EUROfusion

PLASMA-SURFACE INTERACTIONS IN THE STELLARATOR W7-X: CONCLUSIONS DRAWN FROM OPERATION WITH GRAPHITE PLASMA-FACING COMPONENTS

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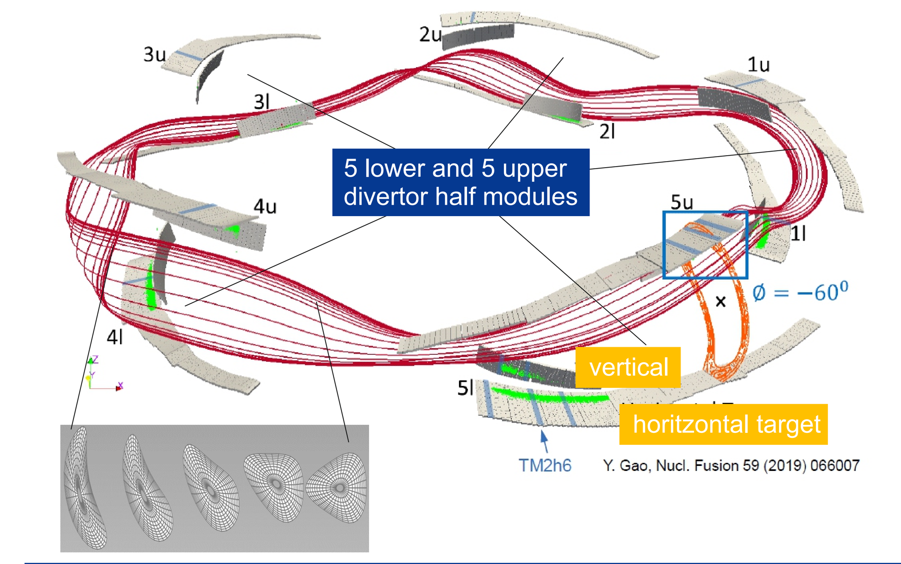
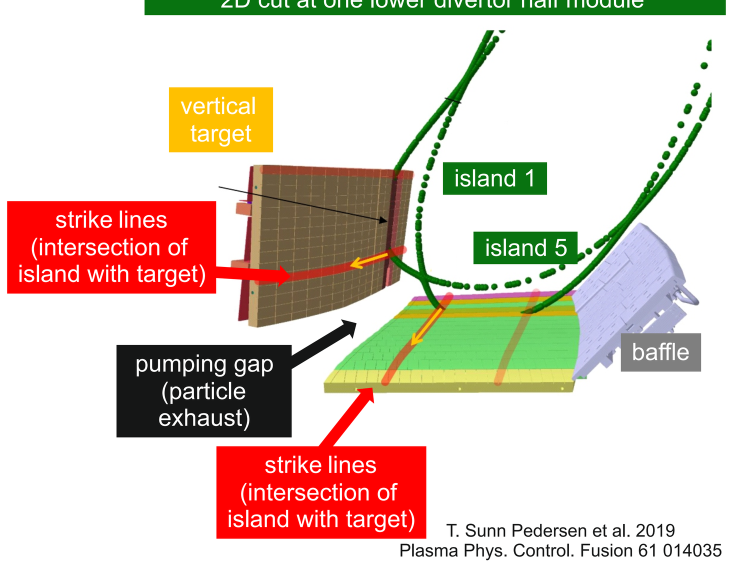
Introduction to the Optimised Stellartor Wendelstein 7-X

- Optimised stellarator design with 5-fold symmetry
- Magnetic field: **2.5 T** (steady-state)
- Heating power: **7.5 MW ECRH / 3.4 MW NBI**
- Major Radius: **5.5 m** / Minor Radius: **0.53 m**
- Island divertor for power and particle exhaust and impurity screening
- Divertor target plates follow the magnetic islands geometry



Y. Gao, Nucl. Fusion 59 (2019) 066007

magnetic topology in standard divertor configuration: 2D cut at one lower divertor half module

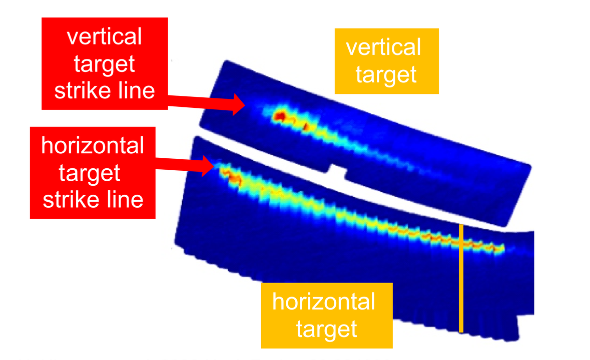


T. Sunn Pedersen et al. 2019 Plasma Phys. Control. Fusion 61 014035

- attached and detached divertor operation executed in 2 campaigns
- OP A: **~3776 s (He+H plasma)** | OP B: **~9054 s (~H plasma)**
- max. plasma duration: **100 s** | max. input energy: **0.2 GJ**
- at the strike line in attached plasmas: T_e~25 eV | n_e~1.0×10^{19} m^{-3}

