EUROfusion

WP PWIE Annual meeting – March 26, 2025

TSVV6 Impurity Sources, Transport, and Screening

G. Ciraolo on behalf of TSVV 6 team

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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.

TSVV 6: ROAD MAP

Aims

- **Establish an integrated modelling suite to predict the W impurity distribution** in ITER and DEMO, including W source generation, W screening, W transport, W exhaust and its impact on the plasma performance.

- Develop **3D kinetic transport models for heavy impurities** (including W) and seeding species like Ar, Kr, Xe in the SOL and pedestal regions of DEMO.

- **Assess the effects of 3D perturbations** and ELM suppression techniques **on the W impurity distribution in ITER** reference scenarios, along with their implications for DEMO.

TSVV 6: ROAD MAP

Key Deliverables

1. **Validated suite of 3D codes** and **transport models to describe in an integrated way the W content** and **its distribution in metallic devices**, in particular DEMO and ITER, with discrimination of main chamber and divertor sources, screening, transport, and exhaust along with its impact on the main plasma dynamics and performance.

2. **Assessment of the W influx, W screening**, and **W transport** in **ITER plasmas envisaged for pre-fusion and fusion power operation** with semi-detached divertor and application of resonant magnetic perturbations for ELM suppression. Discussion of the impact on a potential loss of semi-detachment and ELM suppression on the W influx, W screening, and W transport in those ITER scenarios.

3. **Applications of the developed model**. Assessment of the **seeding impurity screening and transport** in DEMO and **ITER scenarios**

TSVV 6 TEAM: expertise and codes

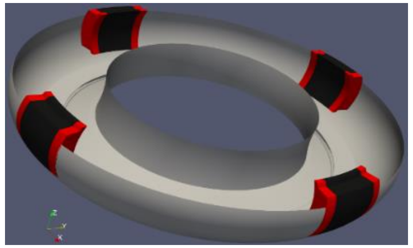
Expertise / codes

- CEA / FR-FCM : SOLEDGE3X-EIRENE, GYSELAX
- FZJ : EMC3-EIRENE and KIT module, ERO2.0
- AALTO UNIV. : integrated modeling core-edge JET plasma, W transport with for example JINTRAC-ERO2.0 package
- EPFL: theoretical framework, tungsten impurity transport in 3D equilibria with VENUS-LEVIS code (2024-2025)
- GRATZ TU: kinetic modeling of ion transport with GORILLA code

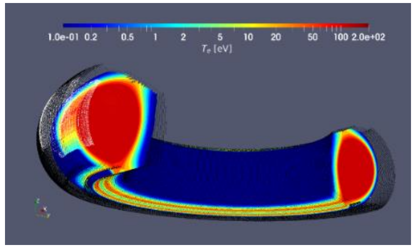
TSVV-6: code development and validation of SOLEDGE3X-ERO2.0 on WEST experiments

INVESTIGATION OF **W CORE CONTAMINATION IN WEST GEOMETRY DUE TO ANTENNA LIMITER** WITH **3D TRANSPORT SOLEDGE3X-ERO2.0 SIMULATIONS**

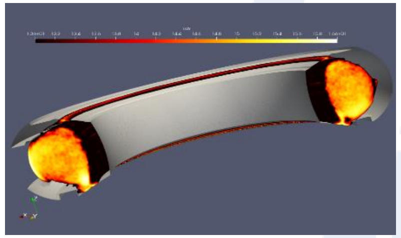
3D non-axsymmetric wall :
Radial Outer Gap: 1.5 cm

