TSVV Task 6: Impurity Sources, Transport, and Screening

[1]G. Ciraolo*,[1]H. Bufferand,[1]N. Rivals,[2]S. Di Genova,[3]J. Romazanov,[3]D. Harting,[3]S. Rode,[3]A. Knieps,[3]S. Brezinsek,[4]Y. Marandet,[4]M. Raghunathan,[5]E. Gravier,[5]G. Lo Cascio, [6]M. Eder,[7,3]H. Kumpulainen,[7]M. Groth,[1]S. Sureshkumar,[1]N. Varedarajan,[8]J. Koerfer,[7]R. Maeepa

[1]CEA, IRFM, Saint-Paul-lez-Durance, France
[2]Aix-Marseille Univ, CNRS, Centrale Marseille, M2P2, Marseille, France
[3]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Jülich, Germany
[4]Aix-Marseille Univ., CNRS, PIIM, Marseille, France
[5]Université de Lorraine, Institut Jean Lamour, Nancy, France
[6]Fusion@ÖAW, Technische Universität Graz, Graz, Austria
[7]Aalto University, Espoo, Finland
[8] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland
* E-mail: guido.ciraolo@cea.fr

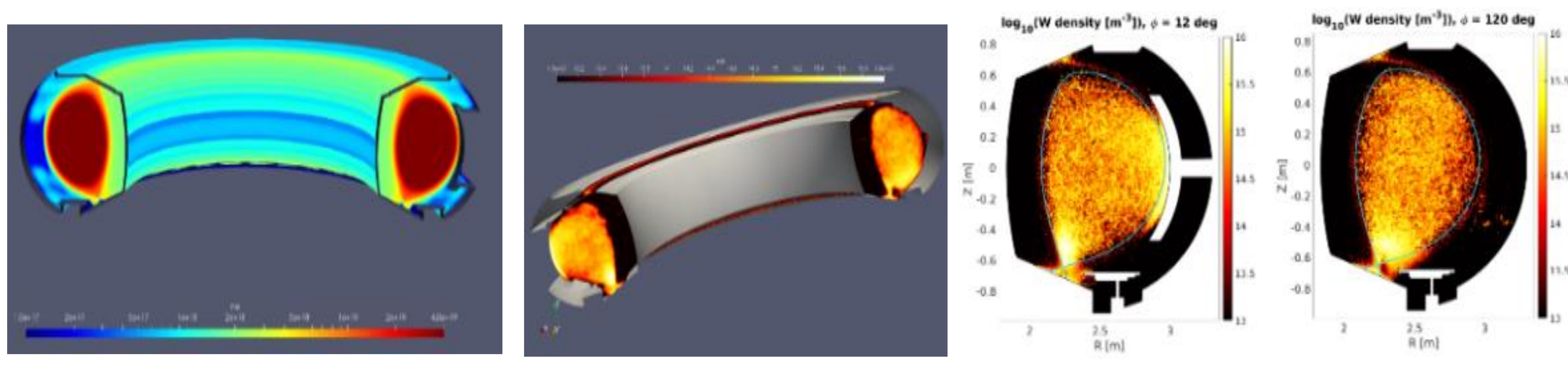
ABSTRACT

- In this poster, we report part of the work performed within the EUROfusion Theory, Simulation, Validation, and Verification project entitled **"Impurity sources, transport, and screening" (TSVV 6)**. The main goal is the development, verification, and validation of advanced numerical tools in order to **predict impurity sources, transport, and screening in the edge plasmas of ITER and DEMO fusion devices**. The achievements obtained during these three years and half of the project will be detailed, both on **numerical improvements** as well as **validation studies** on present experiments, in particular **WEST**, **JET, W7X** and numerical investigations focused on **ITER** plasmas.