Can we interpret the plasma-wall interactions in W7-X?
What can be expected for 30 min. plasmas with actively cooled divertor?
Recommendations regarding the divertor operational regime?

attached island divertor conditions in W7-X



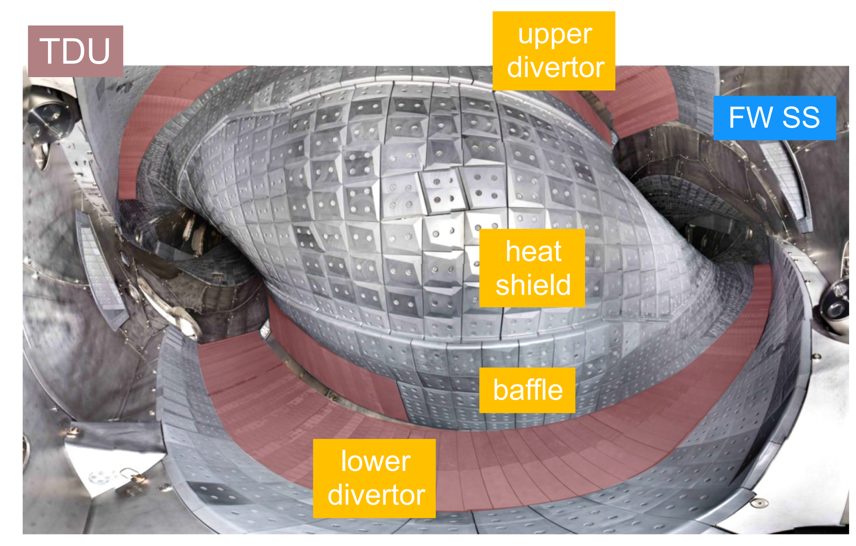
H. Niemann et al. 2020 Nucl. Fusion 60 084003

IR thermography: heat load footprint in standard magnetic divertor configuration

Plasma-Facing Components in W7-X

Island Divertor with Test Divertor Unit (**TDU**)
- 5 modules with 2 halfs
- Divertor material: fine grain **graphite**
- Divertor area: **19 (25) m²**
- Max. divertor heat load: **10 MW/m²**
- No active cooling at this stage

First wall coverage (**FW**)
- Main FW wall area: **45 m²** with C
  - 15 m² up to 0.5 MW/m²
  - 30 m² up to 0.25 MW/m²
- Recessed wall area: **70 m²** with SS
  - 70 m² up to 0.2 MW/m²
- Nominal wall temperature: **RT**



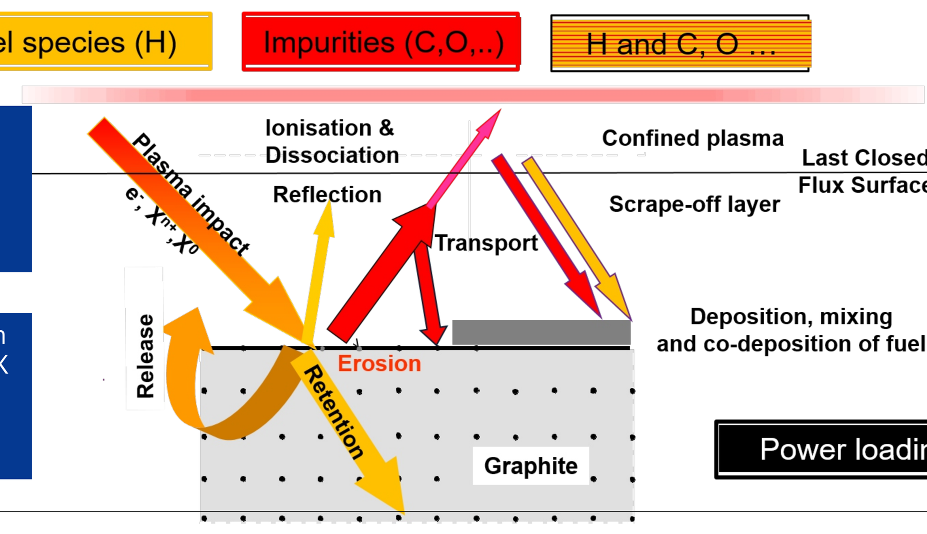
C. P. Dhard et al. 2020 Phys. Scr. T171 014033

