Updates on the ITER project

EUROfusion WP PWIE Midterm Meeting - September 25th - 28th 2023

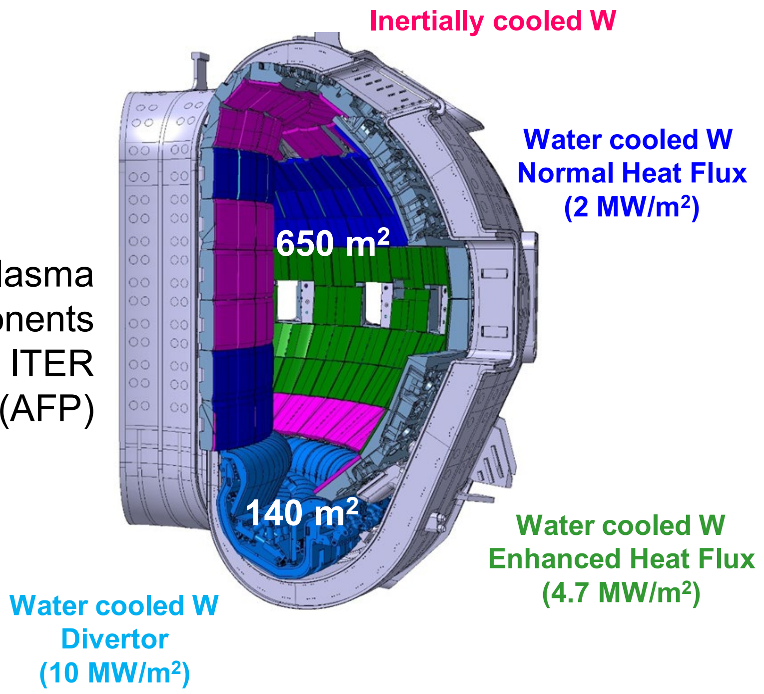
Tom Wauters - ITER Organization - SID/SCD/Experiments & Plasma Operation

china eu india japan korea russia usa

Outline

- IO proposal for ITER re-baseline
- Physics assessments for the new baseline
  - Heating requirements
  - W sources,
  - Impact of W on Q=10
  - Assessments for boronization in ITER
  - Disruptions and runaway electrons
- Open research questions

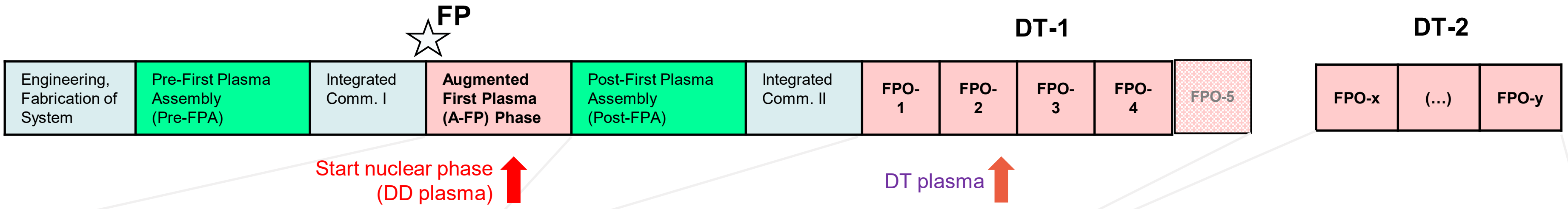
Proposed plasma facing components in the first ITER campaign (AFP)



IO proposal for ITER re-baseline

- Three scenarios were explored of which one (B) was selected by IO and proposed to the ITER Council
- This new scenario was further elaborated and will be presented to the STAC this week and at the November Council meeting
- Final decision on the new baseline including schedule and cost expected end of 2024
- Main features of the new scenario :
    - Augmented First Plasma Phase with partially inertially cooled first wall and plasma operation up to 15 MA
    - Two main DT phases with multiple campaigns
    - Change of first wall material from beryllium to tungsten

IO proposal for ITER re-baseline



- Operation up to 15 MA / 5.3T
- 40 MW EC heating
- 5 MW IC Wall Conditioning
- PCS and DMS commissioning

- DT operation with limited neutron fluence (nuclear licence I)
- 67 MW EC heating
- 33 MW NBI
- 20 MW ICRH (if W contamination and coupling acceptable in AFP)

- DT operation with full neutron fluence (nuclear licence II)
- Possible NBI upgrade to 50 MW

Opportunities

- Avoid Be handling and assembly difficulties
- FW more resilient to transient heat loads (PCS, DMS and ELM-control commissioning in AFP)
- Reactor relevant FW (change to W anticipated)
- Merge of FP with first experimental campaign

Challenges

- Plasma start up difficult with W
- Boronization is mandatory and needs to be implemented in ITER
- B layers retain T → fuel removal scheme required
- Risk for Q=10 due to enhanced radiation losses

