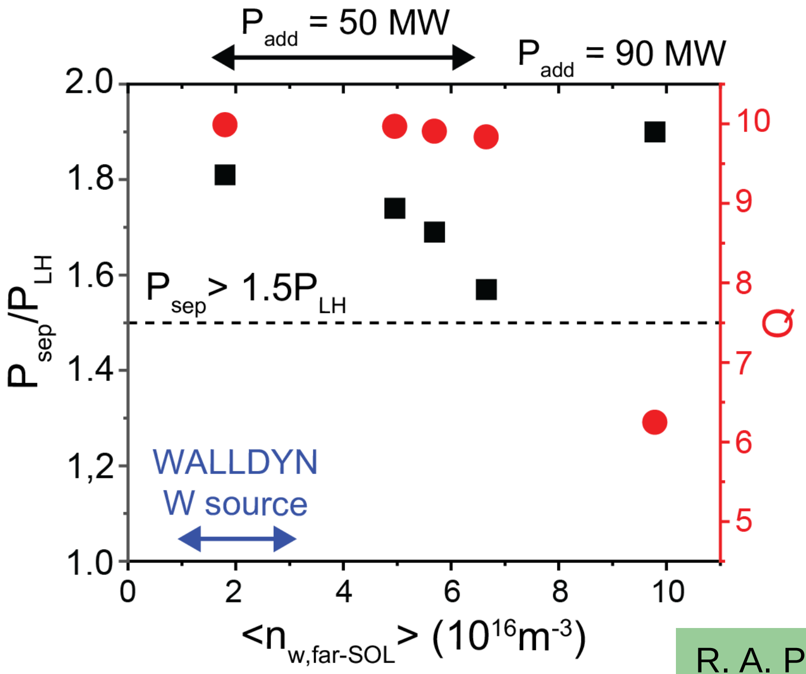
R. A. Pitts et al., NF 62 (2022) 096022
R. A. Pitts et al., PSI (2024)

Impact of a W First Wall on Q = 10 target ?

- WallDYN2D W source calculated for range of Q = 10 background plasmas (SOLPS-OEDGE)
  - W source dominated by Ne + W self-sputtering (CXN sputtering negligible)
  - Source is strongly determined by far-SOL assumptions: worse case is hot, stagnant far-SOL
- Need to improve far-SOL transport predictive capability: exp. + sim.
  - Far-SOL characterization and model validation: sources and transport
  - All W, B erosion/deposition simulations require plasma solutions out to the main chamber walls





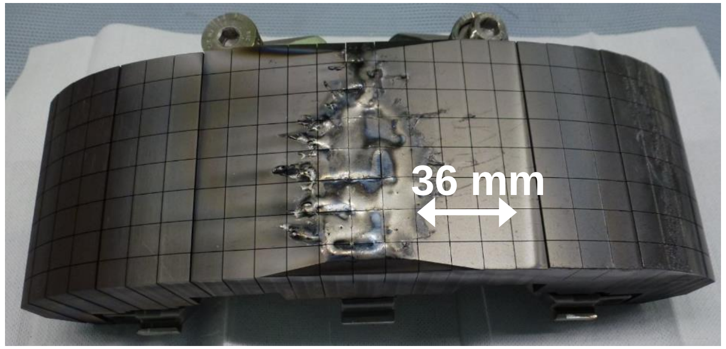


JINTRAC integrated modelling with effective WallDYN source

- Q = 10 operation even with > 2x worst case W source
- Uncontrolled W peaking not found in ITER high Q plasmas

R. A. Pitts et al., PSI (2024)
K. Schmid, PSI (2024)

Transients

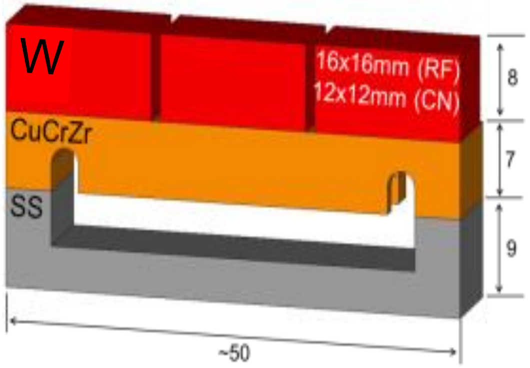


I. Jepu, IAEA 2023 NF subm.

- Determine detailed physics mechanisms leading to splashing of W PFCs under **disruptions or RE** in tokamak experiments