Plasma-Wall Interactions Processes

Fuel species (H) | Impurities (C,O,..) | H and C, O …

In-situ information via emission spectroscopy, Langmuir probes, IR thermography

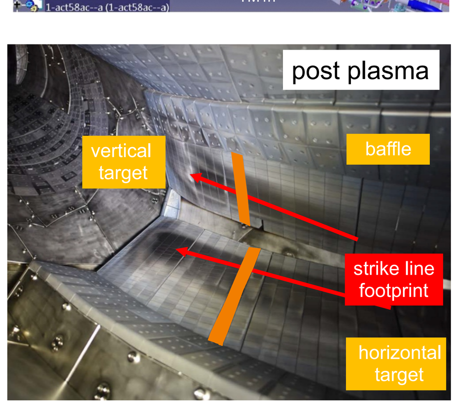
Ex-situ information via SEM, FIB, EDX IBA, EBS, SIMS LIBS, LIA-QMS Colorimetry …

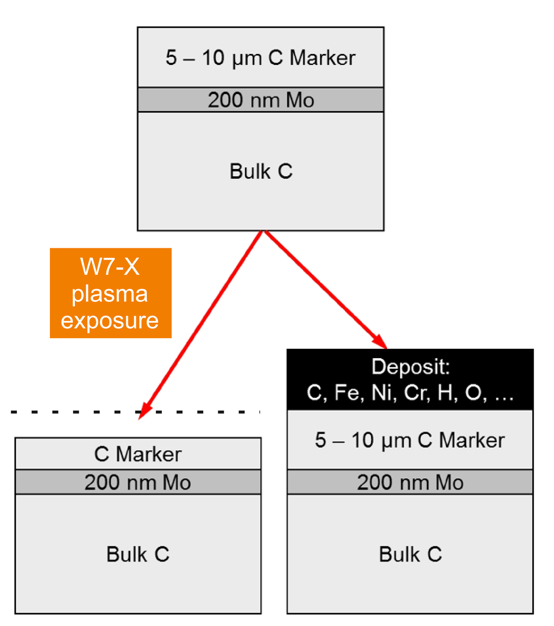


Key PWI questions:
- C erosion pattern / strength
- C deposition pattern /strength
- C migration paths
- H retention pattern / strength

Erosion / Deposition Measurements Utilising Marker Divertor Target Elements

Multiple divertor target elements with Mo interlayer and C marker for net erosion / depostion information installed per campaing. 2 locations on the vertical and 3 locations on the horizontal target plate in each of the ten half modules.

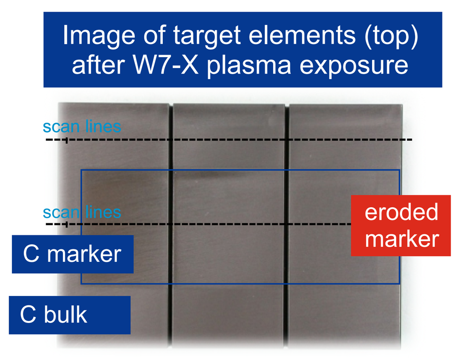




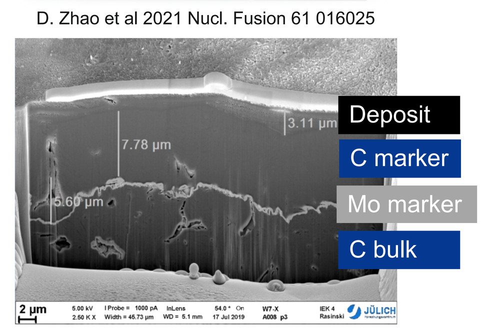
M Mayer et al. 2020 Phys. Scr. T171 014035

OP A: complete erosion of C marker and Mo interlayer and peak erosion zones only due to oxygen and carbon ions

