

Separatrix Position Correction in SOLPS-ITER Edge Transport Simulations of the Tokamak COMPASS

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Abstract

Reliable edge simulations hinge on an accurate magnetic separatrix for mesh construction, yet Grad–Shafranov reconstructions routinely carry centimetre-scale errors in its position. We evaluate the impact of these uncertainties on SOLPS-ITER transport simulations by combining four refined EFIT++ solutions with comprehensive edge diagnostics of COMPASS L-mode discharge #17692. Each equilibrium serves to generate an independent computational mesh. Four SOLPS-ITER simulations, each with the same input parameters as the baseline simulation but differing only in the underlying magnetic equilibrium and mesh, are compared. Optimal radial shifts of the separatrix position align simulations and experiment to within 3 mm when the underlying equilibrium reconstructions differ by 2 cm. The averaged separatrix coordinates are imposed in EFIT to build a final, separatrix-constrained equilibrium; its subsequent SOLPS-ITER run requires only a 3 mm correction at plasma top. The study demonstrates that radial profile shifts are a robust method to compensate for magnetic equilibrium reconstruction errors in interpretative modelling and that SOLPS-ITER can be used to evaluate and improve EFIT reconstructions.

1 Introduction

Magnetic equilibrium reconstruction is fundamental to tokamak research. The position of the separatrix is of particular interest, as it provides the basis for interpreting diagnostic measurements, guides plasma simulation geometries, and affects interaction between the scrape-off layer (SOL) and plasma-facing components. The equilibrium is typically reconstructed from magnetic and other tokamak measurements using codes that solve the Grad-Shafranov equation, such as EFIT [2]. However, the quality of magnetic equilibrium reconstructions, especially in terms of the accuracy of the separatrix position, remains a challenge across various tokamaks. The error of the separatrix position, obtained with Grad-Shafranov solvers, is typically of the order of 1 cm and requires corrections which are often case-dependent and ad hoc [10] [11] [14].

During the operation of the COMPASS tokamak [8], several attempts have been made at improving the magnetic equilibrium reconstructions using additional diagnostics, models, and calibrations. A previous study has attempted to evaluate two of these variants using statistical methods and comparison with diagnostic measurements [9]. We use these equilibrium reconstructions for our evaluation.

The separatrix position error presents a particular problem for interpretative edge modelling. If, for example, the separatrix is reconstructed inward of its real position, the values of separatrix T_e and n_e may be unrealistically high and matching experimental and simulated profiles may be difficult. A commonly used approach is to simply shift the simulation profiles radially to match the experiment [4] [10]. We claim that the shift which aligns the simulated and experimental profiles indicates the real separatrix position. Smaller shifts required for the optimal match then indicate a better reconstruction.

This study investigates how inaccuracies in the magnetic equilibrium affect edge plasma transport simulations using SOLPS-ITER [3]. SOLPS-ITER is a combination of the 2D multi-fluid plasma transport code B2.5 and the kinetic Monte Carlo neutral transport code EIRENE [12]. Parallel and perpendicular transport in the SOL has vastly different time scales and behavior. For this reason, the B2.5 computational mesh is constructed using a magnetic equilibrium reconstruction and is aligned to the flux surfaces. Consequently, the result of the simulation may be influenced by the magnetic equilibrium used for its construction. By comparing SOLPS-ITER simulations built upon different meshes, we can evaluate this influence. Finally, we use the transport code to further constrain the position of the separatrix and create a magnetic equilibrium reconstruction with better agreement with the experiment.

2 Experiment

To assess the influence of equilibrium reconstructions on SOLPS-ITER simulations, we investigate the L-mode COMPASS discharge (#17692) in a lower single null configuration. The toroidal magnetic field was $B_T = 1.38$ T with the ion ∇B -drift pointing toward the active X-point, the plasma current was $I_p = 200$ kA, and line-averaged density $\bar{n}_e = 2.2 \times 10^{19} \text{ m}^{-3}$. The plasma was ohmically heated with $P = 200$ kW. The time $t = 1120$ ms was chosen for the analysis, during the flat top, and before the reciprocating probe entered the velocity shear layer.