- Numerical tools involved: **SOLEDGE3X, ERO2.0, EMC3-EIRENE, GYSELA, VENUS-LEVIS, JINTRAC**

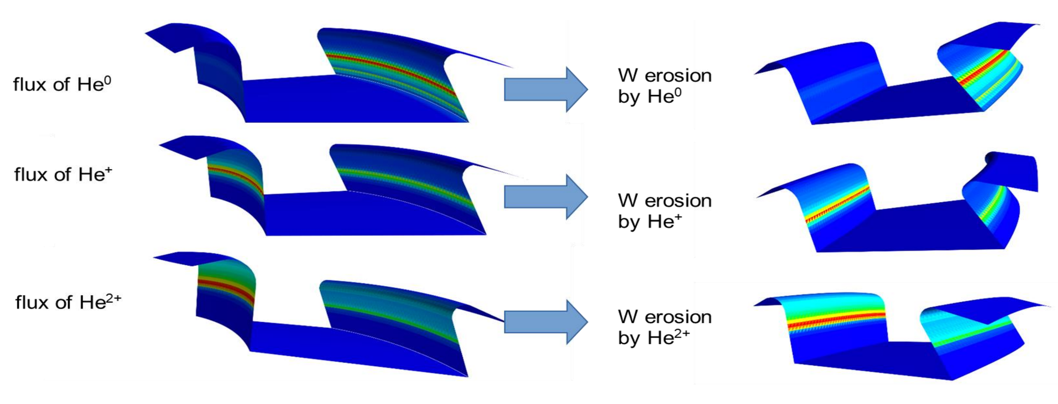
PROGRESS IN NUMERICAL TOOLS

- **SOLEDGE3X simulations** in **3D transport mode with a 3D wall** (toroidally localized antenna limiter) for providing plasma background to be used for computing W sources and transport with ERO2.0 code



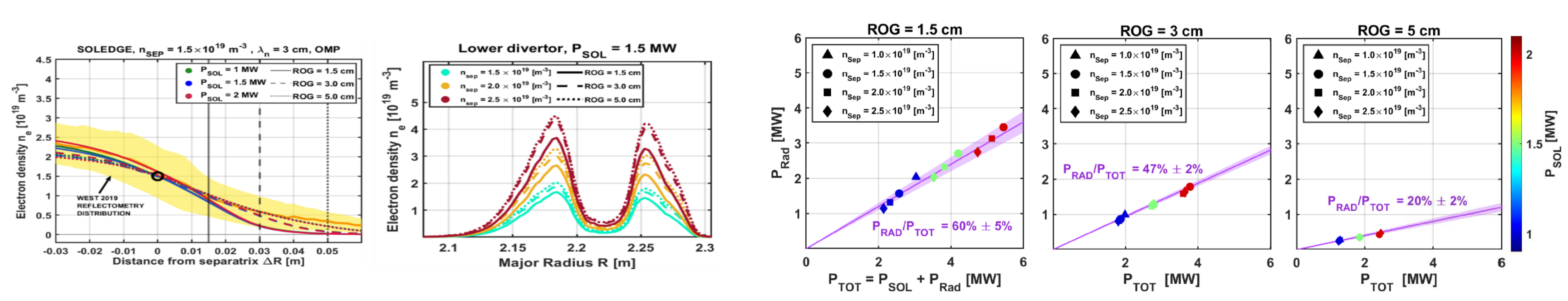
From the left to the right: First panel SOLEDGE3X plasma background with toroidally localized antenna. Second panel: 3D density map of W obtained with ERO2.0 using the SOLEDGE3X plasma background. Third and fourth panels: Poloidal maps of W density at two different toroidal angles (with and without the antenna limiter).

- **ERO2.0 code development:**
  - **Old version**:
    - **only constant concentrations of incoming background particles** could be defined (fraction of electron flux) - e.g. 50% He+, 50% He2+
  - **New version:**
    - **allows to define spatially varying concentrations of incoming background particles including neutrals (decoupled from electron flux)**



SOLEDGE3X-ERO2.0 SIMULATIONS OF WEST EXPERIMENTS

- An important effort to **interpret WEST experiments using SOLEDGE3X-ERO2.0** simulations has been performed.
- Large set of simulations performed in order to have a good representation of the WEST operational domain throughout a WEST campaign.
- **Scan with respect three main quantities** : **Psol,** the power entering the SOL, $\mathbf{n_{sep}}$ the electron density at the outer midplane separatrix and **ROG**, the radial outer gap between the separatrix and the antenna surface.
- Numerical results have been important to interpret experimental results indicating the role of antenna limiter in the W contamination of core plasma



