EUROfusion

“THEORY, SIMULATION, VERIFICATION AND VALIDATION”

TSVV TASK 7: PLASMA-WALL INTERACTION IN DEMO

WP PWIE Meeting | 27.03.2025
D. Matveev on behalf of TSVV-7 team

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TSVV-07 PLASMA-WALL INTERACTION IN DEMO

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TSVV-07 PLASMA-WALL INTERACTION IN DEMO

Aims of the project

Establish an integrated modelling suite capable to treat complex 3D wall geometry to predict steady-state PWI in DEMO

Provide safety-relevant information for DEMO reference scenarios concerning first-wall erosion, dust, and fuel inventory

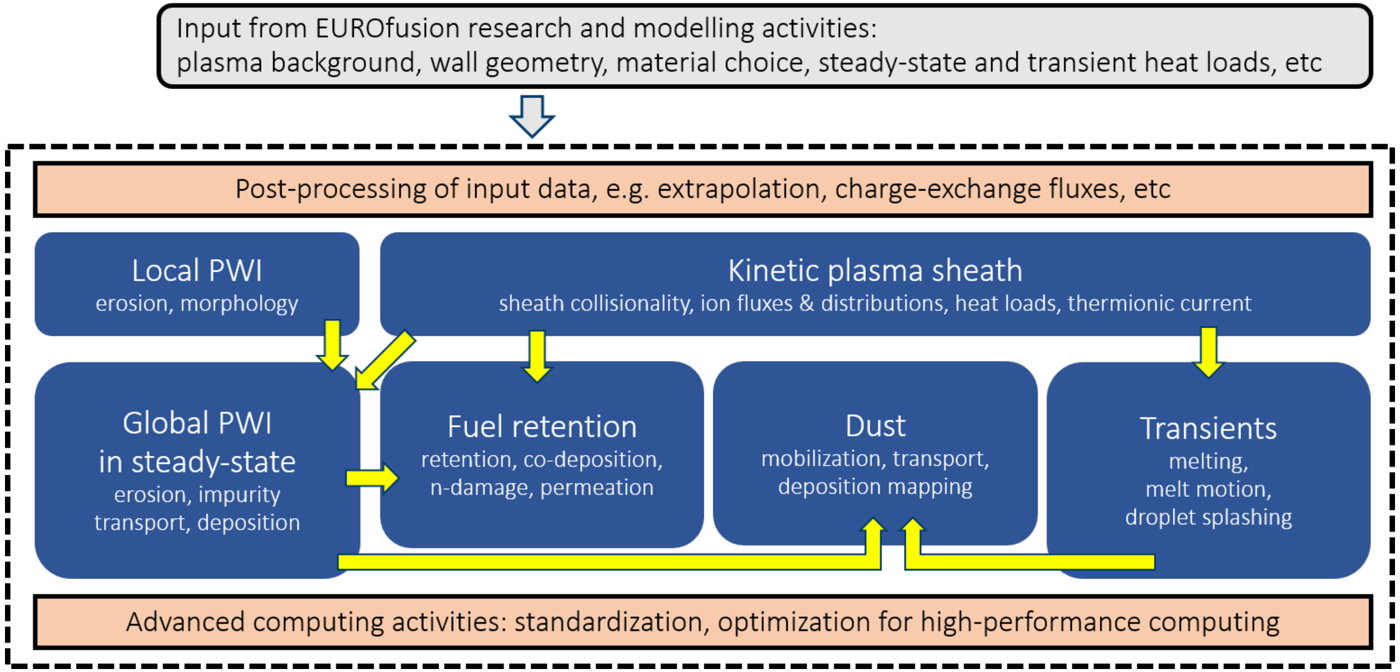
Develop and apply modelling capabilities to treat PWI in DEMO-relevant transients regarding their impact on PFC integrity

TSVV-07 PLASMA-WALL INTERACTION IN DEMO

Objectives

Assessment of

- Steady-state W erosion rates
- Preferential W re-/co-deposition locations
- Dust mobilization, survival and accumulation
- PFC response to transients: melting, splashing
- W erosion for locations affected by transients
- Tritium inventory: co-deposition, bulk retention



Input from EUROfusion research and modelling activities:
plasma background, wall geometry, material choice, steady-state and transient heat loads, etc

Post-processing of input data, e.g. extrapolation, charge-exchange fluxes, etc

Local PWI
erosion, morphology

Kinetic plasma sheath
sheath collisionality, ion fluxes & distributions, heat loads, thermionic current

Global PWI in steady-state
erosion, impurity transport, deposition

Fuel retention
retention, co-deposition, n-damage, permeation

Dust
mobilization, transport, deposition mapping

Transients
melting, melt motion, droplet splashing

Advanced computing activities: standardization, optimization for high-performance computing

Codes and model development

ERO2.0
→ PWI & impurity tracing
MIGRAINe
→ dust transport
MEMENTO
→ transient melting

- **BIT-1:** high density divertor sheath for ERO2.0
- **SPICE:** thermionic emission for MEMENTO
  heat & particle fluxes to shaped PFC
- **FESTIM & TESSIM:** - T retention & permeation
- **SDTrimSP, MD:** erosion yields, surface effects

\+ Uncertainty quantification

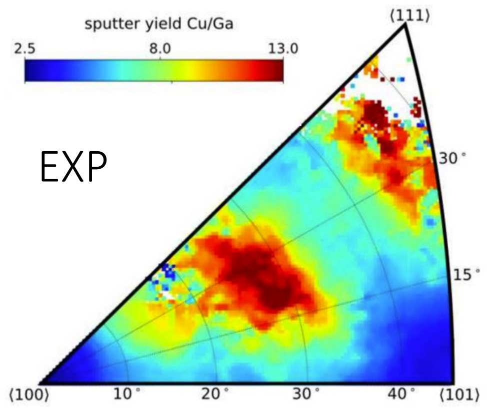
Project overview paper

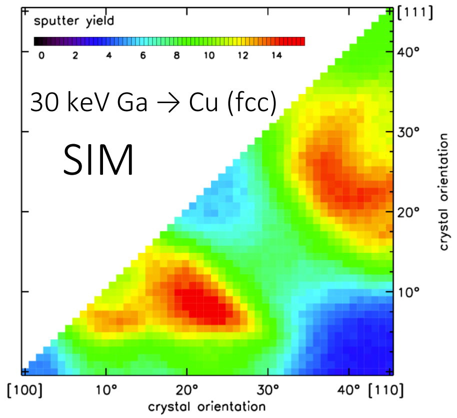
D. Matveev et al, Nucl. Fusion 64 (2024) 106043

