EUROfusion

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Boronisation studies : current status of knowledge and plans for 2024-2025 within WP TE

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Outline

EU has a good portfolio of metallic machines to study boronisation in support of the new ITER baseline : AUG and WEST

- **Current status of knowledge on boronisation from WP TE devices**
  - **Impact of boronisation on plasma operation**
  - **Distribution of boron layers in the vessel**
- **Plans for AUG/WEST in 2024-2025**
- **Summary**

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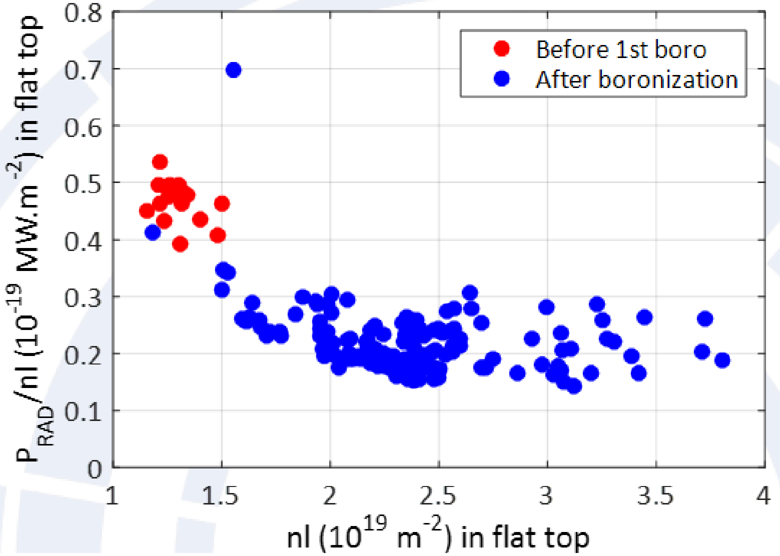
Boronisation opens up the operational domain

WEST : 1st boronization was key in early days of operation

- Usual reduction of oxygen contamination / radiated power
- Improved breakdown conditions
  - Avoidance of Runaway Electrons (high level of impurities ➔ narrow operational window for burn-through)
- Higher density operation achievable

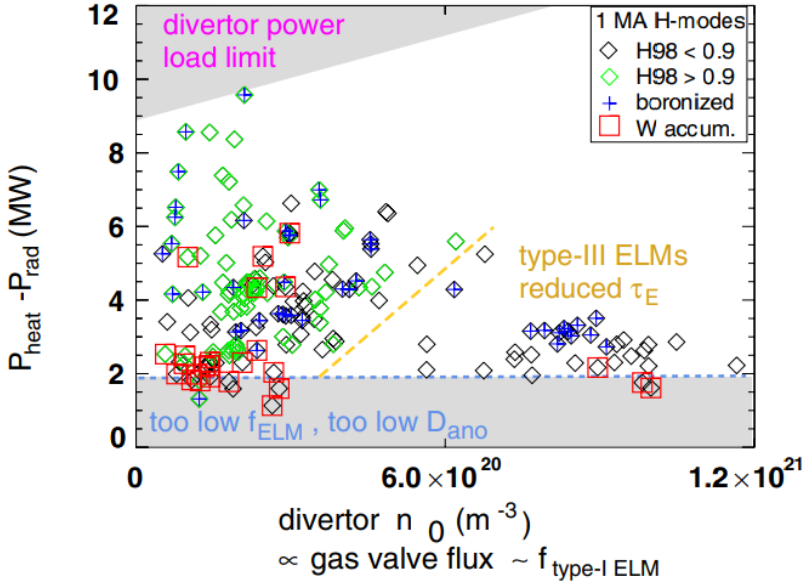
[J. Bucalossi et al., NucFus 2022]



AUG : boronization required for low density operation

- Usual reduction of oxygen contamination / radiated power
- Widens H mode operation space w/o W accumulation
- Low density / high Te operation achievable after fresh boronisation (AT, RMP ELM suppression, fast ion scenarios ...)