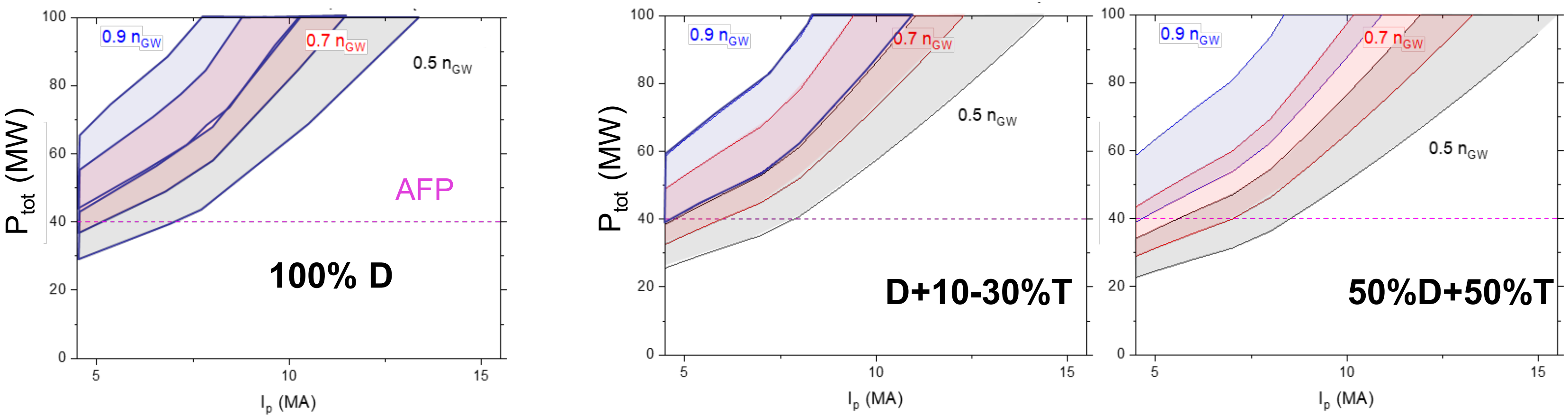
Heating requirement

- **H-mode operational space (W wall): $0.25 \leq P_{rad}^{core}/P_{tot} \leq 0.5$ and $P_{sep} \geq 1.5\ P_{LH}$**

AFP: 40 MW → H-mode at 5-7.5 MA/2.65T*
test W transport and ELM control
FPO: 100 MW → H-mode up to 12.5 MA

FPO: P_{aux} = 100 MW
→ H-mode operation up to 15 MA for 10-50%

[A. Loarte et al 2021 Nucl. Fusion 61 076012]

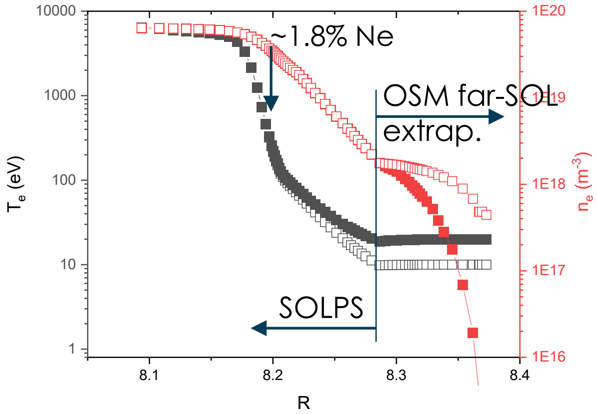


Note: 50% n_{GW} gives optimum access to H-mode

* ECH H-mode operation in DD at low I_p is robust and has low reactivity (T_i < 1/3 T_e) → 10^{15}-10^{16} n/s at 5 MA (x 6 for 7.5 MA)

W sources

- **WallDYN simulation of the W source in Q = 10 plasmas**

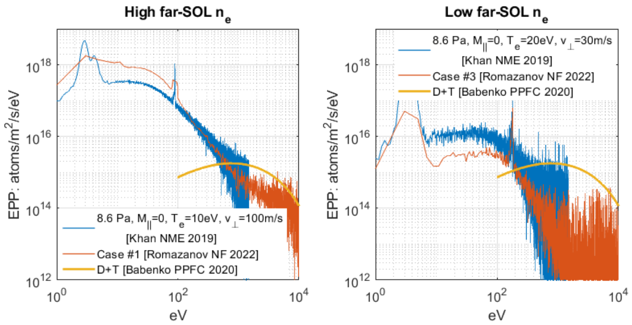


Outer midplane n_e and T_e profiles including the far-SOL plasma extrapolations for ITER Q = 10, P_{SOL} = 100 MW, p_n = 6.3 Pa, 1.8% Ne seeded D plasma. Square edges: high far-SOL n_e ($v_\perp$ = 100 m/s) and low T_e. Filled squares: low far-SOL n_e ($v_\perp$ = 30 m/s) and high T_e.