Image of target elements (top) after W7-X plasma exposure



D. Zhao et al 2021 Nucl. Fusion 61 016025

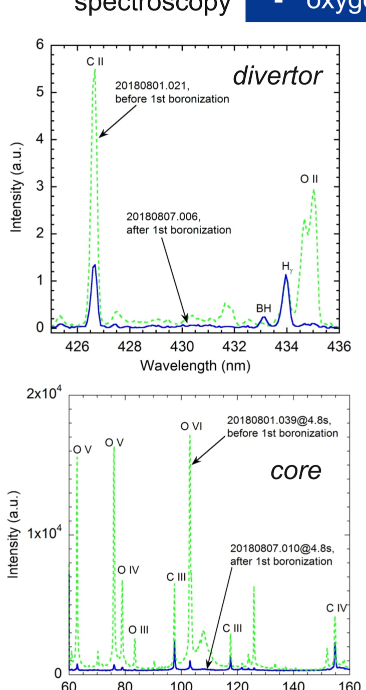


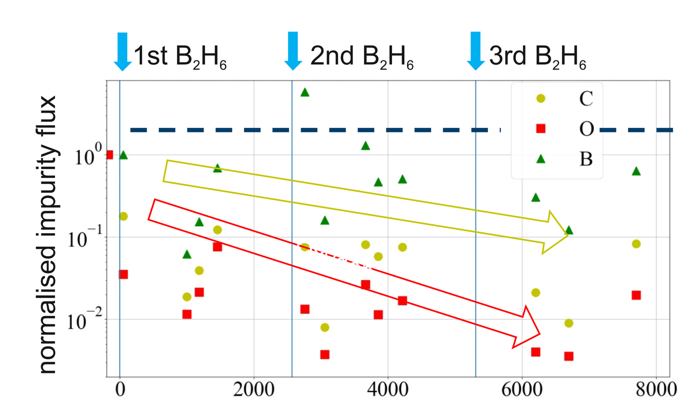
Cross section of target surface in deposotion zone (OP B)

Impact of Boronisation on W7-X Operation in OP B

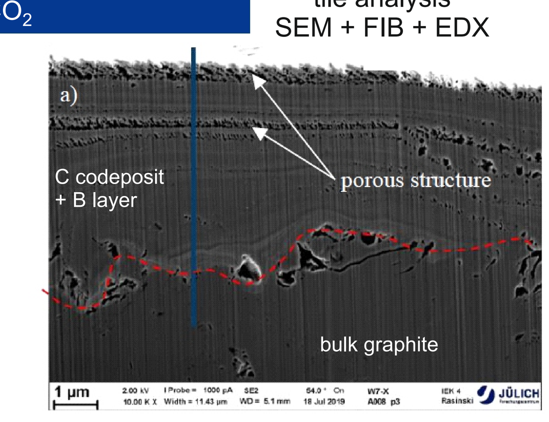
Initial plasma operation (OP A) compromised by high impurity content (O, C) and H outgassing
- residual water in graphite released during PFC heat-up by plasma impact
- physical and chemical sputtering of graphite by O and H as well as C self sputtering
- oxide layers on first wall sputtered by plasma and charge exchange neutrals
- oxygen partially pumped out between discharges in form of CO and CO_2

emission spectroscopy

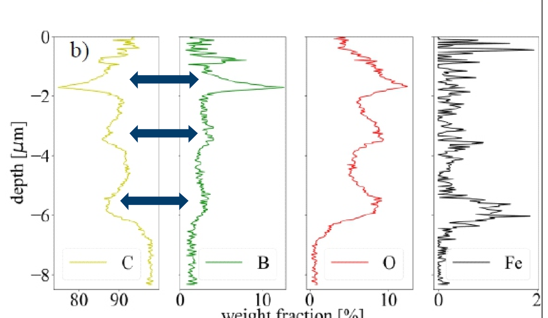




divertor tile analysis SEM + FIB + EDX



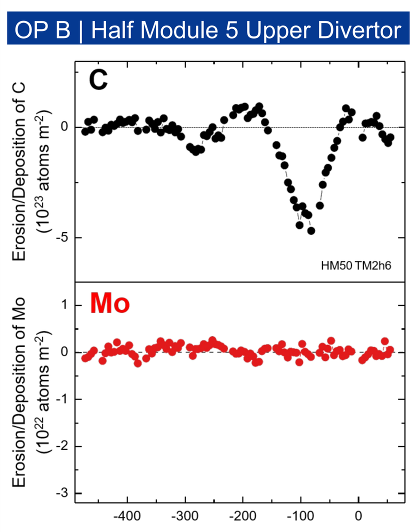
- 3 boronisations via (He+B_2H_6 GDC) applied in OP B
- strong reduction of O influx and content (gettering effect)
- break of O cycle in plasma | reduction of C sputtering by O
- transient reduction of C influx and content in plasma
- long-lasting effect: first wall comonents coverage
- short-lasting effect: transient divertor surface coverage