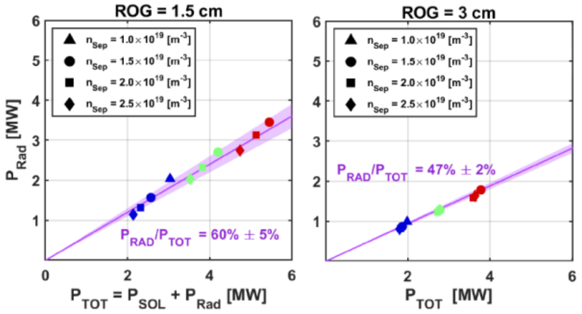


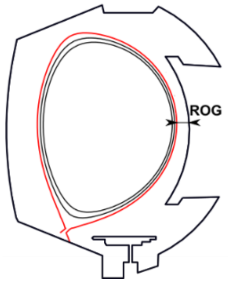
SOLEDGE3X plasma background



3D density map of W obtained with ERO2.0 using SOLEDGE3X backrgound





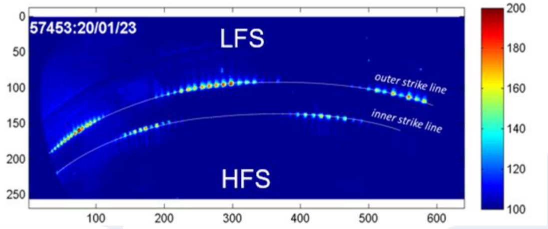


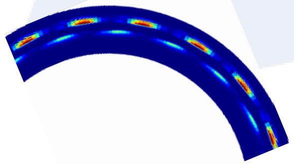
S. Di Genova et al Nuc. Fus. 2024,
G. Ciraolo et al PSI 2024

- Simulations results indicate the **role of the antenna limiter in the tungsten contamination of core plasma** depending on the distance from the plasma (ROG parameter)

Ongoing: impact of **3D non axisymmetric magnetic geometry** on power load patterns on divertor and impact on sources and transport of W

Top view toroidal IR measurements of divertor heat fluxes





SOLEDGE3X simulations

Work performed in interaction with WP TE, WP PWIE

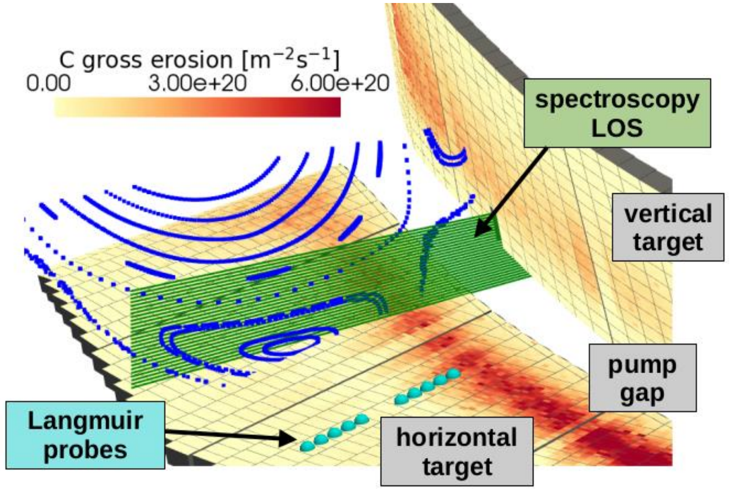
EMC3-EIRENE - ERO2.0 SIMULATIONS OF W7-X EXPERIMENTS

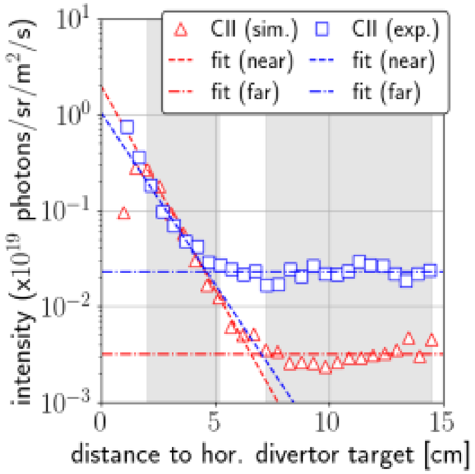
- **Simulations of carbon migration in W7-X OP1.2 campaign standard configuration plasmas were performed**, including chemical erosion and hydrocarbon molecule dissociation chain. **Successful validation using post-mortem analysis from divertor marker fingers and carbon spectroscopy.**
- **Simulations 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.**

[J. Romazanov, Nucl. Fusion 2024] [J. Romazanov, Nucl. Fusion (submitted)]