PWI data and code capabilities improvement (in-brief)

SDTrim-SP

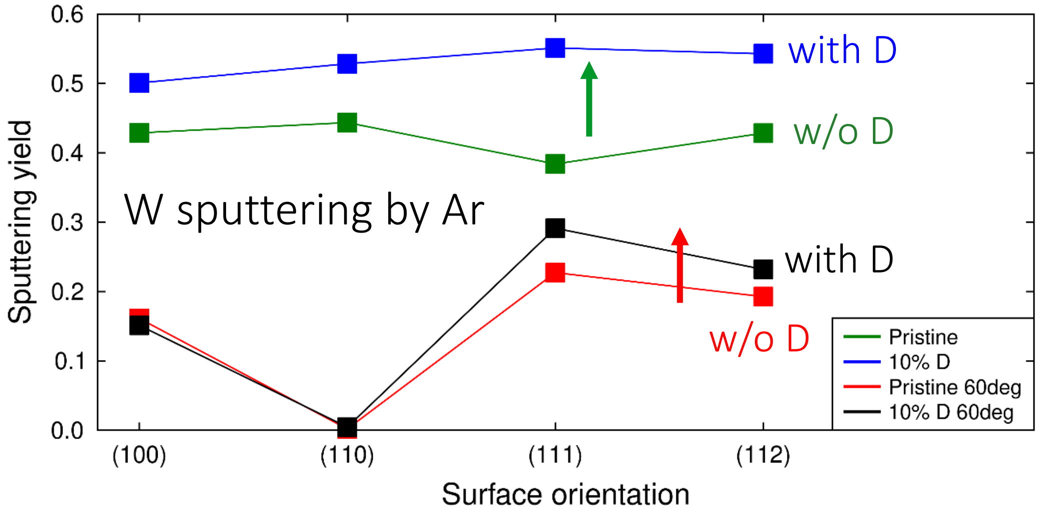
- **“Gyro-motion” extension:**
  - magnetic & electric field effects on impinging ions
  - implemented and verified against computations
  - performance optimization, experimental validation
- **“Crystal” extension:**
  - validated against MD, MARLOWE and experiment





Sputtering data for D supersaturated W from MD

- Ar case studies accomplished: presence of D increases sputtering of W, strong grain orientation effect
- D and D_2 cases delayed by technical challenges (appropriate potential is slow, sputtering yield depends on the simulation cell depth, huge statistics required)
- Work on W-O / W-O-H potential development ongoing



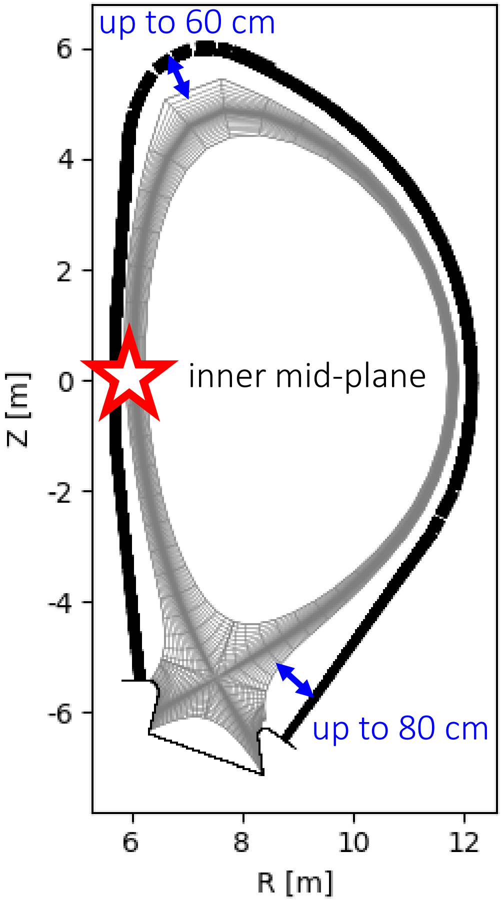
ERO2.0 modelling: erosion and deposition mapping

