PROGRESS IN PLASMA-WALL INTERACTIONS MODELLING FOR EU-DEMO

[1]D. MATVEEV, C. BAUMANN, J. ROMAZANOV, S. BREZINSEK,
[2]S. RATYNSKAIA, L. VIGNITCHOUK, P. TOLIAS, K. PASCHALIDIS,
[3]D. TSKHAKAYA, M. KOMM, A. PODOLNÍK,
[4]J. MOUGENOT, Y. CHARLES,
[5]E. HODILLE, F. MONTUPET-LEBLOND,
[6]U. VON TOUSSAINT, K. SCHMID,
[7]F. GRANBERG, F. KPORHA,
[8]J. KOVAČIČ, S. COSTEA

[1] Forschungszentrum Jülich GmbH, Institute of Fusion Energy and Nuclear Waste Management – Plasma Physics, 52425 Jülich, Germany
[2] Space and Plasma Physics—KTH Royal Institute of Technology, Stockholm, Sweden
[3] Institute of Plasma Physics of the CAS, Prague, Czech Republic
[4] University Sorbonne Paris-Nord, Process and Materials Sciences Laboratory, Villetaneuse, France
[5] CEA Cadarache, Saint Paul Lez Durance, France
[6] Max Planck Institute for Plasma Physics, Garching, Germany
[7] Department of Physics, University of Helsinki, Helsinki, Finland
[8] Reactor Physics Department, Jožef Stefan Institute, Ljubljana, Slovenia

Email: d.matveev@fz-juelich.de

Plasma-wall interactions (PWI) are recognized as design- and safety-relevant aspects that can impose significant constraints on the operational space and availability of a reactor-scale fusion device such as DEMO. The “EUROfusion Theory and Advanced Simulation Coordination (E-TASC)” initiative launched in 2021 [1] includes PWI modelling for DEMO as one of “Theory, Simulation, Verification and Validation (TSVV)” tasks [2] aiming at addressing high-priority issues along the roadmap to fusion energy with help of advanced simulations. Following the initiation of TSVV projects, the integral approach to PWI modelling for DEMO and first preliminary results were reported in [3]. This contribution reports on the progress of the project.

The multilateral modelling effort is focused on assessment of safety-relevant information regarding plasma-facing components (PFC) in view of material erosion, dust production, and fuel inventory in steady-state plasma operation, as well as large-scale wall deformation during transient events. A set of powerful and validated computer codes provides the foundation for the modelling framework. In the core of the framework are such codes as ERO2.0 [4] for material erosion, transport and re-deposition studies in steady-state accounting for realistic 3D wall geometry; MIGRAINe [5] similarly for dust inventory evolution simulations; FESTIM [6] for tritium retention and permeation studies, both globally in 1D and locally on the monoblock level in 3D [7]; and MEMENTO [8] for studies of transient material melting, including melt motion. Additional supporting activities include the work on advancement of physics understanding and numerical description for a variety of related processes and phenomena by means of particle-in-cell (PIC) simulations (BIT-1 [9] and SPICE [10]) and molecular dynamics and Monte-Carlo ion-material interaction codes, as well as efforts on optimization of codes’ performance and standardization of codes’ input and output workflow.

In view of steady-state wall erosion and material re-deposition, due to the prolonged absence of the new plasma solutions for the current Baseline equilibrium and recent design developments towards low aspect ratio DEMO [11], ERO2.0 global erosion and deposition modelling focused on advancement by means of improved physics models. Full kinetic energy spectra of charge-exchange (CX) neutral fuel atoms with poloidal resolution provided by the EIRENE code have been applied. In addition, the boundary condition for the Mach number at the sheath entrance has been refined (normalizing to the sound speed of an effective background, rather than to the individual Mach number of each species) to match the sheath boundary condition in the SOLPS-ITER background, thus increasing the consistency between the codes. Quantitatively, this leads to an increase of Ar impurity background fluxes to the wall, which in turn yields an increase of the W gross erosion flux. The corresponding erosion-deposition map for the main chamber of DEMO is depicted in Figure 1. As earlier, the outer mid-plane is identified as the main erosion zone, while the divertor baffle regions, remote areas above outer divertor and the top of the machine are identified as preferred material re-deposition locations. Apart from that, ERO2.0 was expanded by a thermal force model and an improved sheath module. The latter enables the incorporation of sheath profiles predicted by the BIT1 code into PWI studies (currently under testing).