- Determine the impact of melt damage magnitude and spatial distribution on tokamak operation

- Determine reduction of power fluxes to PFCs under large transients due to the formation of vapour shield



Some FW panels of the actively cooled wall will have thicker armour

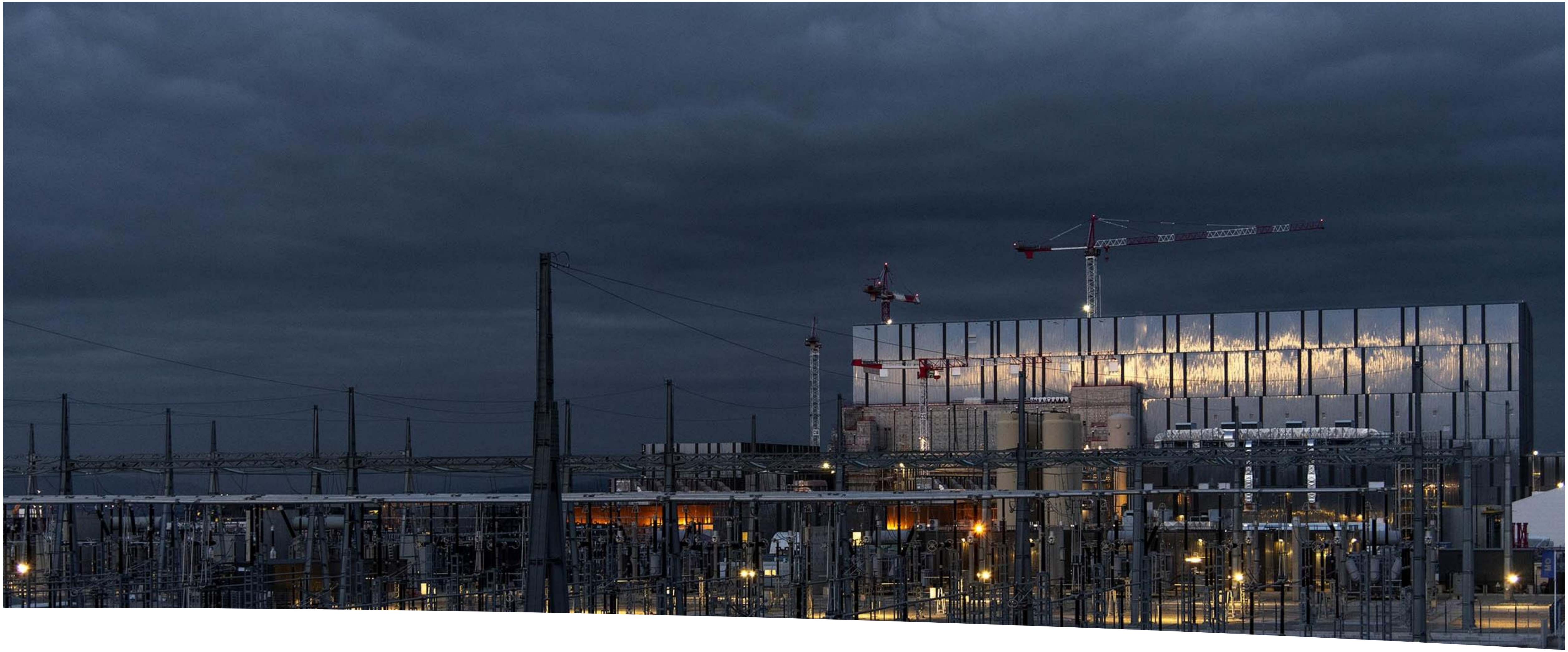
- Determine dominant processes for **dust production** from metallic PFCs with boronization by tokamak operation to provide physics basis for evaluation in ITER

- Determine the net erosion of W divertor and wall by **controlled ELMs** taking into account both sputtering by the plasma (main ion and seeded impurities) and redeposition during the ELMs themselves

Conclusions

- New ITER baseline provides a robust way to the achievement of ITER Projects' goals
- Updated ITER Research Plan (developed jointly with Members' experts)
- Consolidated list of ITPA R&D priorities for new baseline expected end 2024
- Validation of models and tools to predict ITER plasma behaviour and planning of experiments is essential for efficient implementation of Research Plan
- PWI R&D priorities: several new topics due to the change of Be to a W main chamber wall with boronization + continuation of most existing topics

Support by Members' PWI researchers is essential for ITER's success



THE END, THANKS

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china eu india japan korea russia usa