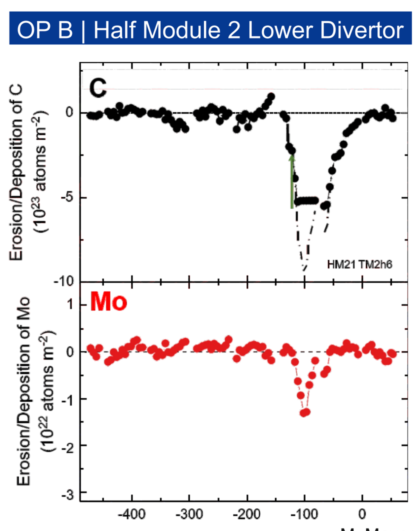
S. Sereda et al. 2020 Nucl. Fusion 60 086007 E. Wang et al. 2020 Phys. Scr. T171 014040

Netto Erosion / Deposition Measurements at the Horizontal Target Plates

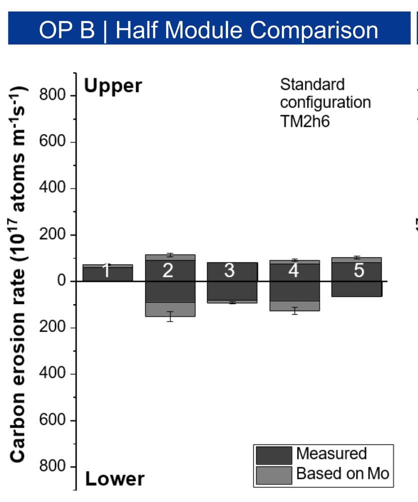
OP B | Half Module 5 Upper Divertor



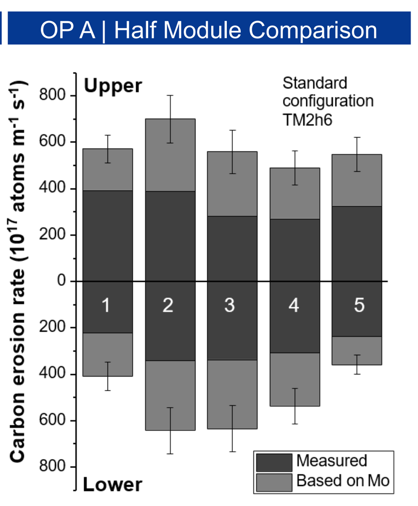
OP B | Half Module 2 Lower Divertor



OP B | Half Module Comparison



OP A | Half Module Comparison



M. Mayer et al. presented at PSI 2021

- net C erosion via EBS measured
- campaign integrated information
- peak erosion at strike-line

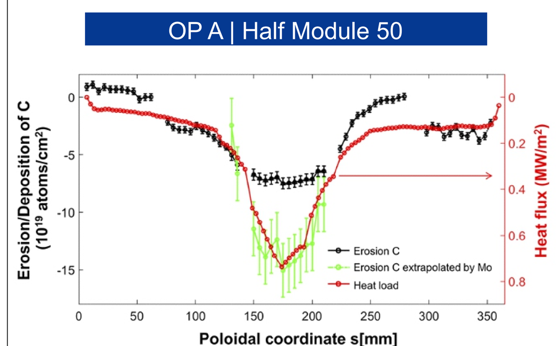
- up-down erosion variations
- Mo interlayer erosion at some half modules due to C and O

- toroidal aymmetry in C erosion reflects heat load asymmetry
- Mo erosion used as proxy for C

- reduction of C and Mo erosion in OP B after boronisation
- erosion rate drops by factor 6-8

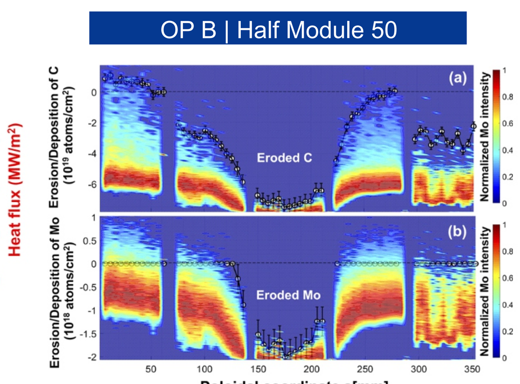
Netto Erosion / Deposition Measurements at the Vertical Target Plates