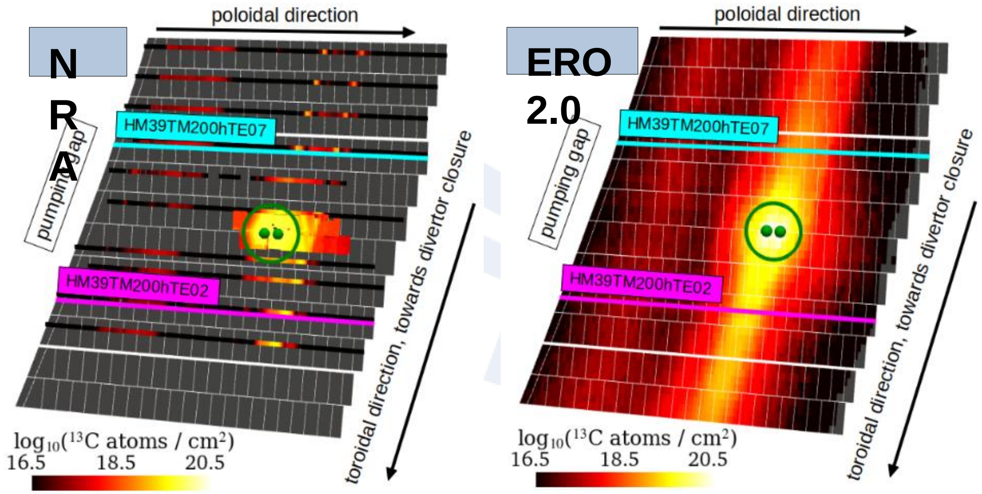
More details in Juri's presentation

12C erosion simulation and spectroscopy comparison





13C injection simulation and post-mortem analysis comparison



Work performed in interaction with WP W7X, WP PWIE, TSVV7

EIRENE KINETIC ION TRANSPORT MODULE

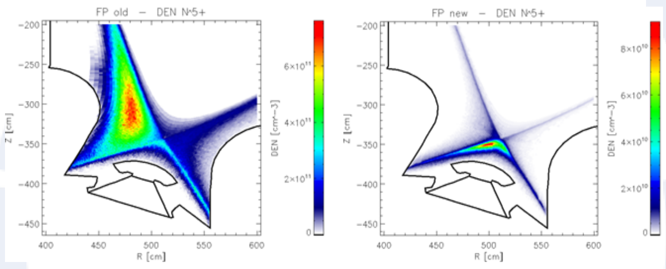
- Another important part of the project focuses on the **development of a 3D kinetic description of impurity transport in edge and SOL plasmas**, necessary both for taking into account the finite Larmor radius effects on prompt redeposition and the short lifetimes of lower ionization stages of such impurities. **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. 2024 (accepted)] *[D. Harting et al, Nucl Mat Ener. 2022]*

Example of ***computation with KIT module on N^{5+} 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)*

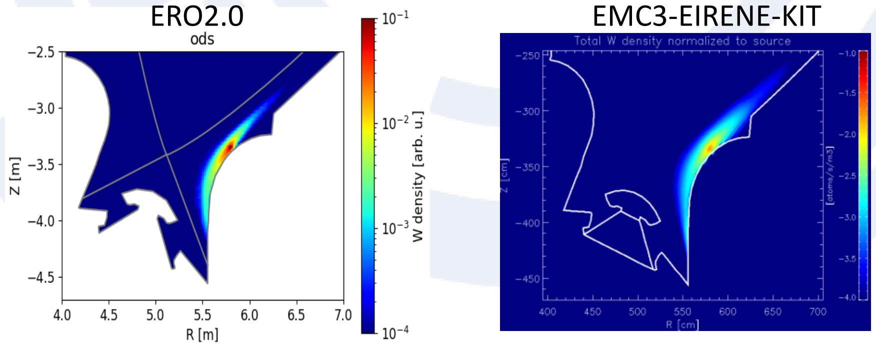


- First **W simulations** with **EMC3-EIRENE-KIT** achieved
  - indication that a large fraction of the lower ionisation stages of W is NOT thermalized with the ion background plasma temperature and thus needs a kinetic treatment.