[K. Schmid, ISFN Fellow, IPP Garching]

Summary of WallDYN calculated gross W source from sputtering by Ne ions, CXN and W self-sputtering for the ITER Q = 10 plasma backgrounds

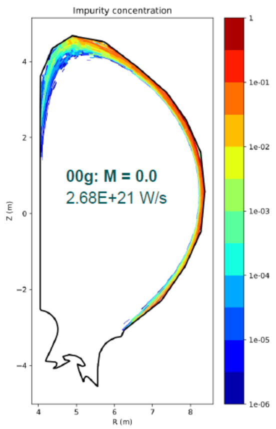
Case	W_{Ne} ($10^{20}s^{-1}$)	$W_{Self\text{-}sput}$ ($10^{20}s^{-1}$)	$W_{C\text{-}X<E>}$ ($10^{20}s^{-1}$)	$W_{C\text{-}X}^{max}$ ($10^{20}s^{-1}$)
High far-SOL n_e and low T_e	3.0	1.3	0.08	0.8
Low far-SOL n_e and high T_e	6.8	19	0.005	0.14



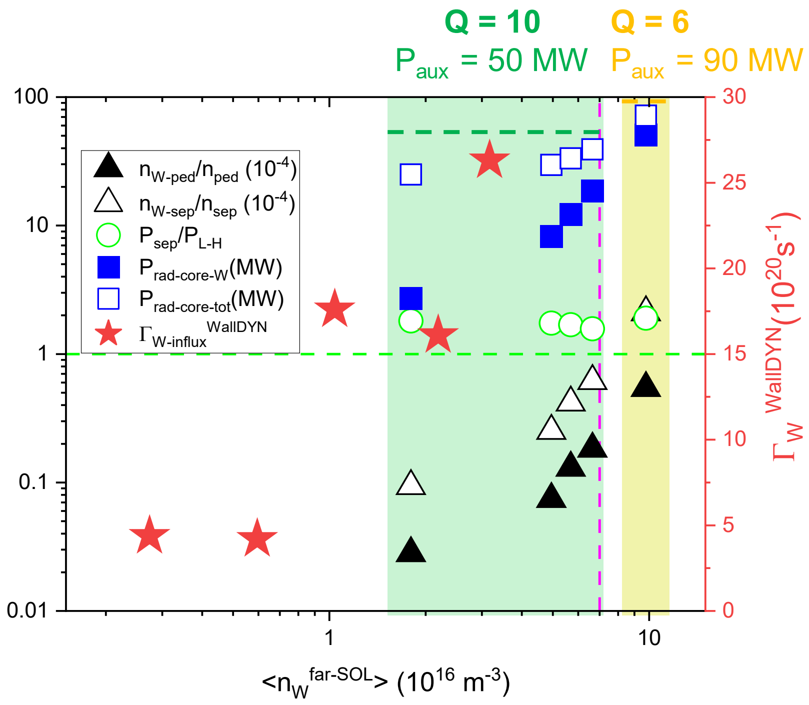
Combines EIRENE and DOUBLE-MC spectra to reflect the role of sputtering by neutrals in the energetic tail of the CXN distribution, as well as the energy and angular dependent W sputtering yield.

Impact of W on Q = 10

- **JINTRAC simulations** show Q = 10 can be maintained for max W influx
  - Higher flux → more heating → lower Q



- Max gross erosion of **2.6×10^{21}** atoms/s obtained by **WallDYN** with background plasmas with 1.8% Ne
  - Main SOL $M_{//}$ = 0 & 0.5
  - Far SOL T_e = 10 & 20 eV ($T_i = 2xT_e$)
  - Far-SOL v_{perp} = 30 & 100 & m/s
  - 60 and 90^{o}C impact

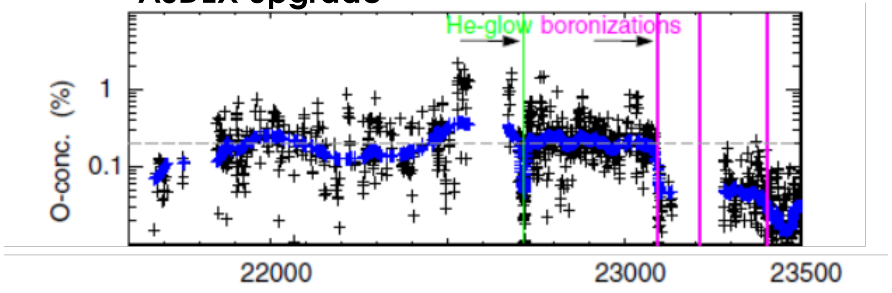


- **Low-medium risk to Q = 10**

Boronization to ease plasma start-up with a W wall

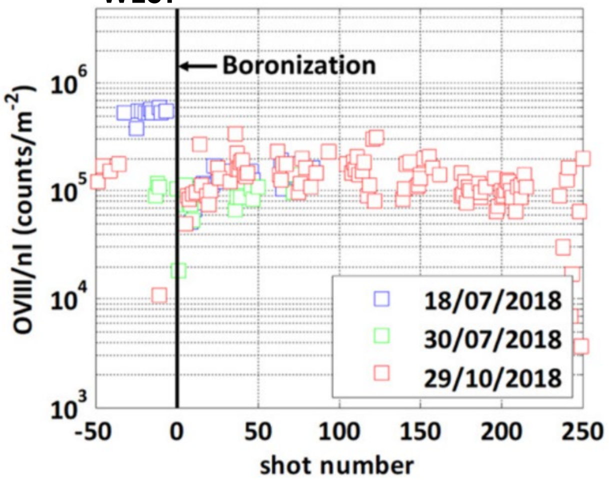
- The reduction of the oxygen impurity concentration achieved through the application of boronization is equivalent to that of Be gettering [Winter 1990 (& seminar at IO 21/09/2023)]
- Without boronization, ASDEX Upgrade, WEST, EAST [Liu PPCF 2007] (and ITER simulations) show narrow operational space for start-up on high-Z limiters due to sputtering by impurities

