

# Modelling studies of the MAST-Upgrade Super-X Divertor with SOLEDGE3X-EIRENE

L. Bramucci<sup>1,2</sup>, P. Innocente<sup>3</sup>, S. Sartorello<sup>1,2</sup>, K. Verhaegh<sup>4,5</sup>, D. Moulton<sup>4</sup>, P. Ryan<sup>4</sup>,

The MAST-U Team\*, The EuroFusion Tokamak Exploitation Team\*\*

<sup>1</sup> *Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Padova, Italy*

<sup>2</sup> *CRF - Università di Padova, Corso Stati Uniti 4, 35127 Padova, Italy*

<sup>3</sup> *ISTP-CNR, Institute for Plasma Science and Technology, Corso Stati Uniti 4, 35127 Padova, Italy*

<sup>4</sup> *UKAEA, United Kingdom Energy Authority, Culham, UK*

<sup>5</sup> *Eindhoven University of Technology, Eindhoven, The Netherlands.*

\* *See author list of "J.R. Harrison et al 2026 Nucl. Fusion 66 116005*

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\*\**See the author list of "N. Vianello et al. Nuclear Fusion 2026 (doi: 10.1088/1741-4326/ae71ec)"*

## Introduction

Heat and particle exhaust represents one of the most critical challenges for future fusion reactors. In reactor-scale devices, power fluxes in the scrape-off layer (SOL) can reach  $150 \text{ MW m}^{-2}$ , far exceeding engineering limits of  $5 - 10 \text{ MW m}^{-2}$  [1]. The MAST-Upgrade (MAST-U) tokamak has been specifically designed to address this challenge through the implementation of alternative divertor configurations (ADCs), combining strong neutral baffling with extreme divertor shaping capability (total flux expansion  $F_R$  up to 2.5) [2]. Recent experimental results demonstrate the superior exhaust performance of the Super-X (SXD) and Elongated (ED) divertors compared to the Conventional (CD) divertor, without adverse impact on core performance [3]. In this work we present SOLEDGE3X- EIRENE [4] simulations of the MAST-U boundary plasma for the CD and SXD configurations, benchmarked against existing SOLPS-ITER results and experimental data [3].

## Mesh Generation

A prerequisite for these simulations is the generation of a suitable computational mesh for the complex MAST-U geometry. The SOLEDGE3X mesh generator requires a well-defined outer flux surface  $\Psi_{out}$  that encloses the entire vessel to construct the computational domain boundary. However, the original MAST-U equilibrium features multiple secondary X-points outside the vessel wall [Fig. 1a]: since  $\Psi$  is non-monotonic in the vicinity of these X-points, any value of  $\Psi_{out}$  exceeding their flux value introduces discontinuities in the flux derivative that prevent mesh generation. This constrains  $\Psi_{out}$  to values that do not enclose the full vessel, making direct mesh generation impossible.

To address this issue, a dedicated flux regularization module was developed. The module modifies the flux function  $\Psi$  exclusively outside the physical wall boundary, leaving the SOL and

EDGE equilibrium fully intact. The modification creates a smooth, monotonic transition from the original flux values at the wall boundary toward a constant asymptotic limit value  $\Psi_{limit}$ , chosen as a fixed multiple of the maximum flux value at the wall boundary (ensuring that the asymptotic flux is greater than any internal values, to prevent the creation of new X-points).

To avoid discontinuities at the wall boundary, a small buffer region is introduced immediately outside the vessel wall where  $\Psi$  remains unmodified. The smooth transition begins only beyond this buffer, and is implemented using a cubic weight function (Eq 1) based on the distance  $d$  measured from the outer edge of this buffer region:

$$w(d) = 3(d/d_{trans})^2 - 2(d/d_{trans})^3 \quad (1)$$

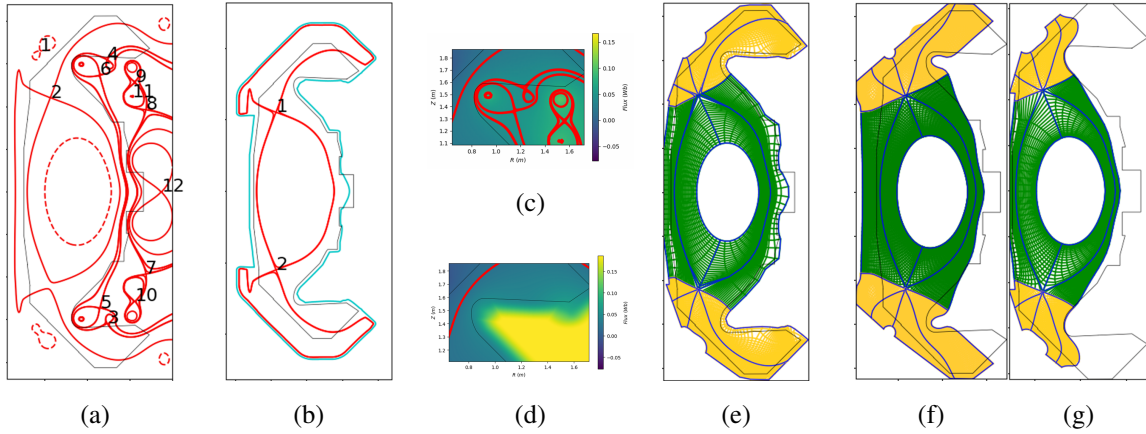
The modified flux is then computed as:

$$\Psi_{modified} = \Psi_{original} \cdot (1 - w) + \Psi_{limit} \cdot w \quad (2)$$