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

Benchmark KIT EIRENE with ERO2.0

Poloidal map of W density



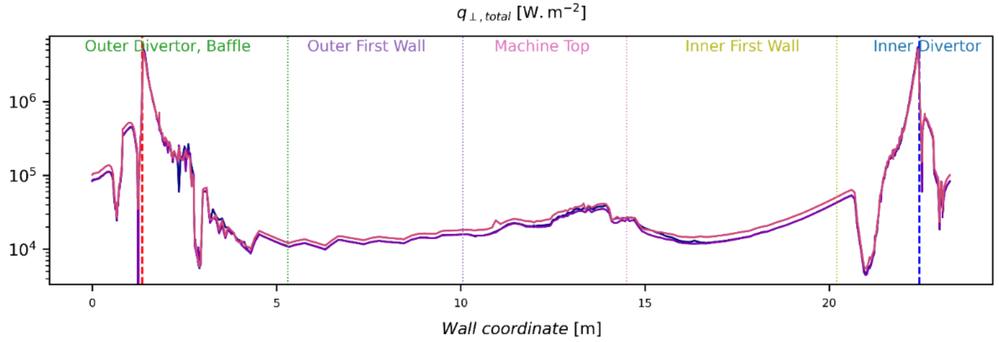
Courtesy: C. Baumann, H. Kumpulainen

Work in interaction with TSVV 5

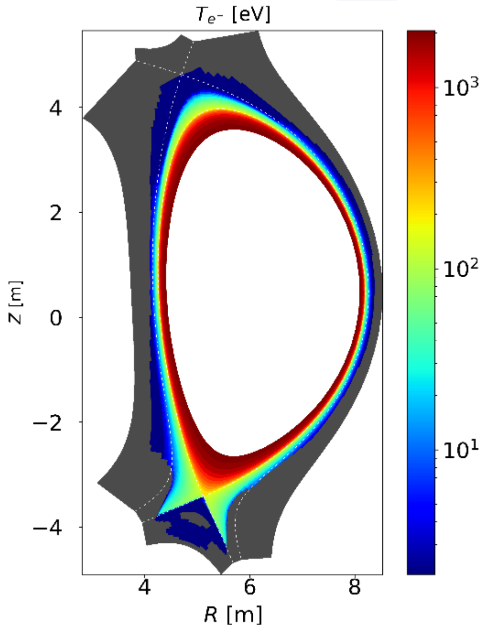
APPLICATION TO ITER SCENARIOS

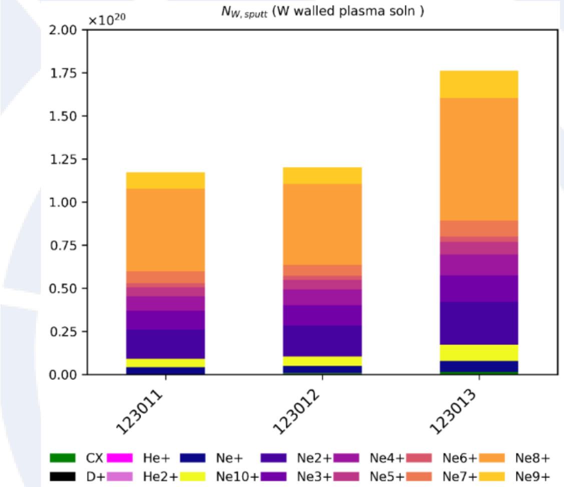
- With the change to **W wall**, we have started (in collaboration with **TSVV 3 and IO**) new SOLEDGE3X simulations for **new ITER full power scenarios with W wall and Ne seeding**

Input conditions:
- $P_{sol} = 100\ MW$
- Species: D, Ne – injected from upper gas puff; He fusion product as 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



Perpendicular heat flux along the wall





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

Next step: computation of W sources and migration with ERO2.0

See also Juri's presentation for more complete picture of application of ERO2.0 to ITER plasma background