OP A | Half Module 50

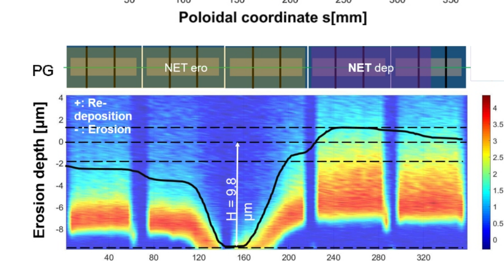


D. Zhao et al. 2021 Nucl. Fusion 61 016025

OP B | Half Module 50

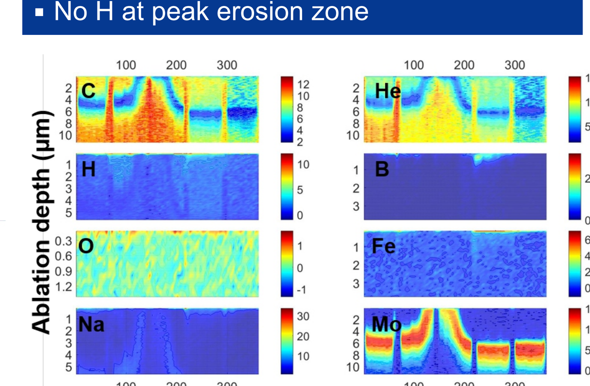


- net C erosion via LIBS technique
- total C marker erosion and Mo erosion
- Mo erosion due to C, O and He in OP A
- extreme location of C erosion in W7-X
- poloidal C erosion distribution in-line with IR heat-flux distribtuion at vertical target



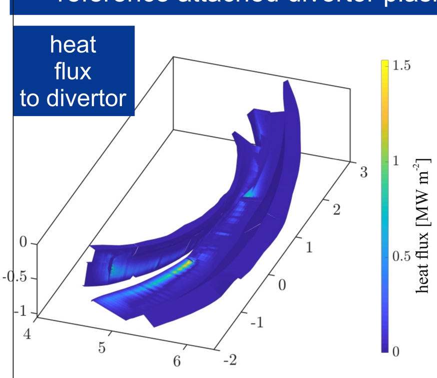
- EBS and LIBS in good agreement

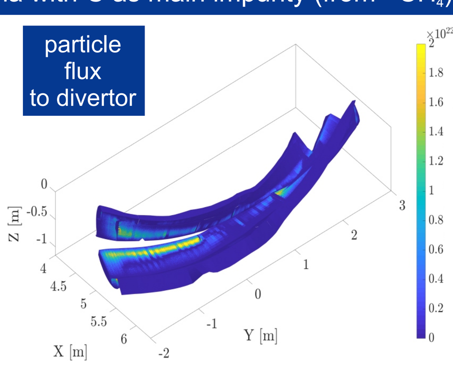
- Reduction of C erosion after boronisation only a factor 3 at this location
- Ersosion of Mo interlayer continues
- Strong local deposition zone towards baffle
- ps-LIBS analysis reveals composition
- Mixture of B, C, O, H and Fe in deposition
- Fe due to He-GDC in boronisation
- No H at peak erosion zone



3D Simulation of Material Migration in Standard Configuration with ERO2.0

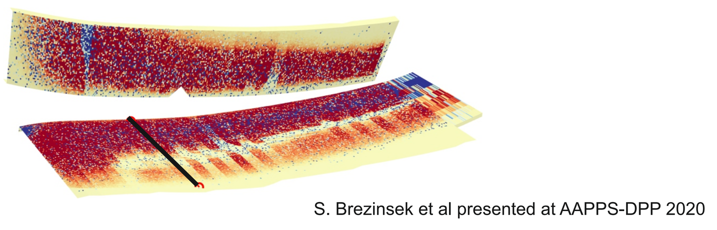
- significant operation in standard configuration (>50%: 4809 s)
- main interaction area almost unique for this magnetic configuration
- representative hydrogen plasma background from EMC3-EIRENE reference attached divertor plasma with C as main impurity (from $^{13}CH_4$)





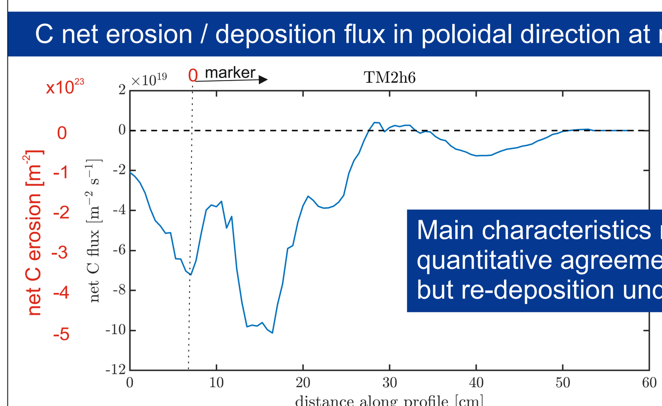
F. Effenberg et al 2019 Nucl. Fusion 59 106020