[A. Kallenbach et al., Nuc Fus 2009]

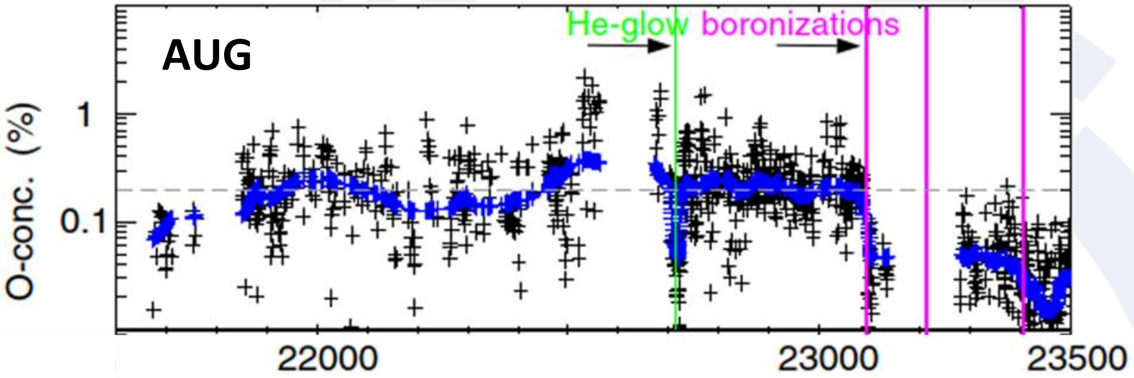


Both devices use boronisation for initial conditioning after venting

Operation without boronisation is possible but requires specific tuning

AUG : successful restart w/o GDB in full W configuration performed

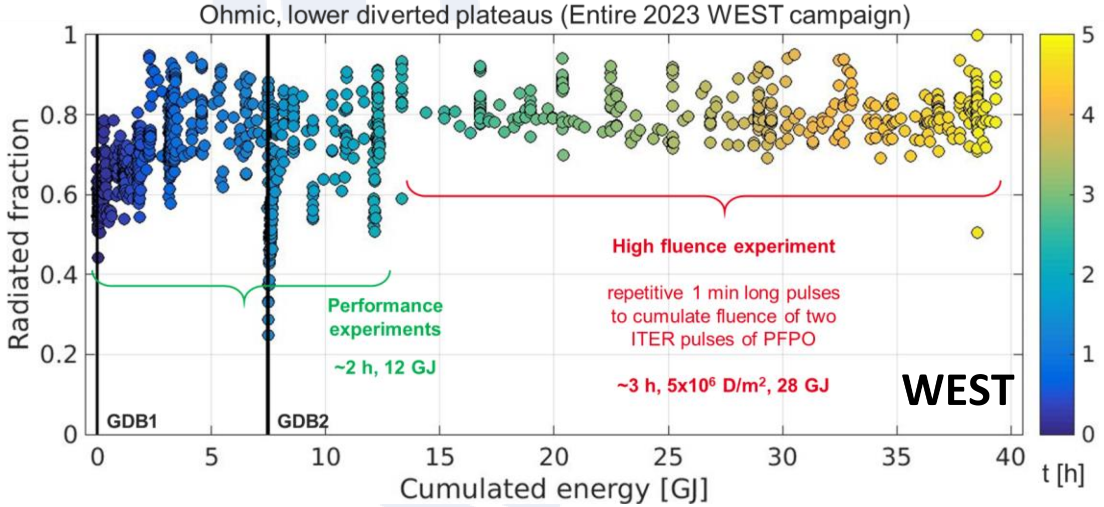
- Plasma restart possible, ~ 1500 pulses before GDB
- Operational limit : W core accumulation / core radiative losses compared to core heating (ELM frequency)
- Recipe : use ECRH for central heating / operate at large gas puff



[A. Kallenbach et al., NF 2009]