ASDEX upgrade



Development of O concentrations during the unboronized, full-W ASDEX Upgrade campaign and after boronization, from x-ray lines measured by a Bragg crystal spectrometer ($n_e > 4.5 \times 10^{19}\ m^{-3}$). [Kallenbach NF 2009]

WEST



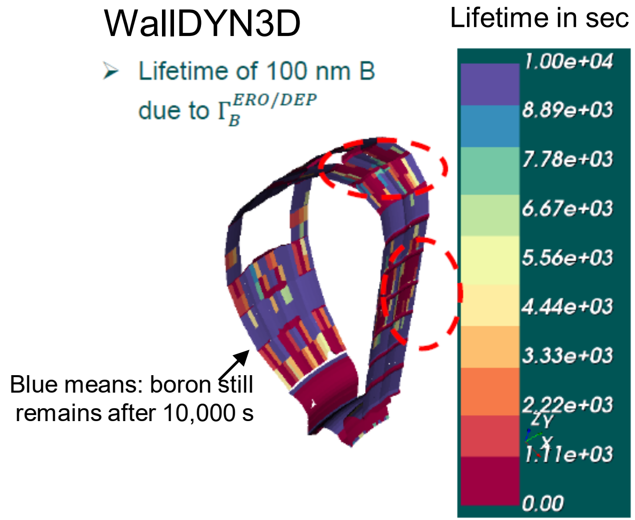
Oxygen radiation before and after the first, second and third boronizations performed on WEST [Bucalossi NF 2022]

Layer lifetime : plasma erosion and oxygen ingress

1. Boron erosion by plasma depends on the location of PFC
   - B in "remote areas" lasts 10,000 s for "worst" Q = 10 plasmas (widest far-SOL, near DN)
   - 2 weeks of operation = 10,000 s of heated flat top (65 s)

WallDYN3D

- Lifetime of 100 nm B due to $\Gamma_B^{ERO/DEP}$



[K. Schmid, ISFN Fellow, IPP Garching]

2. Layer capacity for O gettering
   - 50 nm of boron layer: 1-5 x 10^{20} O/m^2
   - 10% of effective O-gettering surface due to erosion
   - Conservative O outgassing and leak rate from ITER Vacuum handbook

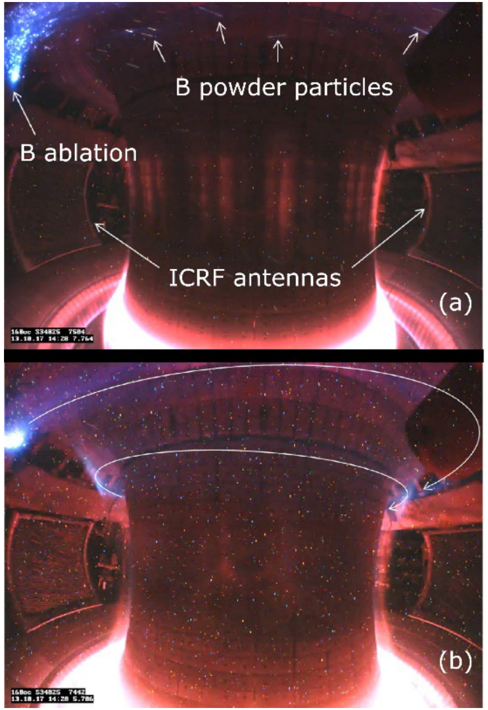
   → Capacity for storing 2.5 to 12.5 weeks of O ingress

- Boronization cycle of 2 weeks (during STM) considered as reference for maximum average frequency over long operating periods

Boron powder dropper

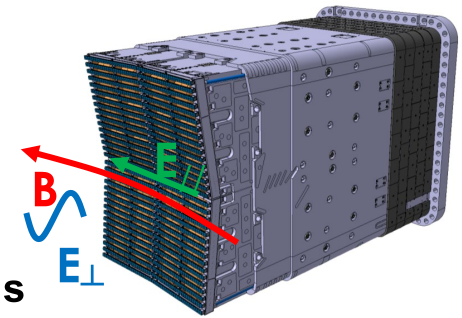
- Impurity Powder Droppers (IPDs) have been installed on ASDEX-U, DIII-D, EAST, LHD, KSTAR and WEST as well as a modified horizontal injector deployed on W7-X.
- IPD introduces sub-mm particulate material by resonant piezo-electric vibration and gravitation In present devices IPD provides an actuator for controlling intrinsic impurities and density control.
- **In ITER, the IPD is proposed as an actuator to increase performance of a limited number of pulses, e.g. Q = 10, by providing a temporary low-Z main chamber wall**
  - → with less W, less radiation, less heating, higher Q
  - → Requires tens of grams of B powder / pulse (vs. 86 g-B / 2 weeks in GDC boronization)
- Complements GDC-boronization in ITER:
  - Coating of plasma wetted surfaces disappears quickly, likely before restart after STM reaches full power
- A preliminary assessment by the IO and PPPL experts found no showstoppers to integrating a B IPD in ITER