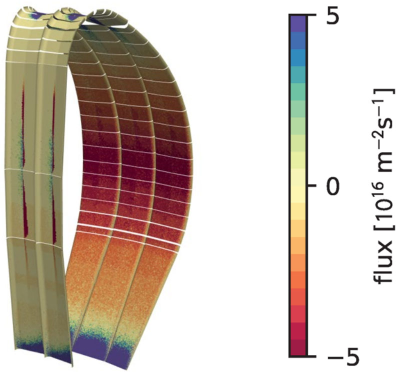

Figure 1. ERO2.0 erosion-deposition rate map for the main chamber of DEMO under accounting for kinetic energy distribution functions of charge-exchange neutrals at various poloidal locations.

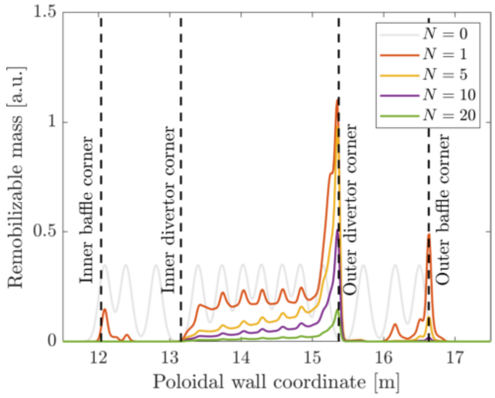

Figure 2. Example of simulated evolution of the spatial distribution of the remobilizable dust mass in the divertor region after given number of discharges (N), with ion drag activated.

Considering predominant deposition locations predicted by ERO2.0, MIGRAINe dust transport simulations have been carried out in steady-state DEMO plasma with and without accounting for the drag force due to bulk ion flows. 14 dust injection sites (13 sites in the divertor region, plus one site on the top of the vessel) have been selected based on ERO2.0 simulations. The results confirm the conclusions from previous preliminary studies, namely that: (i) vaporization is dominant for small grains; (ii) initial velocity has major impact on the survival of particles of all sizes by governing how far they penetrate into the hot and dense plasma regions; (iii) dust accumulates primarily in corner-like geometries at the bottom of the vessel such as the divertor legs and the boundaries between the baffles and the main chamber. While ion drag has only a small effect on the shape of the spatial distribution of trajectory termination points, its cumulative impact on the total number of surviving particles – and hence on the characteristic inventory decay time can become significant over many consecutive discharges. As expected from first-principle scalings, ion drag has the strongest impact in scenarios where dust injection velocities are the smallest.

These and other results will be detailed in the contribution, including recent assessments of fuel retention in neutron damaged tungsten [12] (as a function of the damage rate), coupling of He induced bubble formation with tritium transport, limiter melting under spatially and temporarily varying heat loads during vertical displacement events, as well as an update on the current status on PWI data improvements and integration.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

REFERENCES

[1] X. Litaudon et al, Plasma Phys. Control. Fusion 64 (2022) 034005
[2] F. Jenko et al, this conference
[3] D. Matveev et al, Nucl. Fusion 64 (2024) 106043
[4] J. Romazanov et al, Nucl. Fusion 62 (2022) 036011
[5] L. Vignitchouk et al., Plasma Phys. Control. Fusion 65 (2023) 015014
[6] R. Delaporte-Mathurin et al, Int. J. Hydrogen Energy 63 (2024) 786
[7] R. Delaporte-Mathurin et al, Nucl. Fusion 64 (2024) 026003
[8] K. Paschalidis et al, Fus. Eng. Des. 206 (2024) 114603
[9] D. Tskhakaya, Plasma Phys. Control. Fusion 59 (2017) 114001
[10] M. Komm et al, Plasma Phys. Control. Fusion 59 (2017) 094002
[11] C. Bachmann et al, Fus. Eng. Des. 204 (2024) 114518
[12] J. Dark et al, Nucl. Fusion 64 (2024) 086026