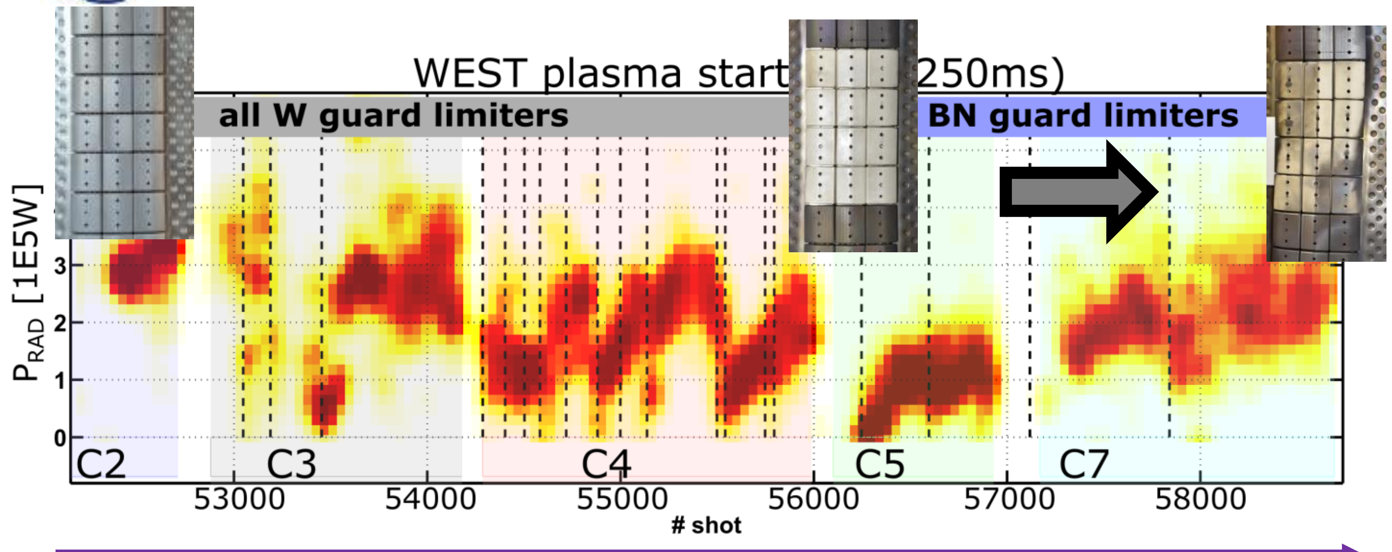
WEST : successful long pulse operation w/o boronisation

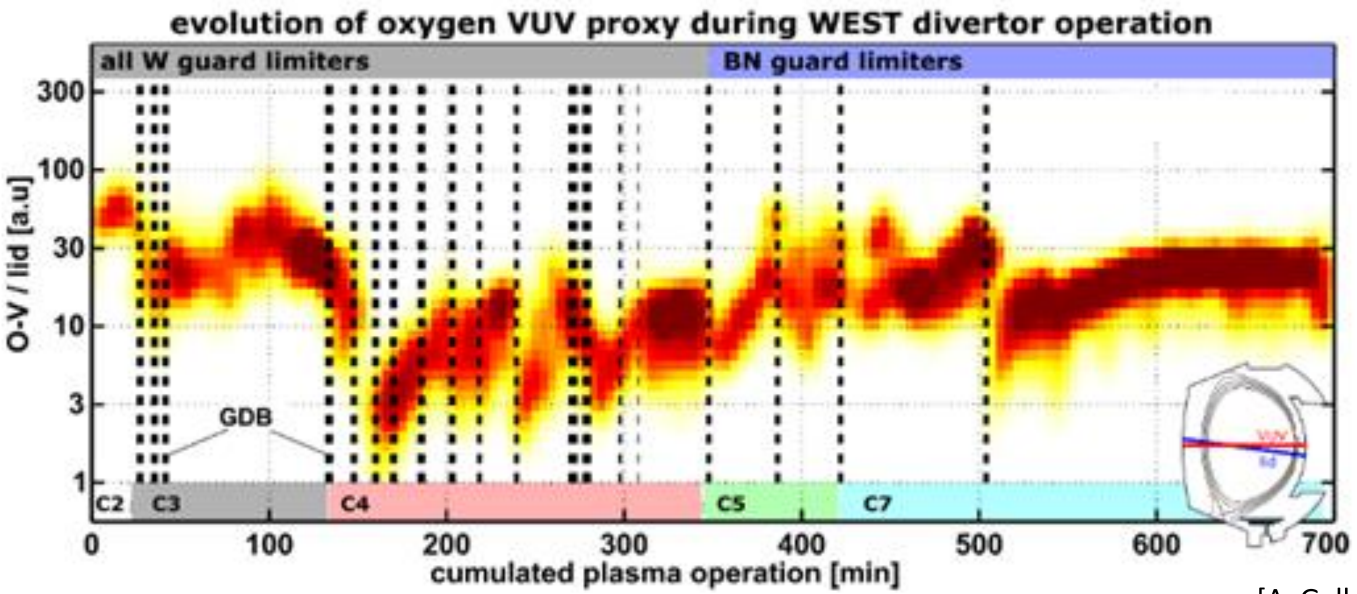
- Operation w/o boronisation for dedicated PWI campaigns where no modification of wall conditions required
- High D fluence campaign (> 400 long pulses, ~ 30 GJ of coupled energy, ~3h of plasma) : no evolution of the radiated fraction in the ohmic phase