B powder in ASDEX Upgrade

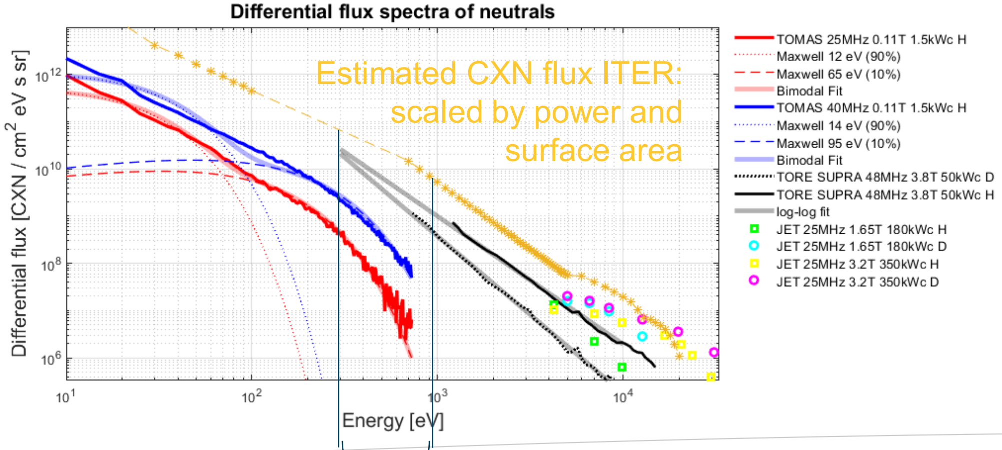


[Bortolon, Nuclear Materials and Energy Volume 19, May 2019, Pages 384-389]

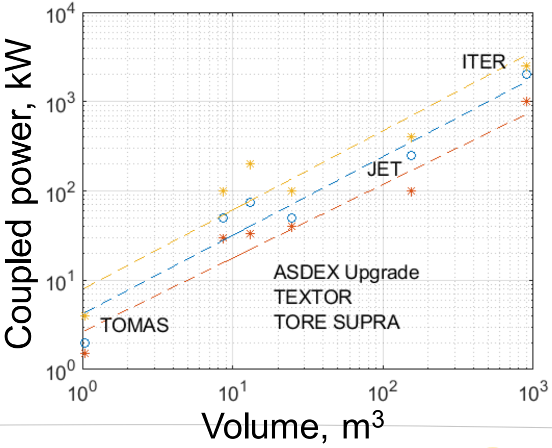
ICWC for tritium recovery in ITER



- Uniform discharge produced by collisional absorption of ICH waves
- Requires 2.0-2.5 MW coupled to plasma at 40-50% efficiency
- **Accesses main chamber recessed areas by charge exchange neutrals**
  - B: removal in implantation range only (10’s nm) → requires energetic neutrals 300 eV
  - W: removal by diffusion, trapping / detrapping from traps with multiple occupancy (~1 μm)



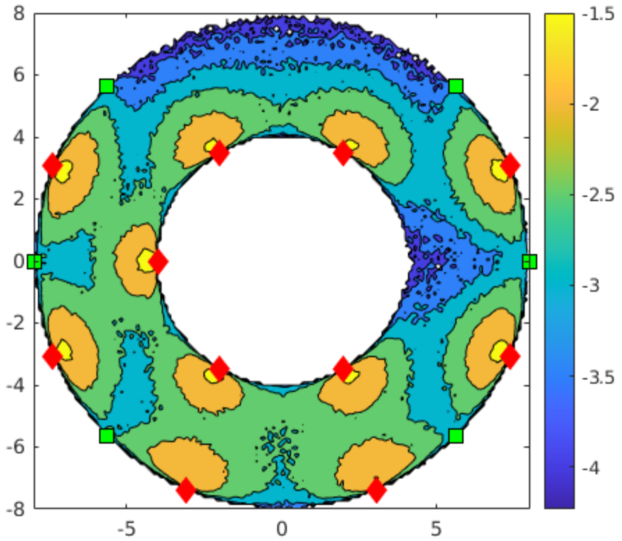
Mean free path D$^+$ > 100 m at 2.5 mPa



Optimal anode and diborane injection configuration for uniform coating

- Obtained by Monte Carlo modelling of the ITER boronization GDC, based on
  - Previously obtained H_2 and He GDC plasma backgrounds [Hagelaar 2014]
  - Elementary collisional processes of diborane.
- Example possible equatorial configuration on ITER
  - 0.3Pa, 30A / anode, He glow
  - 6 midplane anodes ■ (placed in the port plugs, no anodes possible in the NBI sectors)
  - Multiple injection points ◊ spaced 4 m (HFS) to 6 m (LFS) apart
  - Additional anodes and injection points need to be considered in the upper vessel part
- Increase of present 7 anodes to 11
- Addition of 21 diborane injection points