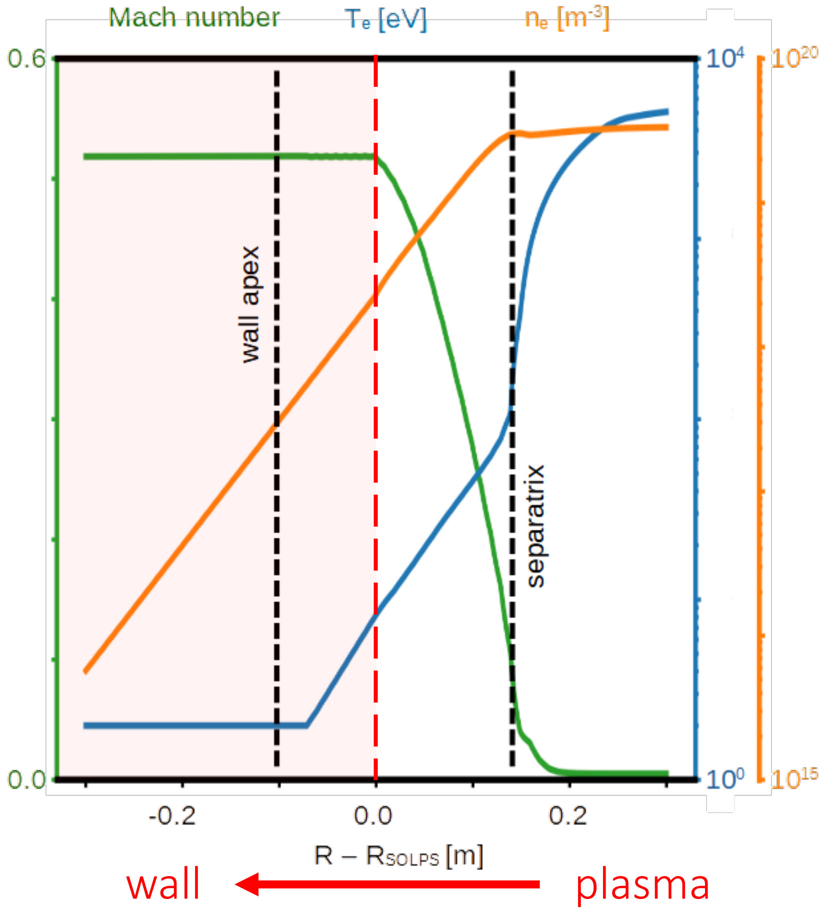
Unprecedentedly large volume for extrapolation of plasma solution to the wall

Large extrapolation volume introduces large modelling uncertainties

Following assumptions in far-SOL:

- Exponential decay for densities
- Exponential decay for temperatures; but capped at 2 eV, 5 eV or 10 eV
- Uniform decay constant of 5 cm
- Constant Mach number





ERO2.0 modelling: erosion and deposition mapping

Dominating role of charge-exchange (CX) fluxes on erosion in the main chamber

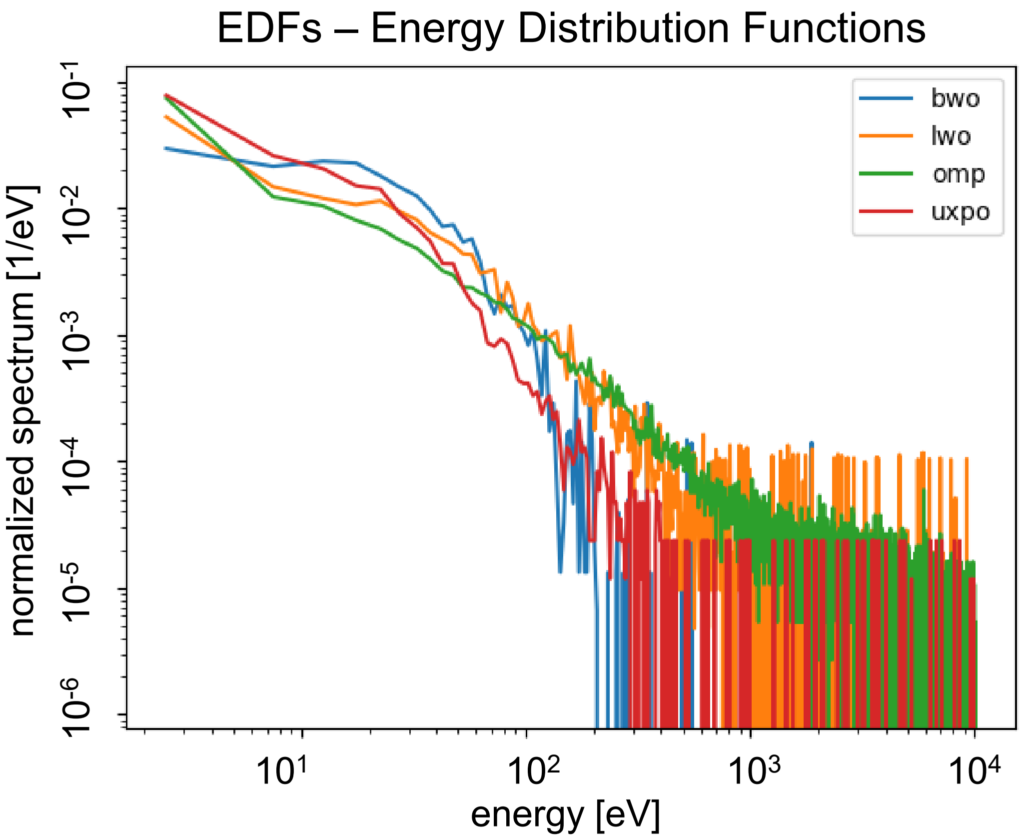
Normally only poloidal profiles and mean energies are available from SOLPS-ITER

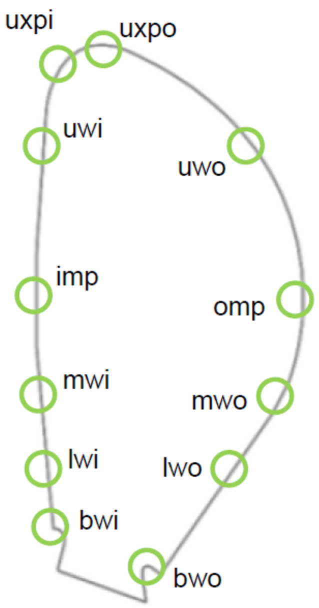
Former assumptions for sputtering:

- Using the **mean energy approach** (strong dependence of sputter yield on energy leads to incorrect erosion patterns)

Current approach - **EDF**:

- EIRENE post-processig of the SOLPS-ITER solution to provide **energy-resolved neutral fluxes** (angular-resolved in progress)