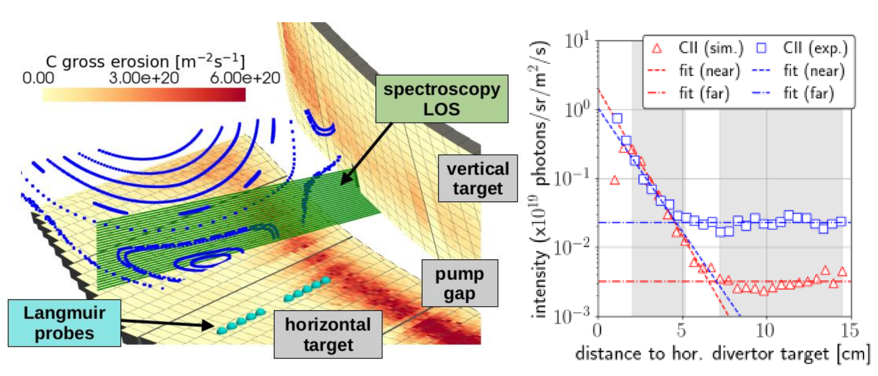
[G. Ciraolo et al, PSI conf. (2024)] *[S. Di Genova et al, Nucl Fus. (2024)]*

EMC3-EIRENE-ERO2.0 SIMULATIONS OF W7-X EXPERIMENTS

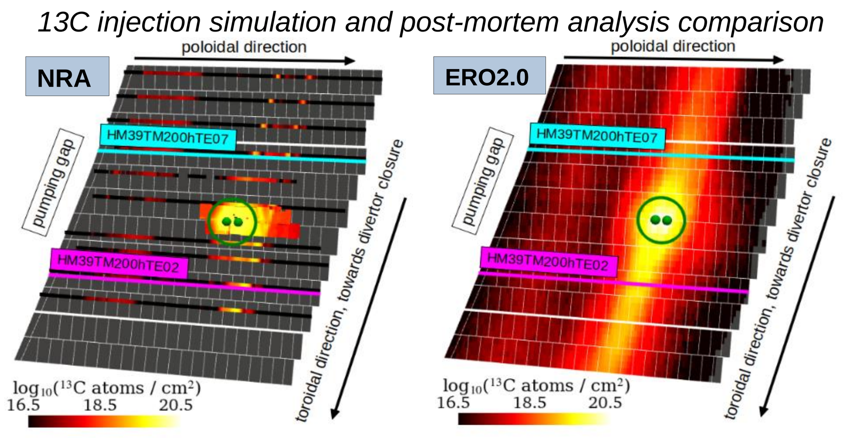
- Simulations of carbon migration in W7-X OP1.2 campaign standard configuration plasmas were performed, including chemical erosion and hydrocarbon molecule dissociation chain. Successful validation using post-mortem analysis from divertor marker fingers and carbon spectroscopy.
- Simulations of ^{13}C tracer experiment in OP1.2 were performed, with parameter studies on the influence of various effects (local vs global transport, re-erosion, transport coefficients, hydrocarbons, sticking coefficients, ExB drifts, parallel flow velocity). Successful validation using ion beam post-mortem analysis on divertor targets.
- Next steps: simulation of W tiles and analysis with OP2 results; **predictions for full-W wall W7-X.**

[C. P. Dhard, Phys. Scr. 2021] *[J. Romazanov, Nucl. Fusion 2024]*
[S. Brezinsek, Nucl. Fusion 2022] *[J. Romazanov, Nucl. Fusion (submitted)]*