PLANS FOR 2025 AND ACTION ITEMS IDENTIFIED FOR 2026-2027

- **Validation steps**:
  - Application of SOLEDGE3X-ERO2.0 workflow to **WEST experiments** taking into account **3D non axisymmetric features**
    - **wall geometry** (toroidally localized antenna limiter) and 3D non-axysimmetric magnetic equilibria (with magnetic ripple)
  - Application of EMC3-EIRENE plus ERO2.0 modeling on **W7X**: simulations of **W tiles and analysis with OP2 results**; **predictions for full-W wall W7-X**

  - **AUG simulations both with SOLEDGE3X-ERO2.0 and EMC3-EIRENE ERO2.0** of a common case related to **WPTE** experimental proposal on W sources and migration (interaction with **TSVV 7, WP TE, WP PWIE**)

- Focus on the determination of 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)

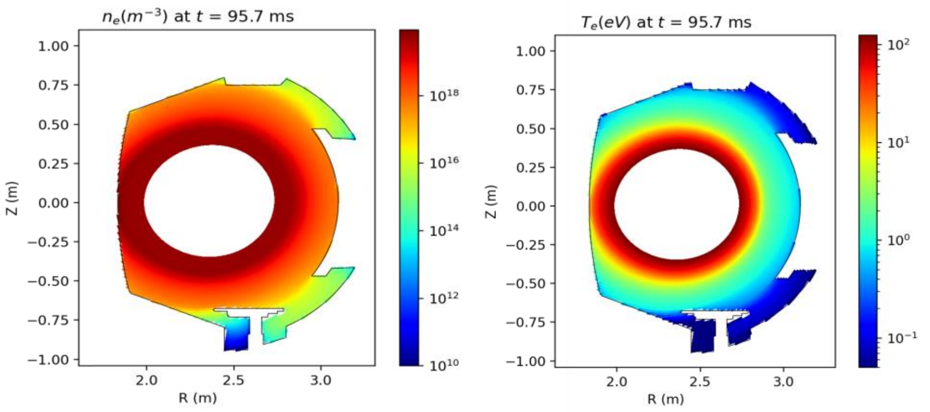
- Apply **EIRENE KIT module for kinetic treatment of impurity transport on ITER cases and comparison with fluid approach**

- **Application to ITER scenarios**
  - Complete **SOLEDGE3X and EMC3 EIRENE** plasma backgrounds for **ITER scenarios with W wall** and investigation of W sources, transport and screening using **ERO2.0**
  - Perform 3D SOLEDGE3X-ERO2.0 simulations for **ITER start-up phase (after validation steps on WEST and JET experiments)**

Start up limiter phase: preliminary results in 2D for WEST and JET validation cases

WEST

Pulse #60529: P_in = 400kW,
Greenwald fraction ~ 0.4.



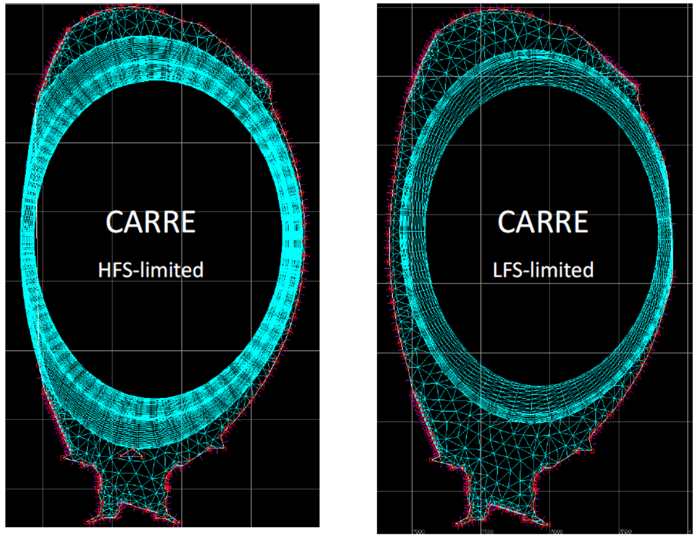
SOLEDGE plasmas far too dense, too cold. Further tuning to be done, starting with performing feedbacks on probe location