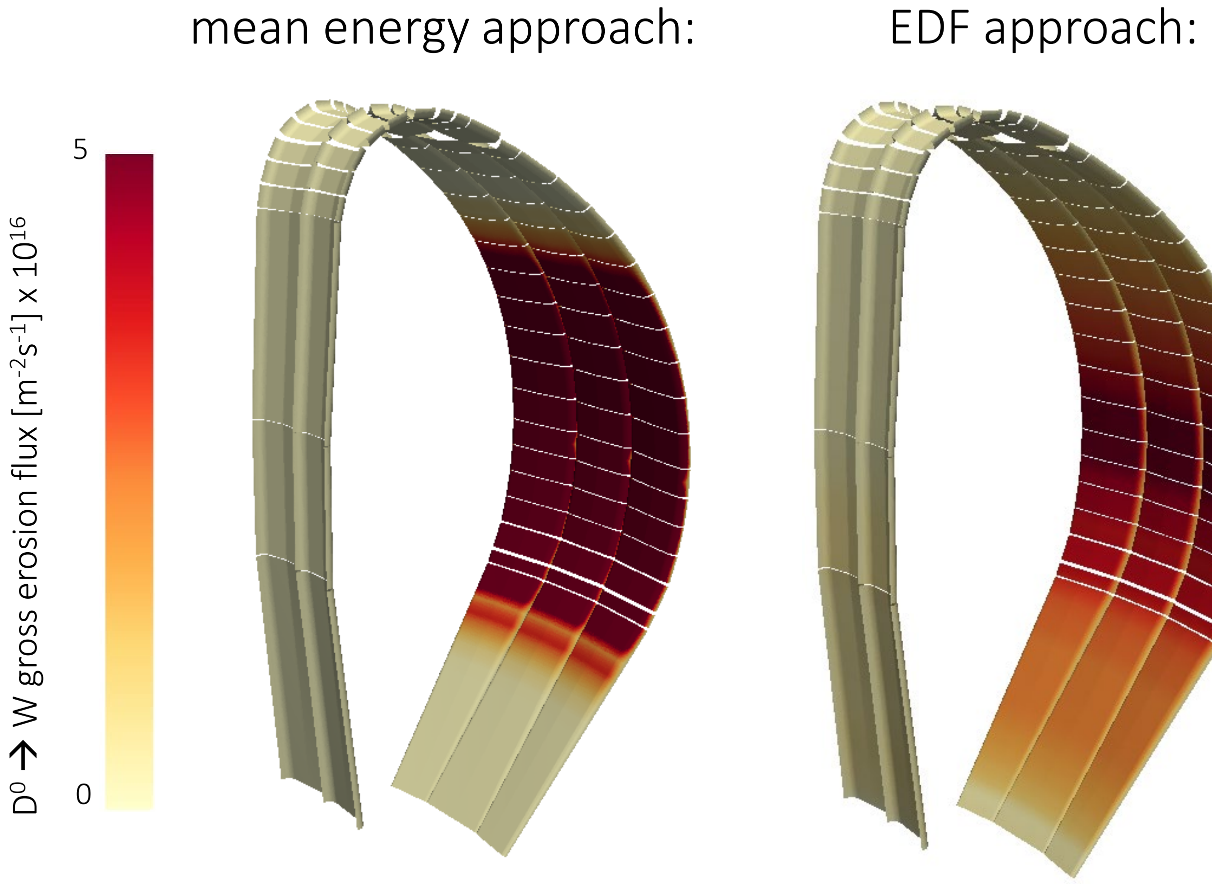


© S. Wiesen / DCT

+ charge-resolved spatially non-uniform impurity ion fluxes (He, Ar)

ERO2.0 modelling: erosion and deposition mapping

Dominating role of charge-exchange (CX) fluxes on erosion in the main chamber (cont'd)


mean energy approach:

EDF approach:

	mean energy	EDF
peak flux [$m^{-2}s^{-1}$]	1.56×10^{17}	5.41×10^{16}
integrated rate [s^{-1}]	5.75×10^{19}	2.76×10^{19}

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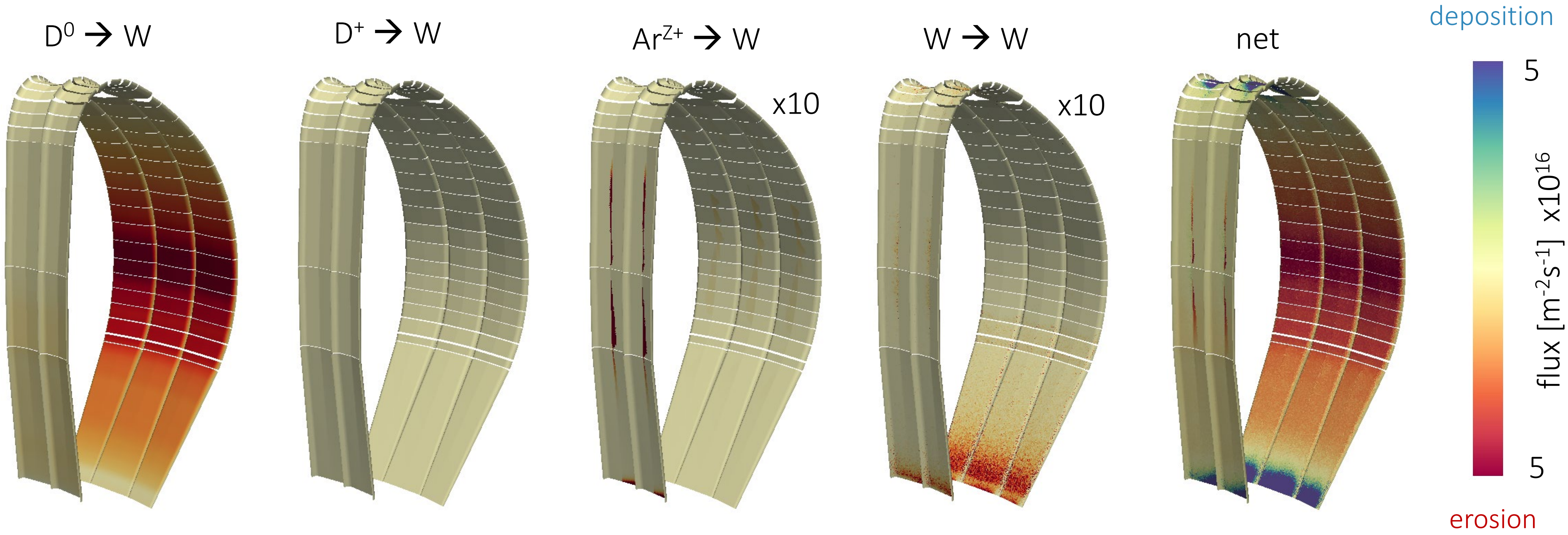
EDF approach:

- Reduction of main chamber gross erosion by factor 2-3 compared to the mean energy approach
- Additional wall area locations are subject to finite gross erosion

ERO2.0 modelling: erosion and deposition mapping

Erosion and re-deposition maps (T_e in far-SOL capped at 2 eV)



[10^{18} atoms/s]	net	gross	… by D^0	… by Ar^{Z+}	… by W^{Z+}
main chamber	-16.4	28.3	27.6	0.3	0.4
divertor	15.0	86.8	0.0	57.8	28.9

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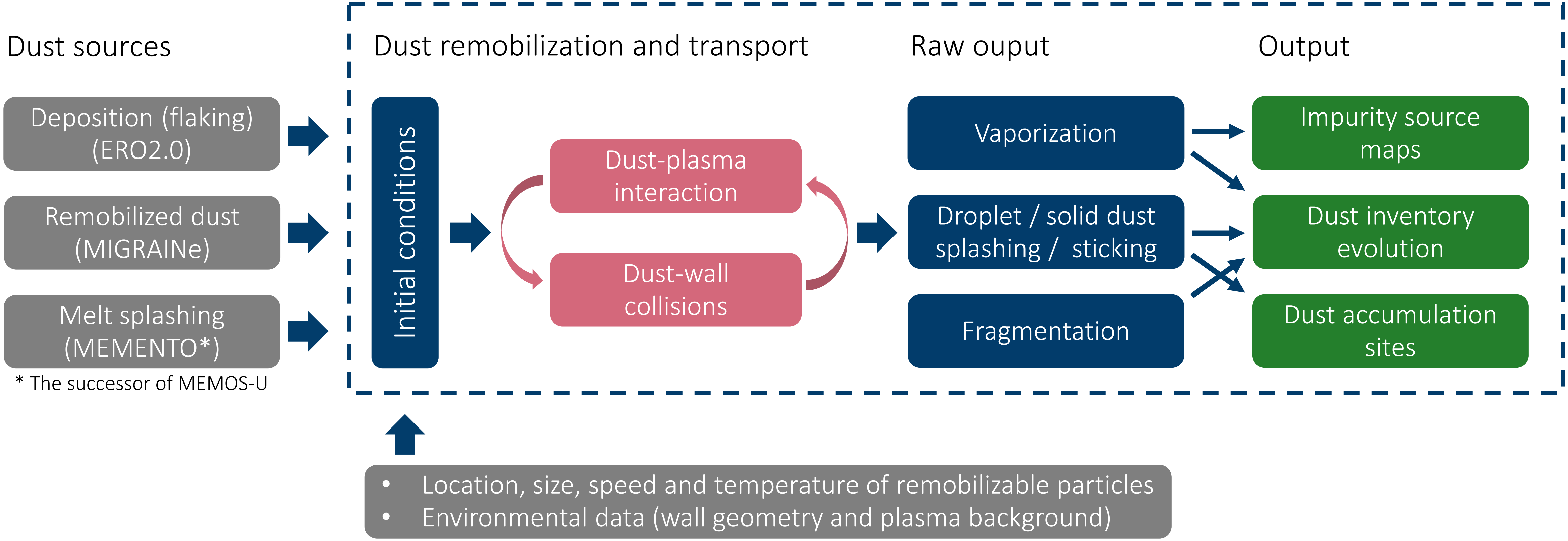
- Main chamber erosion dominated by CX neutrals
- Divertor erosion dominated by Ar ions and self-sputtering
- Strong transport from main chamber into the divertor (long ionization mean free path), no transport from the divertor
- Main deposition locations: inner and outer divertor, wall gap above outer divertor, top of the machine

Dust inventory evolution

Ratynskaia et al. Rev. Modern Plasma Phys. 6:20 (2022)

Metallic dust in fusion devices – safety and licensing issue (fuel retention, radioactivity, chemical reactivity)

MIGRAINe simulations


Dust sources

Deposition (flaking) (ERO2.0)

Remobilized dust (MIGRAINe)

Melt splashing (MEMENTO*)