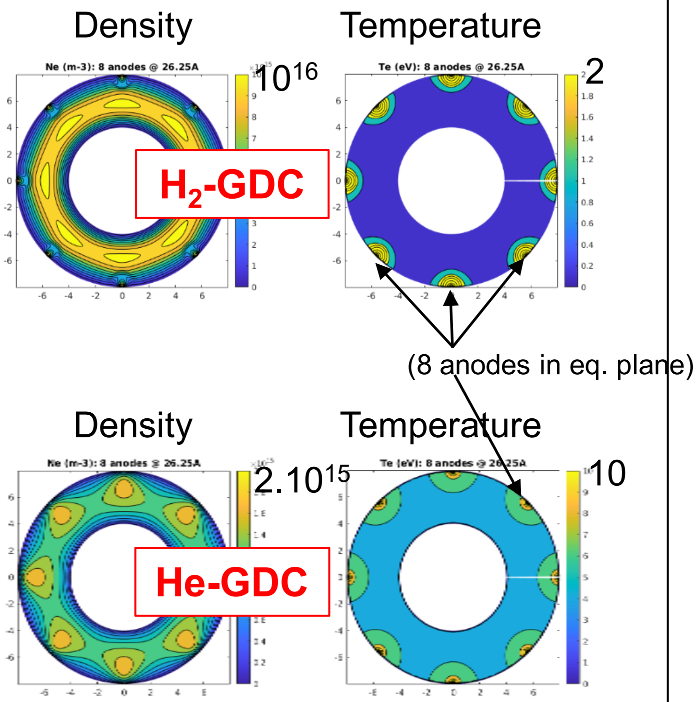
Normalised decomposition counts



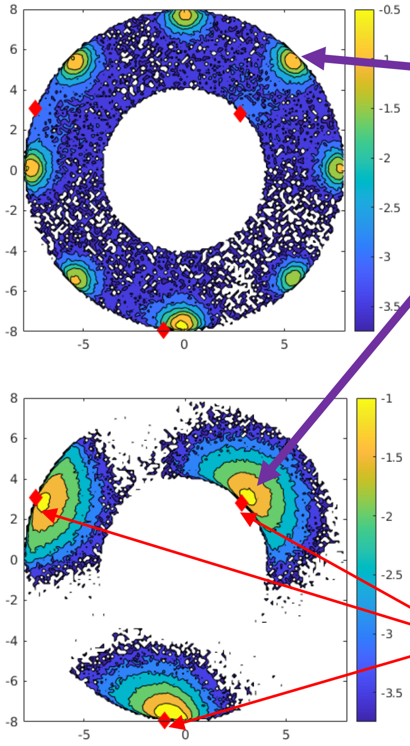
B_2H_6 injected at red diamonds ◊
6 anodes located at green squares ■

Comparison of He and H_2 as diborane carrier gas

- Model input



- Simulation result



- Conclusion

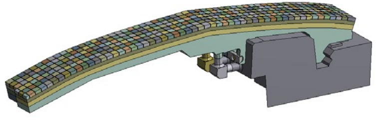
  - B_2H_6 decomposes
    - in anode glow in H_2-GDC
    - near injection points in case of He-GDC

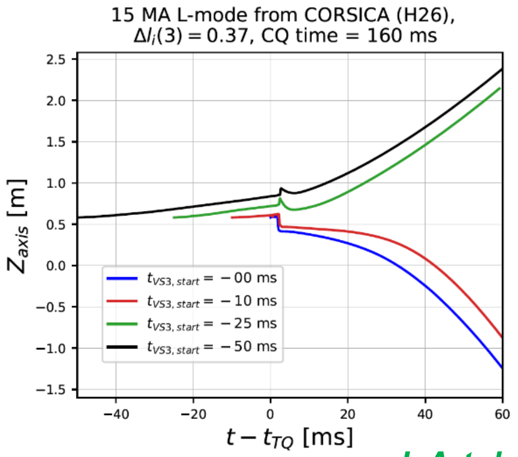
  - **While He-GDC may cause bubble formation and He/H retention, the use $He+B_2H_6$ and uniform fuelling will allow for best uniform deposition layers, and to avoid coating in anode port**

Normalised decomposition counts
B_2H_6 injected at red diamonds ◊

Disruptions

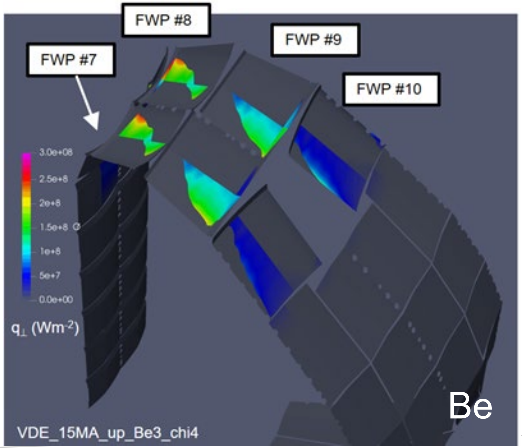
- Disruptive plasmas (or plasmas for DMS commissioning) in AFP must deposit energy (and REs) on inertially cooled wall to avoid W divertor damage
- FWP melting during CQ can cause bridging of gaps between fingers leading to **high forces in subsequent disruptions from eddy currents**