Courtesy N Varadarajan (PhD CEA)

JET

2025: perform SOLPS-ITER density and power scans in HFS and LFS limited configuration ⇒ extract CX fluxes for ERO2.0 Ni, W erosion and migration

Pyry Virtanen

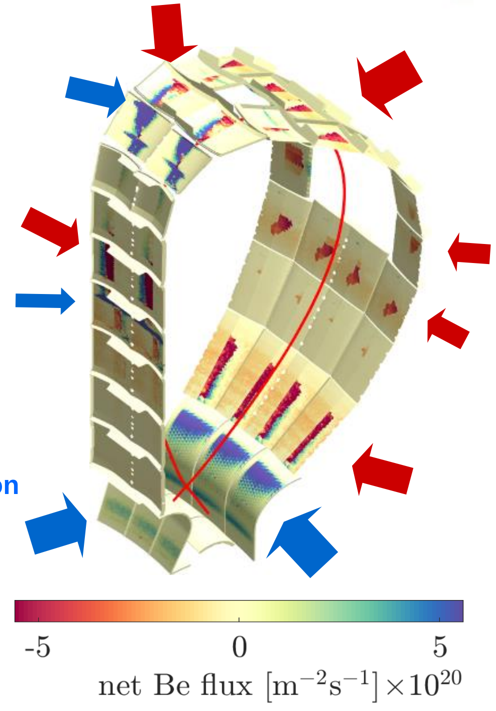


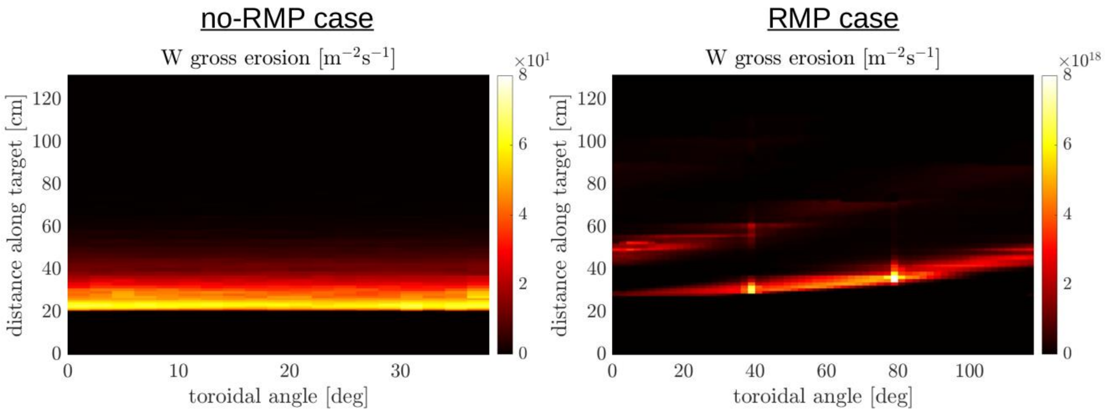
- First proof-of-principle SOLPS-ITER runs achieved for HFS-limited case → setup and predicted plasma parameters being cross-checked with David Coster and Xavier Bonnin
- Using ERO2.0, CX atomic flux contributions from limiter configurations to campaign-integrated Ni, W and Be migration topic of Pyry Virtanen's M.Sc. thesis in 2025 → PSI 2026

From Mathias' presentation

Key Deliverable 2: Assessment of the W influx, W screening, and W transport in ITER plasmas

- **ERO2.0 runs using 2D ITER plasma backgrounds (OEDGE):**
  - Previous work (*J. Romazanov et al. CPP-2019, NME-2021, NF-2022*) focused on Be FW erosion
  - Next step: repeat with considering the W divertor
- **ERO2.0 runs using 2D/3D ITER plasma backgrounds with+w/o RMPs (EMC3-EIRENE)** is work-in-progress:
  - 4 EMC3-EIRENE PFPO plasma backgrounds by Heinke Frerichs: 2 with and w/o RMPs, each in low + high density
  - Implementation of EMC3-EIRENE to ERO2.0 data transfer was adapted to tokamaks
  - **First preliminary W gross erosion obtained on inner target for low-density case**
  - Under investigation: improvement of B-field interpolation