* The successor of MEMOS-U

Dust remobilization and transport

Initial conditions

Dust-plasma interaction

Dust-wall collisions

Raw ouput

Vaporization

Droplet / solid dust splashing / sticking

Fragmentation

Output

Impurity source maps

Dust inventory evolution

Dust accumulation sites

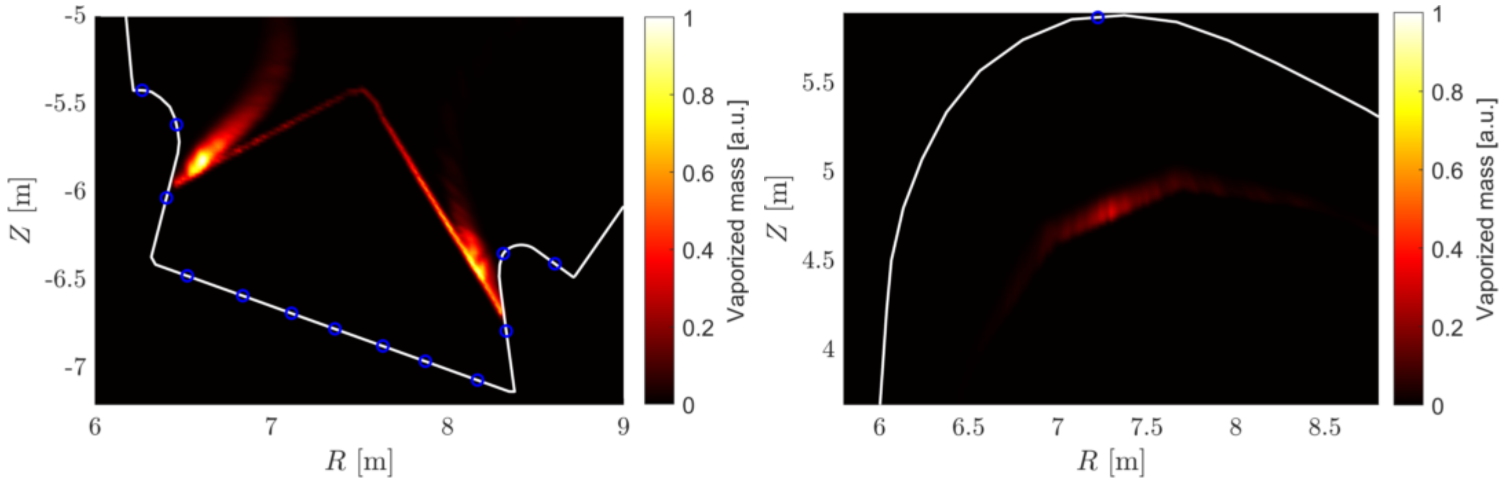
- Location, size, speed and temperature of remobilizable particles
- Environmental data (wall geometry and plasma background)

Dust inventory evolution

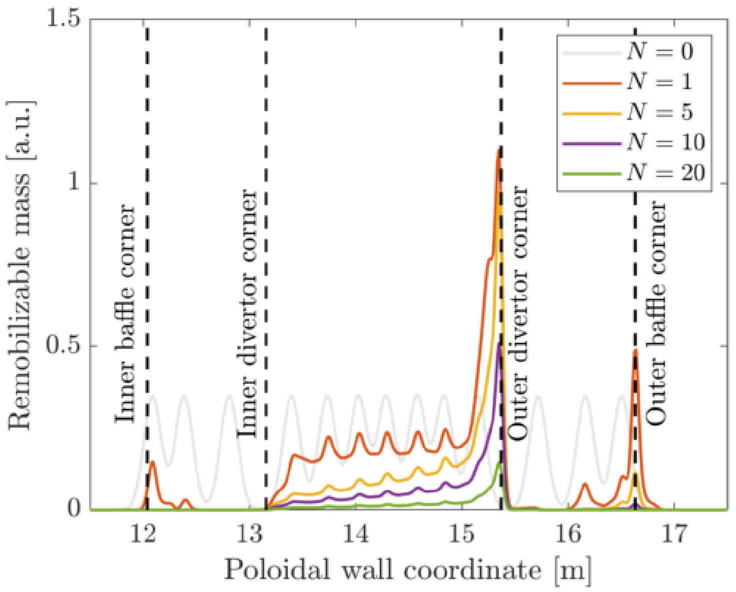
DEMO scenario and addressed questions © L. Vignitchouk

- Using baseline 2017 equilibrium with SOLPS-ITER plasma
- Tracing dust with pre-defined grain size distributions and speeds
- Injection sites in the divertor and at the top of machine (ERO2.0)
- Vaporization dominant for small grains (<25 µm) along separatrix
- Dust accumulates primarily in corner-like geometries

Maps for W vaporization (ion drag activated, r = 10 µm, v_{max} = 10 m/s)



Evolution of dust spatial distribution in divertor (ion drag activated, r = 40 µm, v_{max} = 50 m/s)