The discharge featured an extensive set of SOL diagnostics, see figure 1 [17] [18]. This allowed us to constrain the upstream separatrix position from the Thomson scattering at the plasma top, and from the reciprocating probe at the outer midplane. The divertor featured independent measurements from an infrared camera [16], a swept Langmuir probe array [5] [13], and a probe array using a combination of Langmuir and ball-pen probes. [1]

The COMPASS tokamak is well-suited for this study because of its sheath-limited regime [6] and well-established divertor probe diagnostics. The absence of large parallel gradients allows for easier interpretation and constraint of upstream parameters from divertor measurements. The use of SOLPS-ITER for modelling COMPASS plasmas was validated in an extensive study [7].

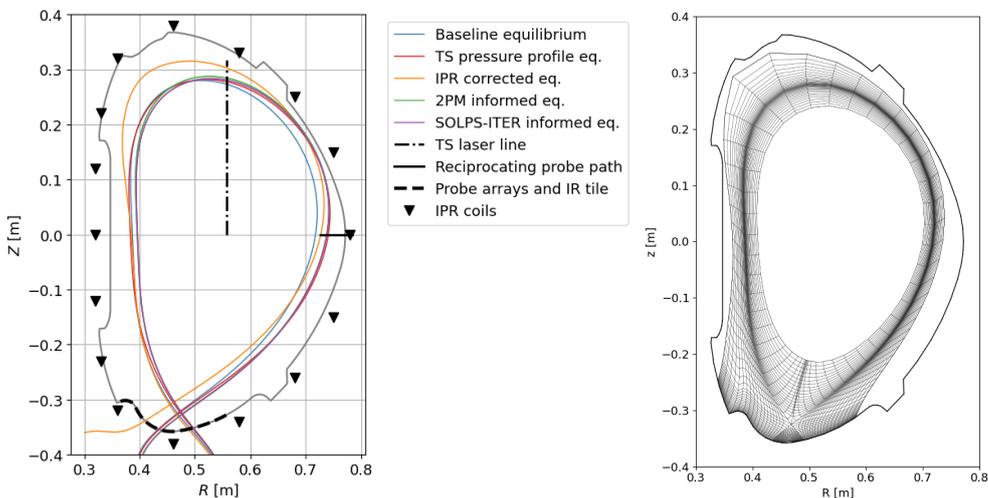


Figure 1: (left) Poloidal cross section showing positions of diagnostics. The colored lines are the positions of the separatrix for the different variants of magnetic equilibrium reconstructions. (right) B2.5 mesh of the baseline case.

3 Equilibrium reconstructions variants

In this study, four distinct EFIT equilibrium reconstructions were used to explore the effect of magnetic equilibrium reconstructions on SOLPS-ITER edge transport simulations, see figure 1. All reconstructions in this study are based on the baseline equilibrium, which uses local magnetic field measurements from 16 inner partial Rogowski (IPR) coils as the principal constraining input. The coils are poloidally distributed around the chamber as seen in figure 1 [9] [17]. The additional variants represent improvements or further constraints to this baseline configuration.

- Baseline reconstruction: This automatically generated equilibrium on COMPASS uses magnetic field measurements from IPR coils as the minimal input for the EFIT code with assumption of parabolic pressure profile [15].
- Realistic pressure profile ($p = 2p_e$): This reconstruction uses electron pressure derived from Thomson scattering measurements. The ion pressure is assumed to be the same, $p = 2p_e$. This total pressure profile is then used in EFIT.
- Corrected IPR coil geometry: This variant incorporates adjustments to the positions and angles of the IPR coils, as described in [9].
- Two-point model for upstream separatrix positioning: Using combined divertor Langmuir probe and ball-pen probe measurements [1], this method applies the two-point model (2PM) to infer upstream electron temperature and find the corresponding upstream separatrix position. The upstream separatrix position is then used as constraint in the equilibrium reconstruction process.

4 Modelling

We use SOLPS-ITER version 3.0.9 for the interpretative simulations of COMPASS discharge #17692. The simulations were run in pure deuterium and in a coupled mode where transport of electrons and deuterium ions was calculated by B2.5 and atomic and molecular deuterium was handled by EIRENE. Drifts were turned off. As the computational meshes of B2.5 and EIRENE are aligned to the magnetic flux surfaces, the meshes were constructed separately for each case. The mesh based on the baseline equilibrium reconstruction is shown in figure 1.

Modelling a tokamak discharge in SOLPS-ITER requires finding the right combination of free parameters, such as boundary conditions and perpendicular transport coefficients, to achieve a match between the simulation and the experiment. The separatrix correction shifts at the outer mid-plane and at the plasma top also act as two additional free parameters and their values are interdependent with the other input parameters. The parameters were varied until a simulation run best matching the diagnostic measurements was obtained.