[A. Gallo et al., submitted to NME]

Boronisation "lifetime" : several time constants involved





- **WEST : impact on radiated power:**
  - Plasma breakdown :
    - strong reduction in radiated power, recovery 40-60 pulses
  - Limiter phase
    - Less pronounced reduction in radiated power, faster recovery (~10 pulses)
  - Diverted phase (LSN) :
    - Reduction in radiated power vanishes rapidly (~ few pulses)

Caveat : comparison difficult as boronisation conditions (nb of anodes, B consumption, T_{wall}…) + recipe for plasma breakdown / ramp up / flat top scenario evolves

- **AUG :**
  - Short term (recycling, B coverage in strike point area) vs long term (O level) effects also evidenced

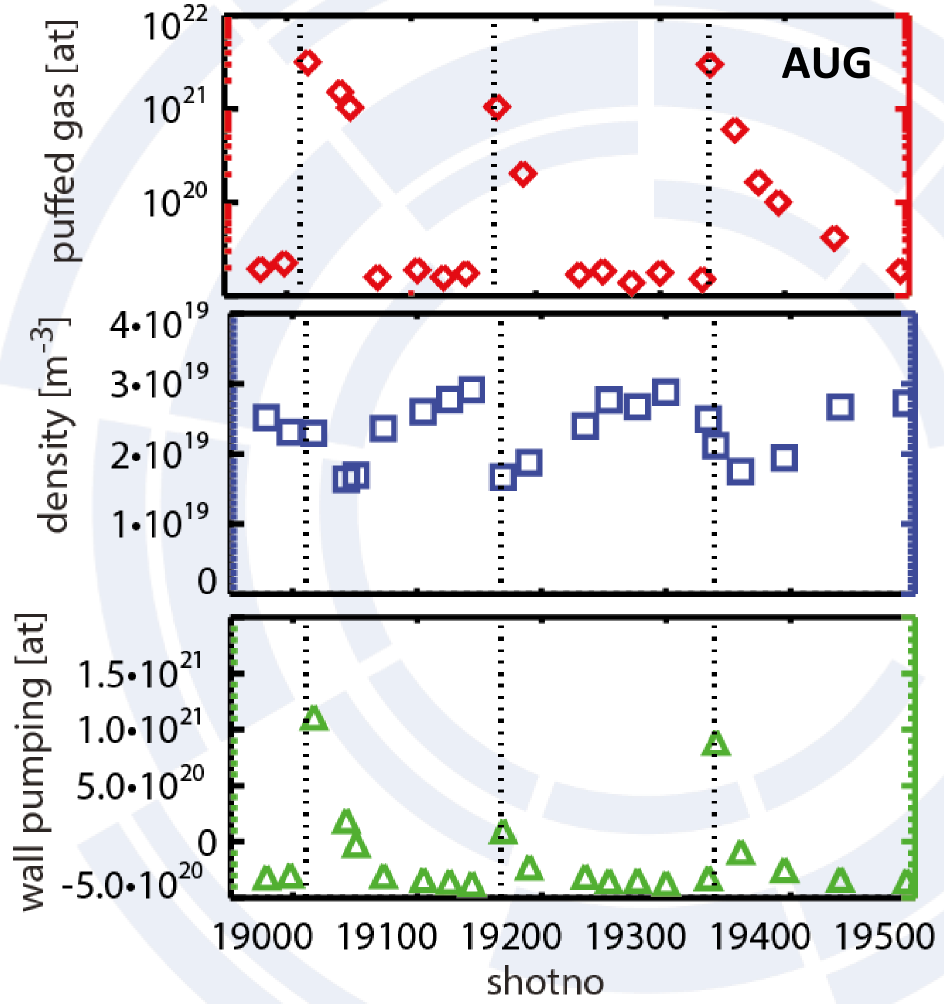
[A. Gallo et al., APS 2022] [J. Bucalossi et al., IAEA 2023, submitted to Nuc Fus]