- 3D simulation of PSI with ERO2.0 of one W7-X module: periodic boundary conditions of fivefold symmetry to mimic full device
- Unfold C gross erosion and C deposition pattern in the divertor
- C net erosion and net deposition areas are located close to each other at the strike-line location in standard configuration
- Comparison with post-mortem analysis (net) and C spectroscopy (gross)

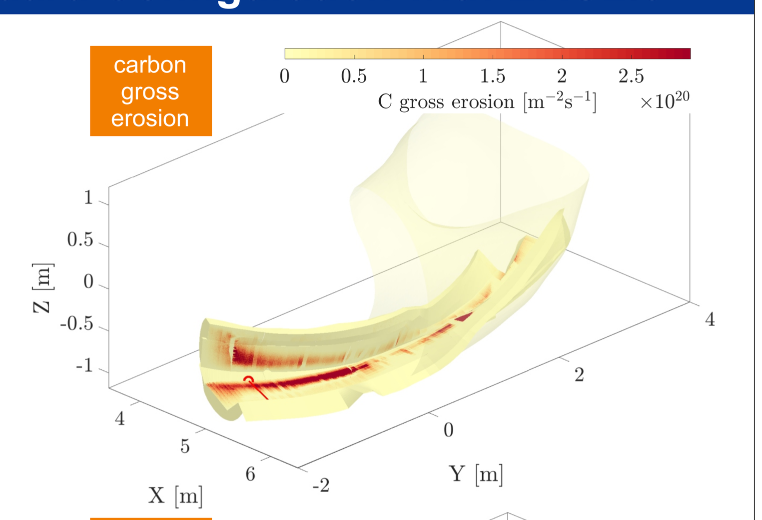


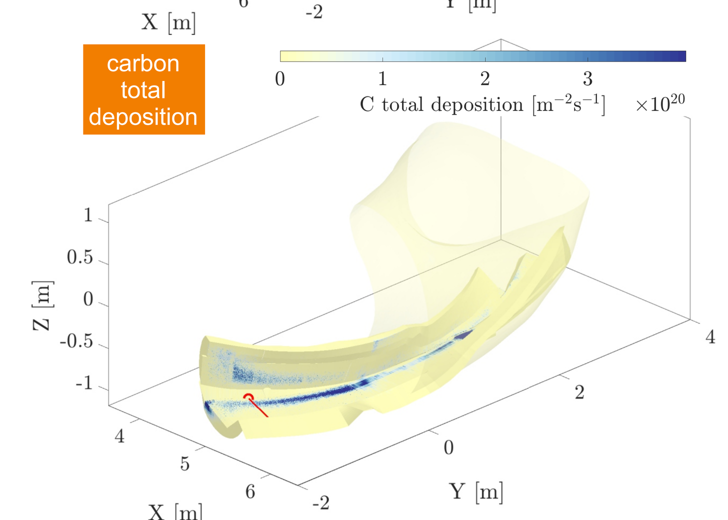
S. Brezinsek et al presented at AAPPS-DPP 2020

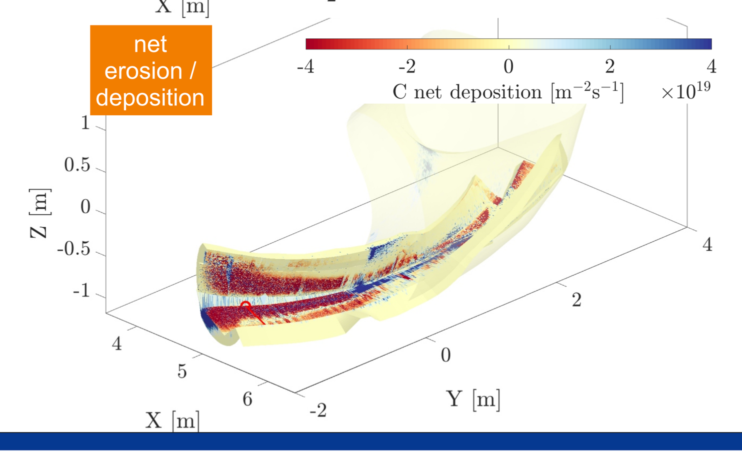
C net erosion / deposition flux in poloidal direction at marker target element



Main characteristics reproduced and good quantitative agreement of peak erosion, but re-deposition underestimated in ERO