12C erosion simulation and spectroscopy comparison

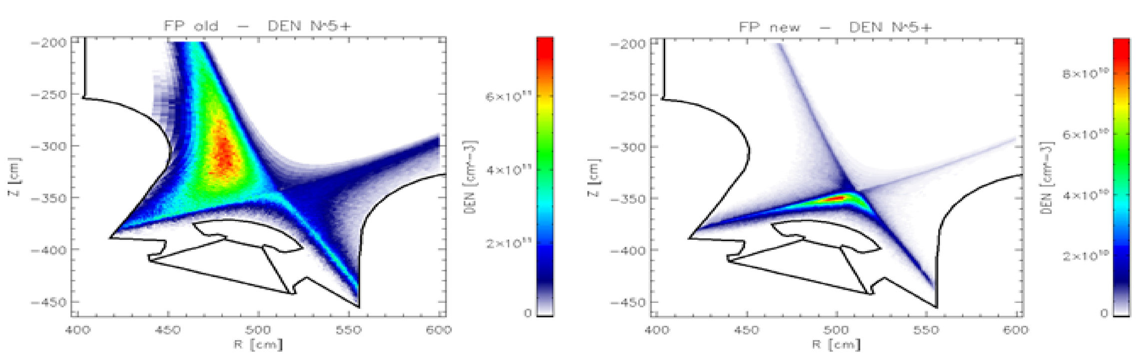


13C injection simulation and post-mortem analysis comparison



KINETIC ION TRANSPORT MODULE

- Another important part of the project focuses on the **development of a 3D kinetic description of heavy impurity transport in edge and SOL plasmas**, necessary both for taking into account the finite Larmor radius effects on prompt redeposition and the short lifetimes of lower ionization stages of such impurities. **The Kinetic Ion Transport (KIT) module of EIRENE** has been chosen as one of the possible solutions for such a description.
- Major improvements have been obtained during these years. For example, the **correct description of grad-B drift and the formation of banana orbits** in the magnetic mirror. A test case with test particle motion in the magnetic mirror at the outer mid-plane of an ITER background plasma has been extensively used for verifying the new version of the module
- **A new Fokker-Planck collision operator has been implemented** which now properly treats the scattering of ions out of the magnetic mirror regions, which takes into account friction with background species.



[D. Harting et al, Nucl Mat Ener. 2022]

[D. Harting et al , Nucl Mat Ener. 2024 (accepted)]

*Example of **computation with KIT module on N5+ Density in the divertor region using an ITER plasma background from EMC3-EIRENE.** One can observe that with the old version of the Fokker-Planck operator (left panel) there was an unphysical accumulation of particles on the high field side region, now solved with the new Fokker-Planck operator (right panel)*

- First **W simulations** with **EMC3-EIRENE-KIT** achieved
  - **indication that a large fraction of the lower ionisation stages of W is NOT thermalized with the ion background plasma temperature and thus needs a kinetic treatment.**

Next steps: Include missing **thermal force** (inline with ERO2.0)
Continue Benchmark with ERO2.0 including **recycling Impurities** and **high Z impurities** (e.g. W, Ar)
Compare kinetic low Z impurity simulation to **fluid solution**

APPLICATION TO ITER SCENARIOS

- We started the **application to ITER scenarios (previous to the decision of changing wall material) adopting a step-by-step approach, starting with 2D axisymmetric SOLEDGE3X-EIRENE simulations**. We focused both on the low power scenarios, the so-called Pre "Fusion Power Operation 1" (PFPO-1) phase. The cases are modeled in 2D, with fixed transport coefficients, and a pure Hydrogen content, at 20MW of injected power
- **A throughput scan containing six simulations to represent from attached to partially detached conditions was successfully run**, which required the development of improvements of both the plasma solver SOLEDGE3X and the plasma-neutrals interaction code EIRENE