Boronisation transiently reduces recycling, but has little long term impact on fuel retention

- **AUG : boronisation transiently reduces recycling**
  - B layers from boronization increase D wall pumping during 1 or 2 days of operation (Reduced D recycling at boronized W surfaces, stronger D gas puff needed to reach given density)
  - Hard to quantify impact of B layers on overall D retention as B layers get eroded from PFCs ==> requires repetitive GDB and fixed scenario

- **WEST : modest/short term impact of boronisation on fuel retention for long pulse operation**
  - Particle balance repeated before / after boronisation on long pulse (~1 minute)
  - Strong impact on 1st short ohmic pulse : strong increase in gas puff needed to reach equivalent density (x2)
  - Modest (inverse) impact after ~100s of plasma on fuel retention during long pulse

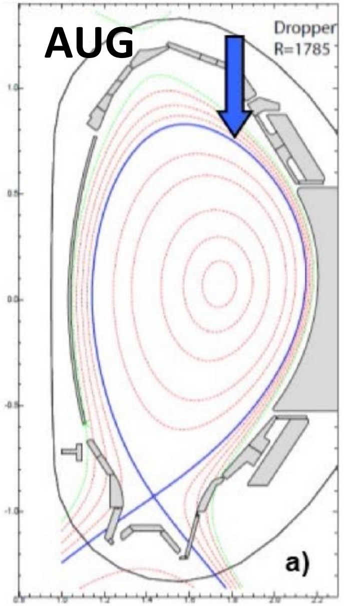
[E. Tsitrone et al., ITPA DivSOL meeting, Kyoto, Feb 2024]

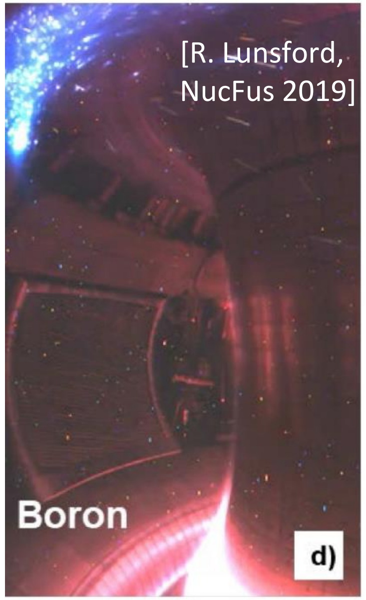


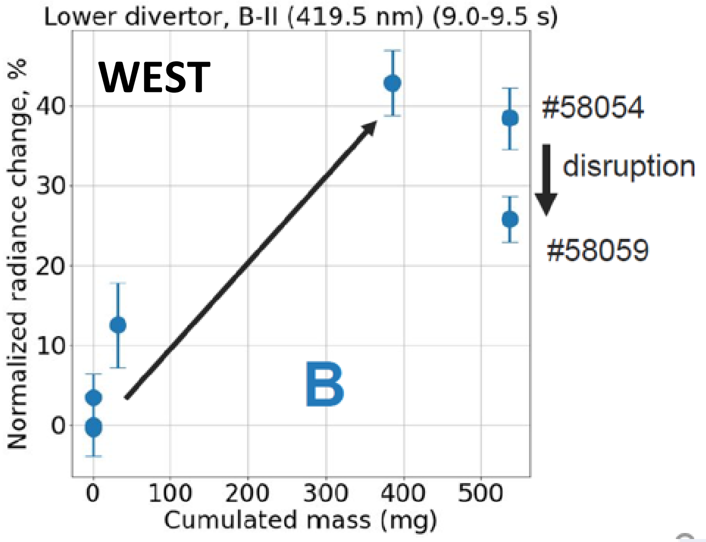
[V. Rohde et al., JNM 2007, A. Kallenbach et al., Nuc Fus 2009]