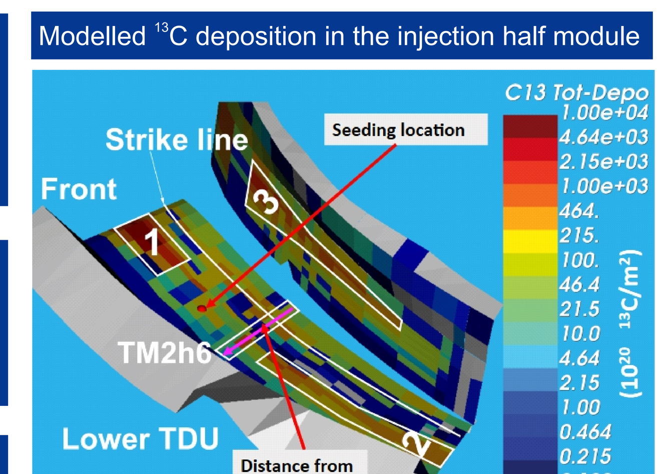
3D Simulation of ^{13}C Migration in Standard Configuration with WallDYN-3D

- benchmark experiment about C transport in a full-C device is a $^{13}CH_4$ injection
- last experiment in OP B before tile removal
- 4.5×10^{22} ^{13}C injected in 330 s of attached
- H plasma in standard configuration single injection location in one half module

- EMC3-EIRENE plasma background which matches plasma conditions and heat flux
- WallDYN-3D material transport modelling and surface composition
- assume ^{13}C atomic source injection

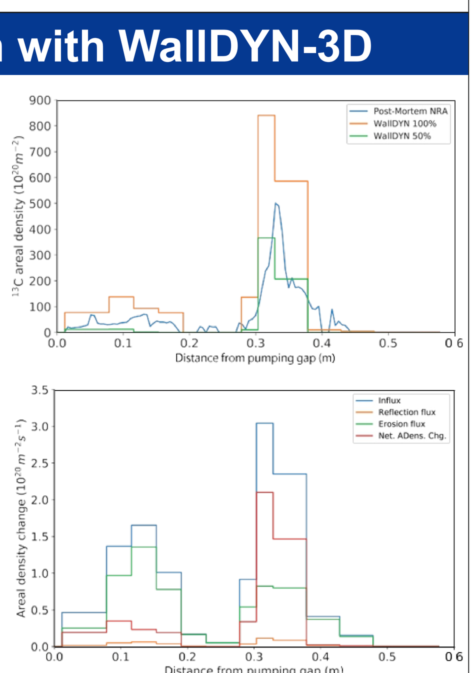
- local deposition near to injection location in island at same half module (1 and 2)
- global deposition on vertical target (3)
- small, but toroidally smeared deposition near strike-line location (multiple cycles)

Modelled ^{13}C deposition in the injection half module



Good agreement between NRA and WallDYN-3D

K. Schmid et a.l Nuclear Materials and Energy 25 (2020) 10082



Conclusion for Long-Pulse Operation in W7-X

- plasma operation with the uncooled graphite test divertor provided vital information on the operational window and PWI processes in W7-X
- operational window widens with the application of boronisation, reducing the impurity production by oxygen / carbon ions on graphite
- plasma operation in attached divertor conditions causes peak C erosion of more than 10 µm or rates of 2 nm/s after bornisation

- best documented plasma from PWI perspective is the standard divertor configuration used for more than 50% of the time in OP B
- net C erosion follows the heat and particle footprint on the divertor target plates with local deposition zones away from the contact point
- material migration paths studied with ERO2.0 and WallDYN-3D with predominant role of divertor in total C erosion and deposition pattern impact of the first wall on C migration under assessment (see C.P. Dhard PFMC 2021) => moderate local erosion/deposition observed

- considering only operation after boronisation and with negligble O level in the plasma (<0.1%): extrapolate to long-pulse operation
- total accumulated H plasma time in standard configuration in OP B (4809s) equivalent ot almost 3 W7-X discharges of envisaged 30 min.
- total C erosion rate in the divertor is about 4.2 mg/s or 20g over the campaign which would convert to 7.6g C per 30 min. discharge
- the total C erosion as well as a the peak C erosion could hamper plasma operation and cause dust issues in campaigns with long pulses

- reduction of C erosion is advisable and could be achieved by transfer to detached divertor operation (see O. Schmitz et al. 2021 NF 61)
- predictive modelling with ERO2.0 and WallDYN-3D should be carried out to simulate PSI in long pulse discharges with attached and detached divertor conditions

JÜLICH Forschungszentrum | IPP Max-Planck-Institut für Plasmaphysik | WISCONSIN UNIVERSITY OF WISCONSIN-MADISON | NINS | IFPiLM | VTT

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