This formulation guarantees  $C^1$  continuity: at the wall ( $d = 0, w = 0$ ) the original flux is preserved, while at the transition distance ( $d = d_{trans}$ ) the flux reaches the asymptotic limit. The geometric offset of the buffer region is applied sector-by-sector along the wall boundary. In the region outside the divertor targets, a large offset is used to provide sufficient radial space for  $\Psi$  to decrease to the values  $\Psi_A$  or  $\Psi_C$  required by the mesh generator. At the midplane – both inner and outer – a minimal offset is applied to prevent the formation of artificial O-points, that would create closed flux surfaces outside the vessel and make mesh generation impossible. The result of this procedure is a single, continuous external flux surface enclosing the entire vessel, as shown in figure 1b, which serves as the outer boundary of the SOLEDGE3X mesh. The effect of the regularization is also clearly visible in the 2D map of the magnetic flux where a zoom of the outer upper divertor region illustrates the flux surfaces before (Fig: 1c) and after (Fig 1d) the procedure. The original equilibrium features multiple secondary X-points with complex, intersecting flux surfaces outside the vessel wall (Fig: 1c), which are eliminated by the regularization, resulting in smooth, well-ordered flux surfaces suitable for mesh generation (Fig 1d).

The module was applied to three MAST-U divertor configurations: the Super-X (SXD, discharge #46860), the Elongated (ED, #47079) and the Conventional Divertor (CD, #46762). The SXD mesh (Fig. 1e) covers nearly the full MAST-U vessel, with only a small excluded region of negligible impact on the simulation domain. For the ED (Fig 1f) and CD (Fig 1g) configurations, the mesh does not include the outer divertor region, beyond the secondary X-points which are located closer to the vessel wall in these cases. Two approaches are currently under investigation to address this limitation; extending the mesh to explicitly include the secondary X-points

regions, or treating the excluded volume as a sub-divertor region for neutral particle transport only. Beyond the configurations presented here, the module has been successfully applied to X-point Target and Super-X geometries in MAST-U by P.Muscente et al. [5] demonstrating its generality across different magnetic topologies.



*Figure 1: **a** Original MAST-U equilibrium from EFIT for the SXD configuration **b** Modified equilibrium after applying the flux regularization module; the blue line represents the continuous external flux surface. 2D map of the magnetic flux before **(c)** and after **(d)** the flux regularization module. Computational meshes generated for the SXD **(e)**, ED **(f)** and CD **(g)** configurations.*

## Preliminary Results

The generated meshes were then used to perform the first preliminary SOLEDGE3X-EIRENE simulations of the MAST-U boundary plasma. Simulations were performed for the CD and SXD configurations at the core Greenwald fraction  $f_{GW} = 35\%$ , using the same transport coefficients as the SOLPS-ITER reference simulations [6] and [3]:  $\chi_e = \chi_i = 10\text{m}^2/\text{s}$  inside the separatrix and  $4\text{m}^2/\text{s}$  in the SOL, with  $D_{\perp} = 4\text{m}^2/\text{s}$  uniform. The core gas puff rate was used as a free parameter to match the experimental upstream density. Upstream electron density and temperature profiles show reasonable agreement with Thomson Scattering data in the SOL region for both configurations, as shown in Figure 2a. Residual discrepancies in the inner SOL suggest further transport profile tuning is required. Upstream profiles are qualitatively reproduced across both configurations using the same transport coefficients as SOLPS-ITER [6], suggesting limited sensitivity of core SOL transport to the divertor magnetic geometry. Residual discrepancies indicate that further transport profile tuning is required to achieve a quantitative match. The 2D map for the CD configurations (Fig. 2b) show physically symmetric profiles between the upper and lower divertor legs.

## Conclusions

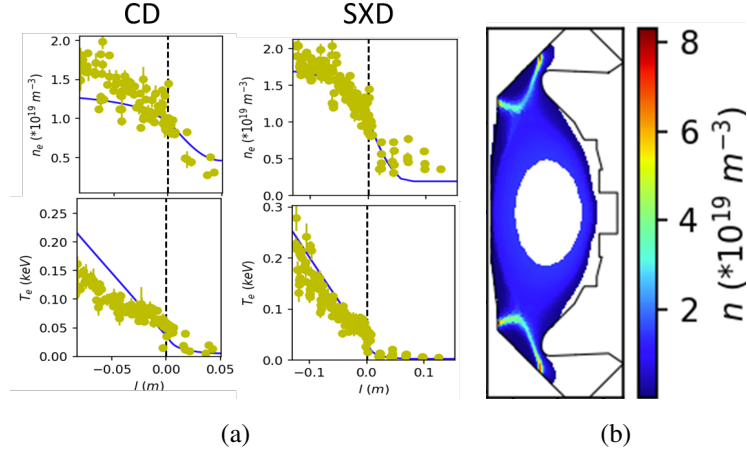


Figure 2: **(a)** Upstream electron density and temperature profiles for the CD and SXD configurations at  $f_{GW} = 35\%$ . Blue lines show simulation results, yellow dots experimental Thomson Scattering data [3]. **(b)** 2D electron density map for the CD configuration.

We have demonstrated that SOLEDGE3X-EIRENE simulations of the complex MAST-U magnetic geometry are feasible through the development of a dedicated flux regularization module, which has been validated across multiple divertor configurations [5]. Preliminary simulations reproduce upstream plasma profiles in reasonable agreement with Thomson Scattering data for both CD and SXD configurations. Core SOL transport shows qualitative consistency across configurations with the same transport coefficients, though quantitative matching requires further profile tuning. Next steps include transport profile tuning to improve target and outer SOL matching, density scan simulations to investigate detachment onset, SXD mesh optimisation, and extension of the study to the Elongated Divertor configuration.

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