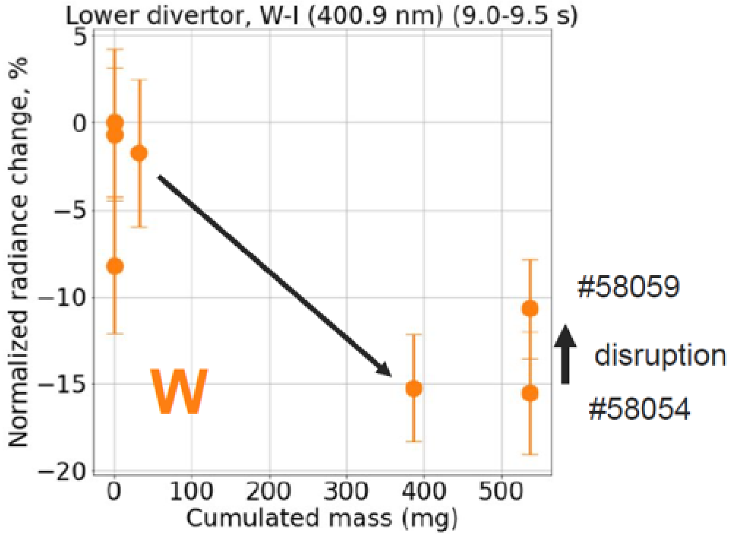
Impurity powder dropper : risk mitigation for ITER

WEST and AUG equipped with IPD : deposition channels / local distribution of B different from GDB
➔ Can extend the lifetime of deposited boron layers on areas prone to rapid erosion









[K. Afonin, NME 2024]

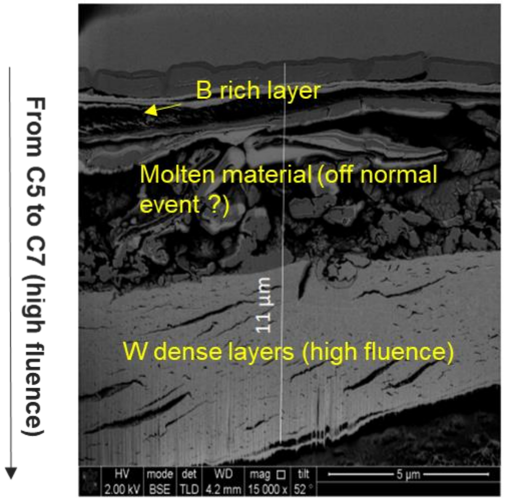
- **Wall conditioning evidenced on both machines**
  - Beneficial effects on wall pumping, reduction of oxygen content and radiated fraction in both devices
  - Improved confinement observed in both devices
  - Large B rate can have adverse effect (up to disruptions)
  - During the drop in WEST : increased W sputtering, but reduced W core transport , beneficial impact above threshold
  - Main chamber in AUG : local limiter B coverage much larger than for conventional GDB : margin for drop rate

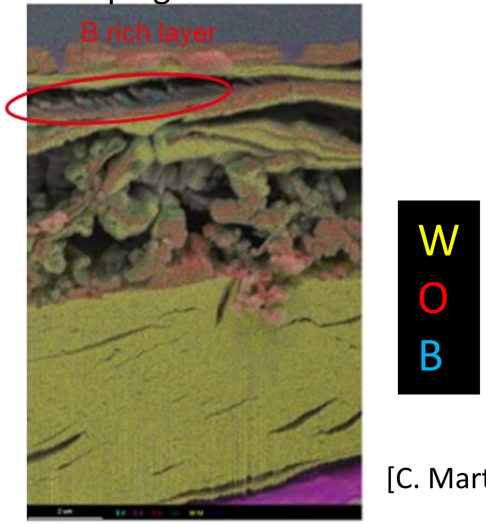
[R. Lunsford, NME 2024] [K. Krieger, NME 2023]

Complex structure of B layers found in tokamaks

- **WEST : non uniform B layers evidenced**
  - Divertor : B rich layer found in HFS deposits (far SOL)
  - First wall : non uniform poloidal / toroidal deposited layer thickness, B rich layers interleaved with W oxide layers

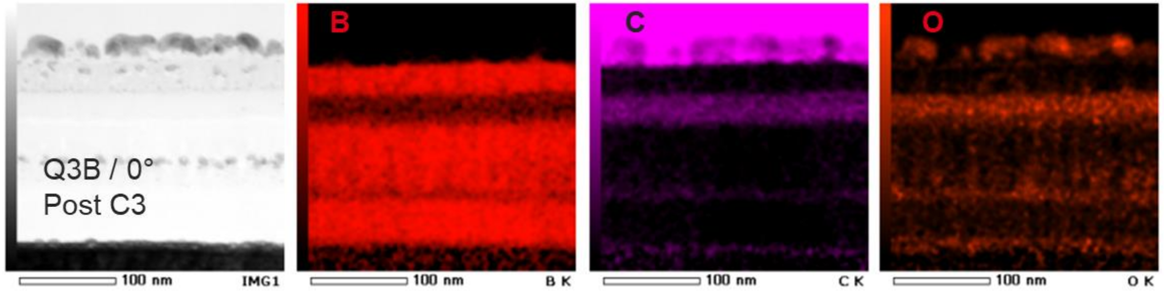
WEST divertor deposits after the C7 campaign