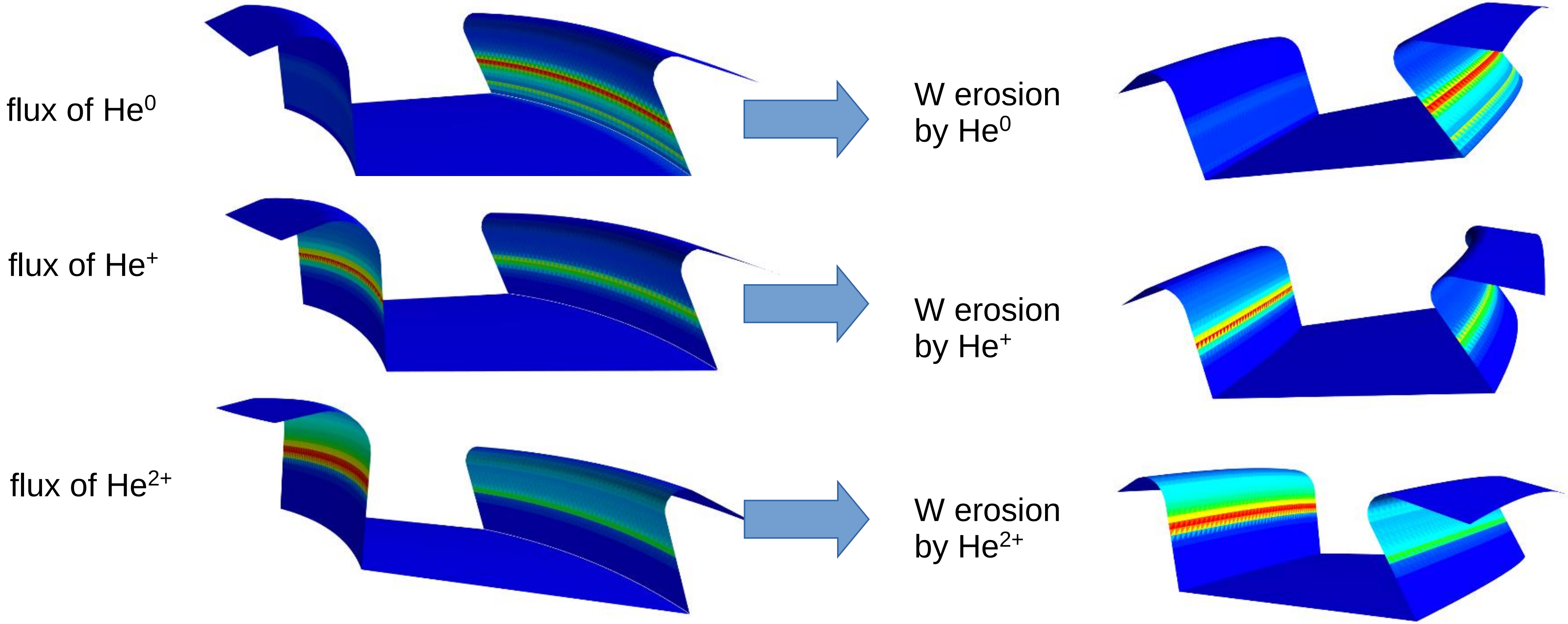
Deliverables for 2022-2023

D2.1	**Characterization of W transport on 2D ITER plasma backgrounds obtained in M2.2 using ERO2.0 (post processing)**	**01/2023**
D2.2	Analysis of EMC3-EIRENE ITER plasma background with 3D perturbation in semi-detached conditions (full 3D solution)	12/2022

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% He^{2+}
- **New version:**
  - **allows to define spatially varying concentrations of incoming background particles including neutrals (decoupled from electron flux)**

Important for Helium plasmas (He^{+}/He^{2+} ratio), oxygen impurities @WEST, seeding impurities, ...



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