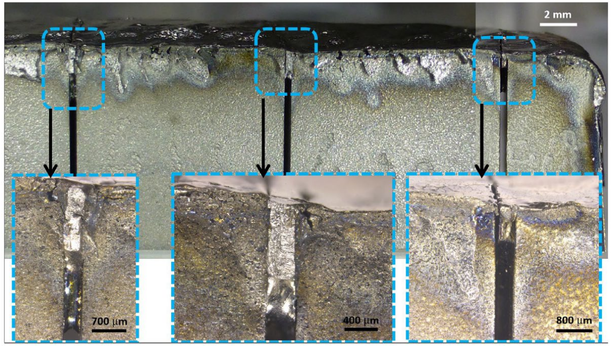
J. Artola

Melting occurs on FWP #8 and #9 during upward moving CQ



J. Coburn, R.A. Pitts, NF 2022

Gap bridging in JET with Be tiles

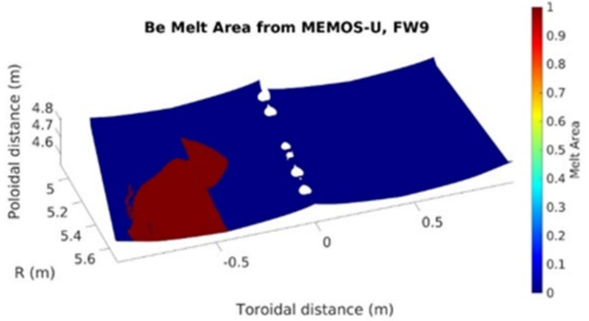


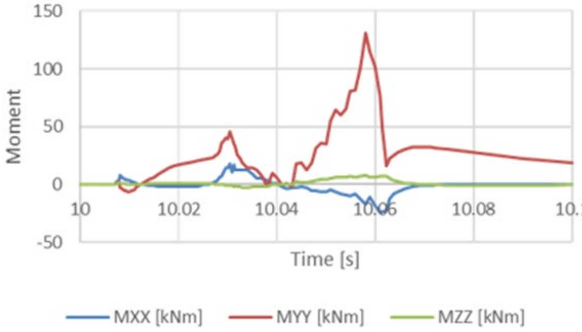
I. Jepu, NF 2019

Disruptions

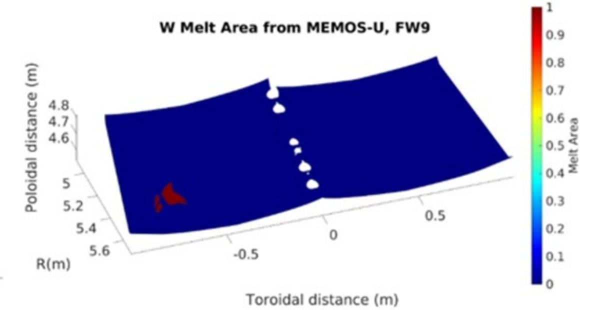
First wall panel #9

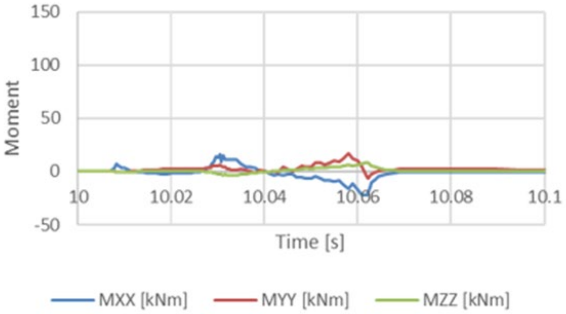
Beryllium
- Large melting area
- High moments on fingers (beyond limits)





Tungsten
- Very small melting area
- Moments stay low
- *Gap bridging less likely (experience at AUG)*



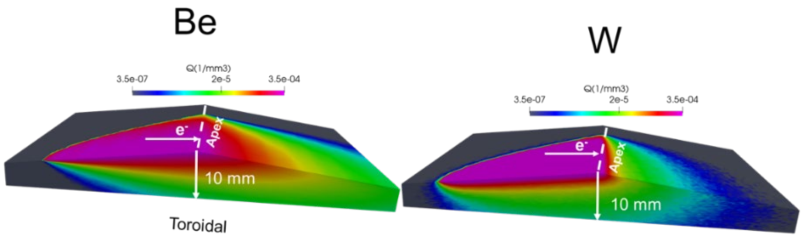


Forces on FWP #8 not much enhanced by gap bridging (lower jxB)