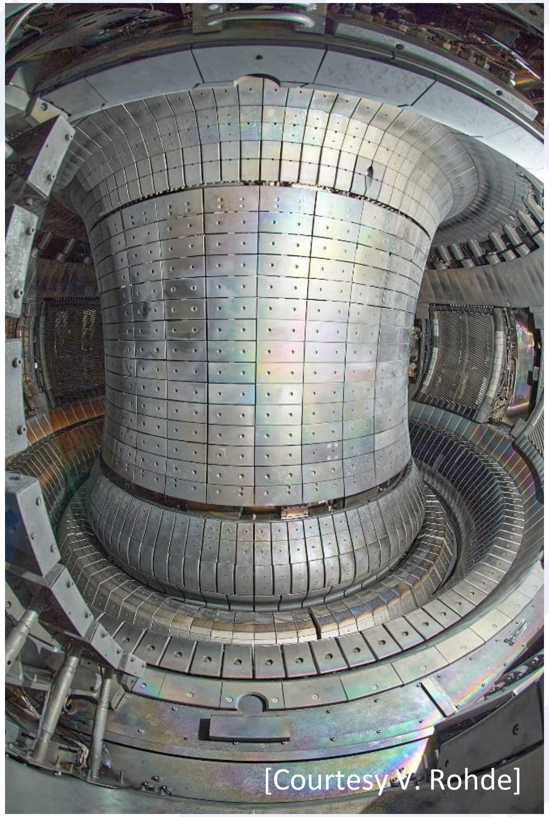


[C. Martin, submitted to PSI 2024]

WEST first wall deposits after C3 [E. Bernard, PSI 2022, R. Sakamoto, private com.]



- **AUG :**
  - Whitish unstable B layers found when venting : cleaned after each campaign with wet wiping


[Courtesy V. Rohde]

- **In both machines :**
  - Difficult to disentangle impact of C and B
  - Wide D/(B+C) range : from 0.1 to 0.4

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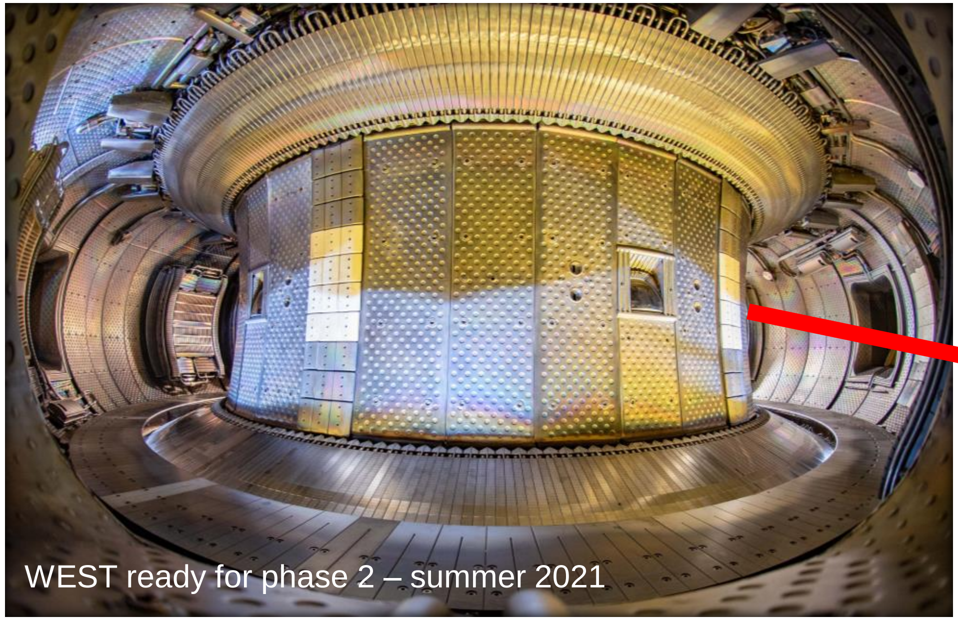
Specific features of WEST / AUG for the 2024 / 2025 campaigns