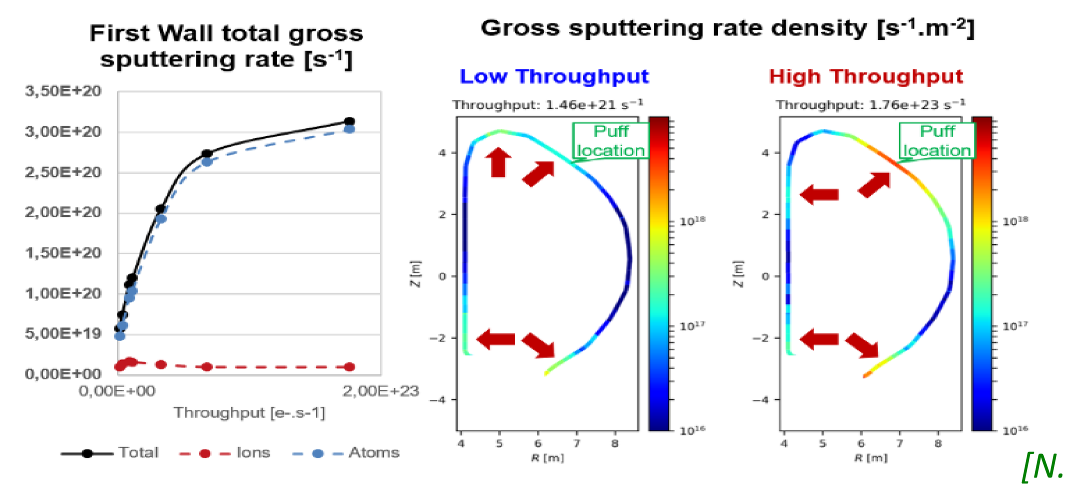


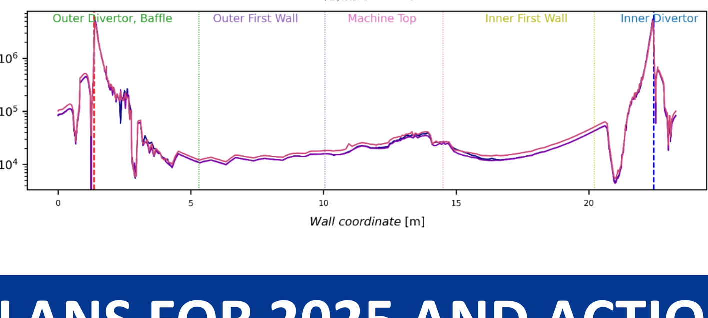
Figure 4: Impact of gas injection on the gross erosion rate calculated with EIRENE. Left: Total integrated rate along the first wall as a function of throughput, with the contribution of ions in red, and that of atoms in blue. Central and right panels: 2D representations of gross erosion rates along the first wall for two different values of the throughput.

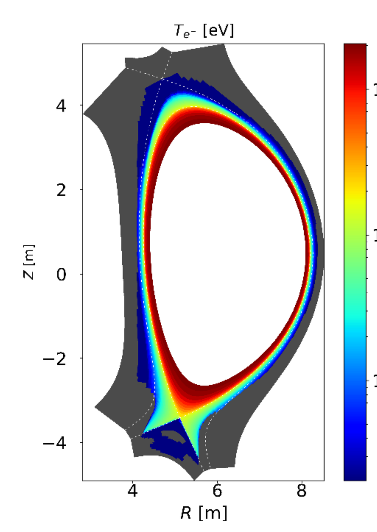
[N. Rivals et al, Nucl. Mat. Ener. 2022]

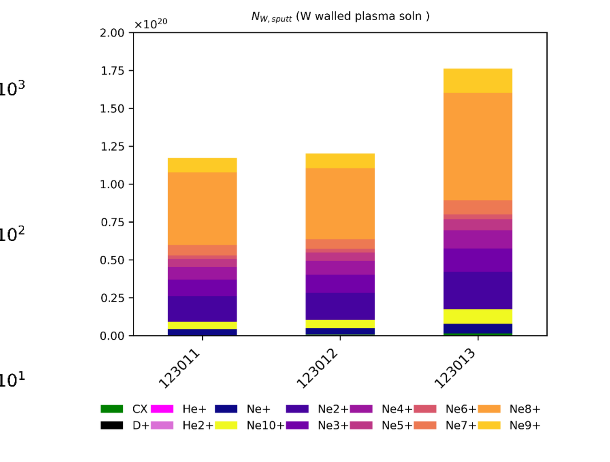
[N. Rivals et al, Nucl. Fus. 2024 (submitted)]

- With the change to **W wall**, we have started (in collaboration with IO) new simulations for **new ITER full power scenarios with W wall and Ne seeding**

Input conditions:
- $P_{sol} = 100\ MW$
- Species: D, Ne – injected from upper gas puff; He fusion product as a flux from core
- H mode – transport barrier with $D_{\perp}^{Far\ SOL} = 0.3 m^2 s^{-1}$ (no balooning or enhanced far SOL transport)
- Scan performed over Ne seeding







Ne^{8+} largest sputtering source across Ne seeding scan (excl. self sputtering)

PLANS FOR 2025 AND ACTION ITEMS IDENTIFIED FOR 2026-2027

- Complete **SOLEDGE3X plasma background for ITER scenarios with W wall** and investigation of W sources, transport and screening using ERO2.0 (as done for WEST previously)
- **Apply KIT module for kinetic treatment of impurity transport on ITER cases and comparison with fluid approach**
- Perform 3D SOLEDGE3X-ERO2.0 simulations for **start-up phase:**
  - **Validation on WEST experiments (now with full W limiter)**
  - **Predictive simulations for ITER scenarios**
- Determine the **impact of energetic particles coming from the pedestal region on divertor power load** improving the modeling of parallel heat transport (for ex. considering non-local approach and/or coupling with other appropriate numerical tools)

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 author(s) 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.