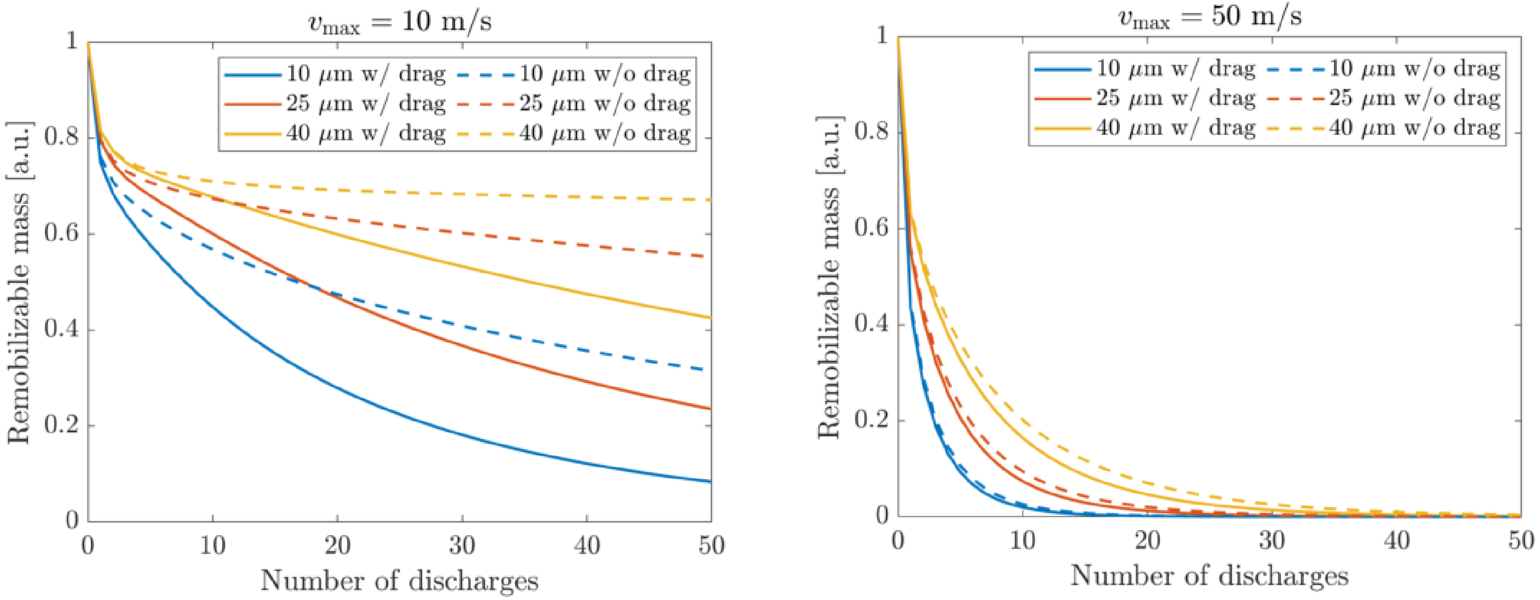


Dust inventory evolution

DEMO scenario and addressed questions © L. Vignitchouk

- Using baseline 2017 equilibrium with SOLPS-ITER plasma
- Tracing dust with pre-defined grain size distributions and speeds
- Injection sites in the divertor and at the top of machine (ERO2.0)
- Iteration of single-discharge results to predict long-term inventory
- Initial velocity has major impact on the survival of particles

Total in-vessel remobilizable dust mass evolution with and without ion drag for various initial dust size and velocity distributions



PFC response to transient events

MEMENTO (MEtallic Melt Evolution in Next-step TOkamaks)

S. Ratynskaia et al. NME **52** (2022)
K. Paschalidis et al. NME (2023)

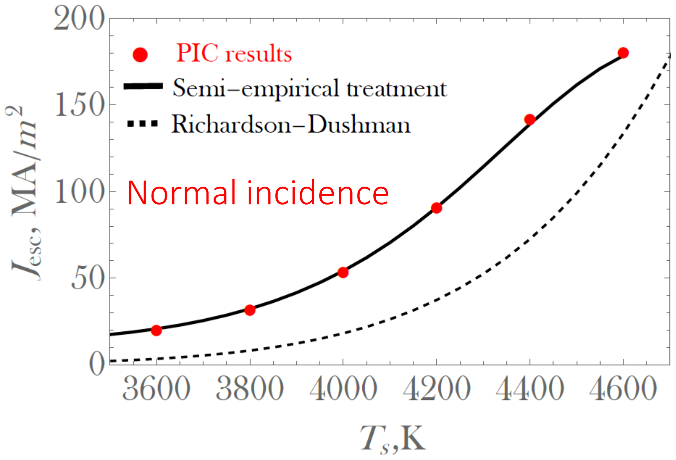
- Successor of MEMOS-U implemented using AMReX adaptive meshing framework (https://amrex-codes.github.io/amrex/)
- Coupled heat transfer, fluid dynamics and current propagation + physics updates (surface tension, dynamo term)
- Critical input: - heat loads and respective time scales (external input from WPDES & DCT)
  - description of escaping thermionic emission (multi-emissive* sheath treatment by SPICE2)

SPICE2 – a 2D3V PIC code (multi-emissive sheaths)

(*relevant for ITER/DEMO)

- Simulations of field-assisted thermionic emission (TE) with secondary electron emission (SEE) and electron backscattering (EBS) confirm the validity of the earlier developed semi-empirical scaling models M. Komm et al. NF 60 (2020)