- **WEST :**
  - Change of inner / outer bumper tiles from BN back to W
  - Boronisation collector probe available in 2025 (LTS available)
  - Longer term : LIBS (LID QMS) for in situ measurements
- **AUG :**
  - Restart after long shutdown with new upper divertor
  - Manipulators available for sample exposure during boronisation (LTS available)
  - New diagnostics for material migration (QMB)



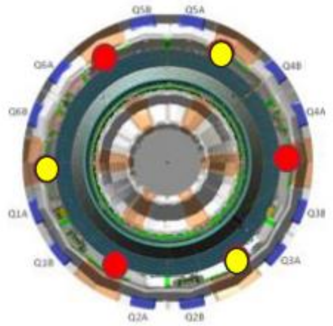
Plans for 2024 : focus on B layer uniformity

Similar restart plan for both AUG/WEST

- **Test (briefly) start up without boronisation :**
  - WEST : restart w/o GDB for a few days
  - AUG : restart w/o GDB for 1 day or until required data (spectroscopy …) available

  NB : restart presently planned on both machines by ~mid October (stay tuned to WP TE news)

- **Perform “half” boronisation :**
  - WEST : 3 of 6 anodes, ITER ref temperature (70°C), no collector probe available in 2024 (will be repeated in 2025 with collector probe, exposing W and SS samples), LTS
  - AUG : 2 of 4 anodes, room temperature, samples exposed in manipulators + LTS + new QMB



- **Perform “full” boronisation :**
  - WEST : 6 anodes at 70°C, no collector probe available in 2024 (will be repeated in 2025 with collector probe, exposing W and SS samples), LTS
  - AUG : 4 anodes, room temperature, samples exposed in manipulators + LTS + new QMB

On both machines : perform start up limiter studies on W inner bumpers for each phase (tbc)

Reference shots required to be repeated for comparison of no boro / half boro / full boro

Longer term plans on AUG/WEST

Call for 2025 experimental proposals now open !

- **Scientific objectives of RT06 (Preparation of efficient Plasma Facing Components (PFC) operation for ITER, DEMO and HELIAS) : increased focus on boronisation**
  - Quantify local power load distributions on castellated and shaped PFCs for ITER and DEMO…
  - Assess the impact of sustained high power / high particle fluence plasma …
  - Quantify material erosion sources from metallic walls under ITER relevant plasma conditions …
  - Quantify fuel retention in devices with metallic walls, with a focus on long pulse operation (using recent fuel retention diagnostic upgrades such as laser-based diagnostics where available) and **including impact of boronisations**
  - Determine fuel-removal in metallic devices in conditions relevant for ITER (**including the impact of boronisation)** and extrapolate to DEMO
  - **Assess efficiency and lifetime of conditioning methods in metallic devices, with a focus on boronisation**

- **Deadline October 11**
  - All details on WP TE wiki :

https://wiki.euro-fusion.org/wiki/WPTE_wikipages:_Call_for_proposals_2025

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Boronisation routinely used in AUG / WEST :

After a vent and/or to access specific plasma conditions

- High Z material coverage by B in plasma exposed area (transient)
- Reduction of D recycling / enhanced wall pumping (transient)
- O gettering (➔ decrease of W sputtering by impurities) (longer term)

➔ Used to gain experimental time ("kitchen physics" based on TEXTOR recipe)

➔ B chemistry complex (and largely unknown in tokamak conditions)

New focus as required for full W ITER configuration :

- Optimize boronisation parameters for ITER (electrodes, injection points, wall temperature etc ➔ design) and assess frequency required (conservative IO estimate : up to once every 2 weeks)
- Impact of B on fuel retention / removal (D/B, disentangling B vs C)
- Increased modelling capabilities needed (B deposition from GDB, subsequent B migration during plasma operation, fuel uptake / removal and O gettering)

Synergies between PWIE / TE : well controlled experiments in linear devices (parametric dependencies) vs integrated tokamak experiments + post mortem analysis of tokamak exposed samples