Runaway electrons

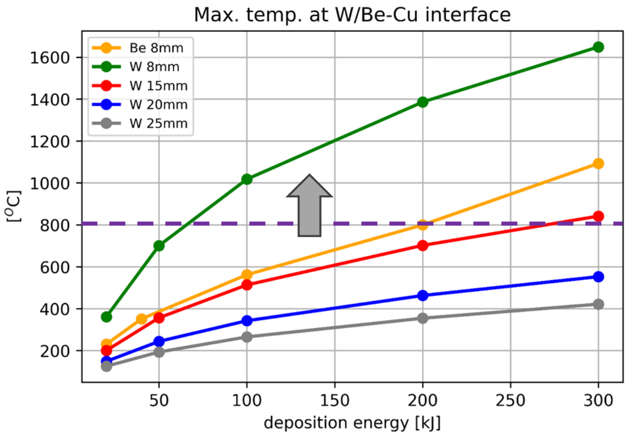
- W has higher stopping power → more localized loads
- Higher heating at cooling interface for W → RE mitigation must be developed with inertially cooled W PFCs (AFP)
- Thickening of the W layer is considered to mitigate higher RE loads on W

SMITER-GEANT4-MEMOS-U workflow



L. Chen, R. Pitts

λ_r = 4 mm / Δt = 100 ms



Threshold for cooling channel integrity with 8 mm W (T ≈ 800°C):
~70 kJ / roof → toroidal wetting 30% → I_{RE} ~ 0.5 MA (100 ms impact, 100% E_{mag} conversion)

Futher research

- Laboratory / analysis
  - Hydrogen retention in boron layers / mixed layers
  - Analysis of hydrogen retention in boron layers / scaling law
  - Gettering and release of O on B layers, W, stainless steel
  - Boron layer flaking
  - Steam event, impact of water ingress on tritium release, oxidation, and dust generation in boron : Chemical reaction rates of boron with water, air, …
  - Study of GDC-boronization and ICWC with sample exposures in magnetized torus, demonstration of O and D removal from B
  - LID-QMS and LIBS on boron layers

Futher research

- Modelling
  - GDC boronization
  - Boron erosion and migration by WallDYN-3D
  - Boron erosion and migration into remote areas (mirrors) by ERO2.0
  - Powder dropper simulations with EMC3-EIRENE and DIS dust injection simulator
  - Fuel retention and removal simulations

Further research

Defined actions in STAC report: IC/STAC-29/3.3. Boronization system

- Detailed modelling using expertise with vapour deposition mechanisms to help confirm the design (#2)
- Boronization/Glow Discharge parametric studies with SWIP (#8)
- ITER GDC electrode testing at EAST (#14)
- Continue to study design solutions to incorporate boron dropper option at ITER (#15)
- Laboratory testing of ICWC, GDC and baking to remove Q2 isotopes from boron layers (#16)
- Characterisation of boron dust and detachment of boron flakes from surfaces (#17)
- Conduct modelling based on results from Actions 17/18 to extrapolate to ITER scale (#18)
- Modelling of boron erosion and migration should be performed to confirm how often cleaning is required (#19)

ITPA open issues in the new ITER baseline with a W wall that require experimental assessment

- Need for boronization with high Z plasma facing components (PFCs)
- Optimum application of boronization
- Formation of boron deposits and fuel retention

Richard Pitts, Alberto Loarte, Ian Bonnett, Peter Speller, Scott Wilms, Michael Walsh, So Maruyama, Tom Keenan, Andrey Ovcharov, Charles Alarcon, Dario Carloni, Fabien Josseaume, Gabor Kiss, Pak Sunil, Victor Udintsev, Arnaud Fossen, Klaus Schmid, Gerjan Hagelaar, Volker Rohde, Gerd Schall, Arne Kallenbach, Karl Krieger, Lilla Vano, Sven Degenkolbe, Alessandra Canton, Jerome Bucalossi, David Douai, Alberto Gallo, Philippe Moreau, Daniel López-Rodríguez, Kurt Holtrop, Rick Lee, Igor Bykov, Robert Lunsford, Alessandro Bortolon, F. Effenberg, Rajesh Maingi, Alexander Nagy, Joe Snipes, Z. Sun, Li Bo, Guizhong Zuo, I. Nunes, S. Pinches, P. de Vries, M. Lehnen, J. Artola, I. Carvalho, A. Polevoi, S-H. Kim, F. Köchl, X. Bai, M. Dubrov, Y. Gribov, M. Schneider, L. Zabeo, M. Merola, F. Escourbiac, R. Hunt, L. Chen, D. Boilson, P. Veltri, N. Casal, M. Preynas, A. Mukherjee, W. Helou, F. Kazarian, S. Willms, I. Bonnet, R. Michling, L. Giancarli, J. van der Laan, M. Walsh, V. Udintsev, R, Reichle; G. Vayakis, A. Fossen, M. Turnyanskiy, J. Rapp, Ph. Snyder, Z. Unterberg, M. Xu, G. Xu, T. Nakano, T. Suzuki, N. Oyama, J. Ghosh, V. Menon , A. K. Singh, H. Zohm, A. Kallenbach, F. Rimini, J. Bucalossi, E. Tsitrone, C. Bourdelle, J. Hobirk, S-W. Yoon, S. Konovalov, V. Rozhansky, N. Kirneva, Y. Liu, J.R. Martín-Solís, C. Angioni, I. Pustzai, …

Thank you!

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EUROfusion WP PWIE Midterm Meeting - September 25th - 28th 2023

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