P. Tolias et al. NF 63 (2023)

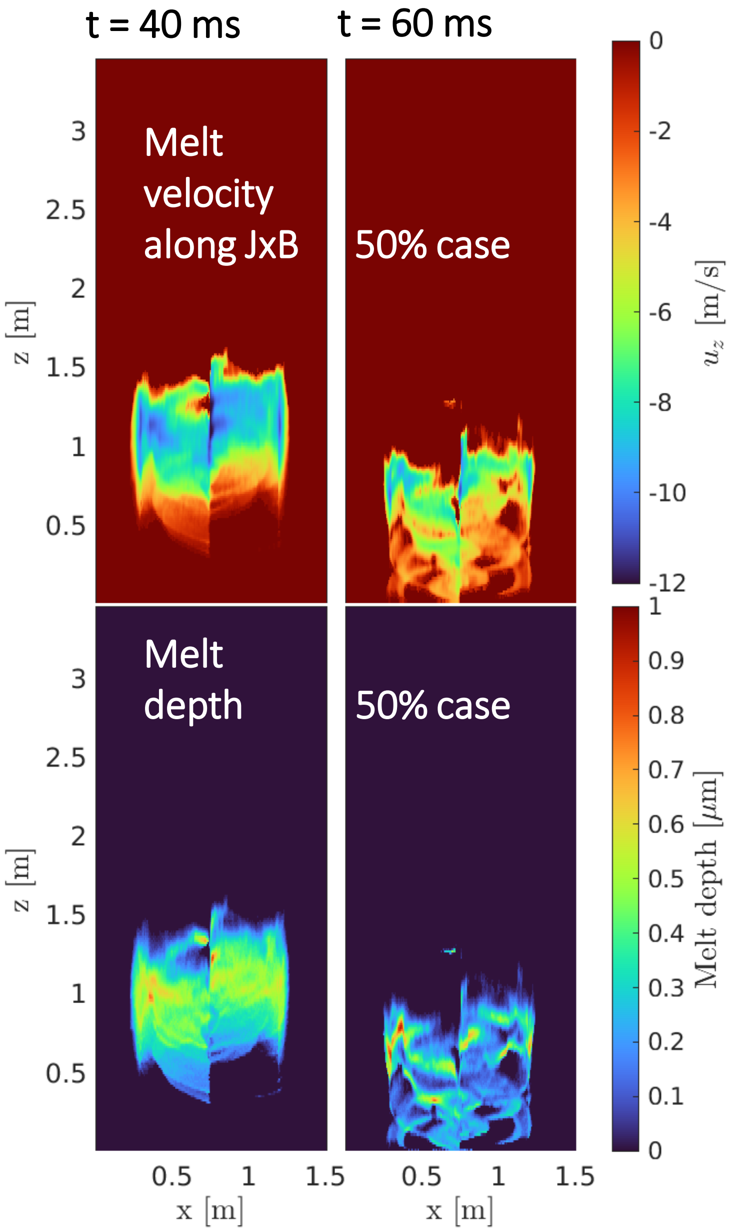


MEMENTO uses respective scalings deduced from PIC simulations

PFC response to transient events

Simulations of transient melting with MEMENTO

- Thermionic emission scaling laws provided by dedicated PIC simulations
- Addressing upper limiter damage under current quench with updated heat loads input accounting for time-dependent loading patterns
- Compared to 2023 PFCFlux input, ~10 times higher max heat flux values, up to $28\ \mathrm{GW/m^2}$ (for 50% conversion from all poloidal magnetic energy)
- 10% conversion is judged as realistic, 50% as a worse case scenario
- No vapor shielding – melting is robust, but erosion damage is not
- Escaping thermionic emission is within $\sim 2\ to\ 3\ \mathrm{MA/m^2}$ in both 10% and 50% scenarios, dominating over the halo current (Lorentz force)
- Instantaneous melt pools up to 0.3 - 0.5 mm depth –> prone to splashing



Fuel retention and permeation

Tritium retention and permeation with TESSIM and FESTIM

- First wall retention and permeation, in particular in view of tritium self-sufficiency (TESSIM-X):
  K. Schmid et al, Nucl. Fusion 64 (2024) 076056
- Implementation of the Soret effect: reduces T inventory and time to steady-state retention
- 3D effects (monoblocks): *R. Delaporte et al, Nucl. Fusion 64 (2024) 026003*
  - Outgassing at sides reduces retention (stronger for thin monoblocks)
  - Surface limited recombination reduces the efficiency of baking
- Neutron-induced traps: *J. Dark et al, Nucl. Fusion 64 (2024) 086026*
  - Increase retention / reduce permeation by orders of magnitude

no damage
0 dpa

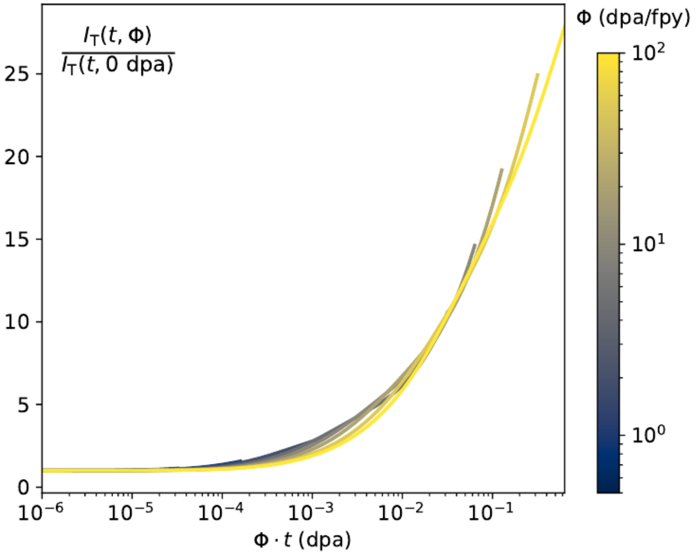
1 dpa/FPY
0.0064 dpa

10 dpa/FPY
0.064 dpa

100 dpa/FPY
0.64 dpa

T retention field
after 200,000 s
of plasma exposure
for different neutron fluxes
using FESTIM code
with neutron damage model

Ratio of T inventory with and without
n-damage using FESTIM code



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ACH support

- ERO2.0: optimization of hybrid parallelization performance and GPU enabling (ACH BSC)
- SPICE2: parallelization of Poisson solver in 2D (ACH BSC)
- MIGRAINE: HPC enabling via MPI parallelization (ACH VTT)
- RAVETIME: HPC optimization (ACH VTT)
- MEMENTO: HPC optimization (ACH VTT)
- IMASification: ERO2.0, MIGRAIN (ACH PSNC)

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- ACH PSNC: Dmytro Yadykin, Grzegorz Pelka, Natalia Grzybicka

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Outlook and perspectives

Capitalize on dedicated experiments under WPTE: focused validation effort ✓ to advance through collaboration with WPTE

- ➢ Validation of steady state erosion in full W device with relevant divertor geometry and impurity seeding: ERO2.0 in AUG (approved)
- ➢ Validation of dust evaporation and impurity deposition: MIGRAINe + ERO2.0 in AUG (possible within AUG internal program)
- ➢ Validation of thermo-mechanical response of W PFCs under runaway electrons (REs): GEANT4 + MEMENTO in AUG (approved)

Address the frontier problem of PFCs damage by REs created during disruptions ✓ to advance through collaboration with TSVV9

- ➢ High sensitivity of PFCs response to REs impact characteristics – can be obtained from nonlinear MHD codes such as JOREK
- ➢ Explosive W PFCs response under REs: GEANT4 (energy deposition) + MEMENTO (heat transfer) + LSDYNA (flow, fragmentation)

Expand the codes with reactor-relevant physics beyond the initial project scope ✓ to advance through collaboration with WPPWIE

- ➢ Effect of multiple isotopes on erosion and fuel retention/permeation for predictive simulations of reactor start-up and T clean-up
- ➢ Elaborating the neutron damage model from phenomenology to physics
- ➢ ERO2.0 coupling to core transport codes; edge turbulent transport effects on PWI ✓ to advance through collaboration with TSVV4&6

Towards DEMO and beyond ✓ to advance through collaboration with WP-DES (plasma backgrounds with AI)

- ➢ Framework test applications (VNS, DTT, BEST, …) and development of surrogate models for iterative design-cycle applications

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Thank you for your attention!