To control the energy flux entering the simulation domain, we used a core energy flux boundary condition P_{SOL} , with power split equally between electrons and ions.

With the particle pump-down time of about 1 s, COMPASS discharges of ≈ 150 ms are not long enough to establish a particle flux equilibrium between the plasma and the wall. Plasma fuelling was therefore controlled by a virtual gas puff. Although a gas puff was not active in the experiment during the simulated time instance, we used a virtual gas puff localized at the outer midplane as an analogue to the outgassing and higher-than-one particle recycling at the wall. The gas puff was controlled with a feedback mechanism to reach a desired separatrix electron density n_e^{sep} . Neutral particles reaching the core boundary were returned to the computational domain as ions. To maintain particle balance, recycling at the main chamber wall, excluding the targets, was set to 0.9 to act as a particle sink.

Perpendicular transport was controlled by particle density-driven diffusivity D_{\perp} and ion/electron thermal anomalous diffusivities $\chi_i = \chi_e$, respectively. Constant radial profiles of D_{\perp} , χ_i , and χ_e were found to be sufficient to fit the experimental data.

The cells used for extracting radial profiles do not exactly coincide with the locations of diagnostic measurements. This discrepancy arises from the discretization of the B2.5 mesh, see figure 1. To accurately determine the separatrix position from SOLPS-ITER data and obtain the correct profile shapes, the center positions of the closest cells were adjusted by locally mapping them along the magnetic field lines to fully align with the diagnostics spatial coordinate axis. Interpolation of cell values was not necessary as upstream parallel gradients are negligible (with only $\approx 1\%$ difference between neighboring cells).

5 Results

The mesh for the initial match was constructed using the baseline magnetic equilibrium case. Separatrix corrections shifts ΔZ at plasma top and ΔR at

Equilibrium reconstruction	ΔR [mm]	ΔZ [mm]	R [mm]	Z [mm]
Baseline	20	10	738	282
Realistic pressure profile	-3	5	737	282
Corrected coil positioning	10	-20	736	281
2PM informed separatrix	-1	0	737	283
SOLPS informed separatrix	0	3	737	284

Table 1: Radial profile shifts ΔR , ΔZ at the outer mid-plane and plasma top needed to achieve a match with the experiment. Final position of the separatrix R , Z after the correction shifts.

the outer midplane were chosen so that they minimize the mean squared error between the plasma parameter profiles of the simulation and the experiment, taking into account the measurement uncertainties.

The parameters best matching the experimental data for the baseline case are $D_{\perp} = 0.3 \text{ m}^2 \text{ s}^{-1}$, $\chi_{i,e} = 1.2 \text{ m}^2 \text{ s}^{-1}$, $P_{\text{SOL}} = 150 \text{ kW}$, $n_e^{\text{sep}} = 1 \times 10^{19} \text{ m}^{-3}$ (with corresponding gas puff intensity $1.3 \times 10^{20} \text{ s}^{-1}$). The separatrix position corrections are $\Delta R = 20 \text{ mm}$, $\Delta Z = 10 \text{ mm}$, meaning the separatrix was shifted outwards in both cases. Figure 2 shows a good match between the baseline simulation (blue) and the experimental measurements on the plasma top, outer midplane, and divertor.

After acquiring the parameters, we constructed SOLPS-ITER meshes based on the remaining equilibrium reconstruction variants. The simulations were run with the same input parameters for every case. The separatrix correction shifts were found separately for each case by minimizing the mean square error between the simulation and experimental profiles.

Comparison in figure 2 shows only minor differences between the simulation profiles, while the match with the experiment remains good. This shows that the error of the magnetic equilibrium reconstruction does not have a large effect on the SOLPS-ITER simulation results if it is corrected using the profile shifts.

Despite large initial differences between the separatrix positions, optimal radial shifts reduced differences across simulations to within a few millimeters; see table 1. This is an expected result of similar simulation profiles, but has further implications. The consistency suggests that a more realistic separatrix position was found.

The consistent separatrix position in the simulations was used to constrain the position of the separatrix at the two locations in a new EFIT run. The positions in table 1 were averaged to get the two constraint positions, $R = 737 \text{ mm}$, $Z = 282 \text{ mm}$. The resulting equilibrium reconstruction was used to create an additional SOLPS-ITER mesh and simulation.

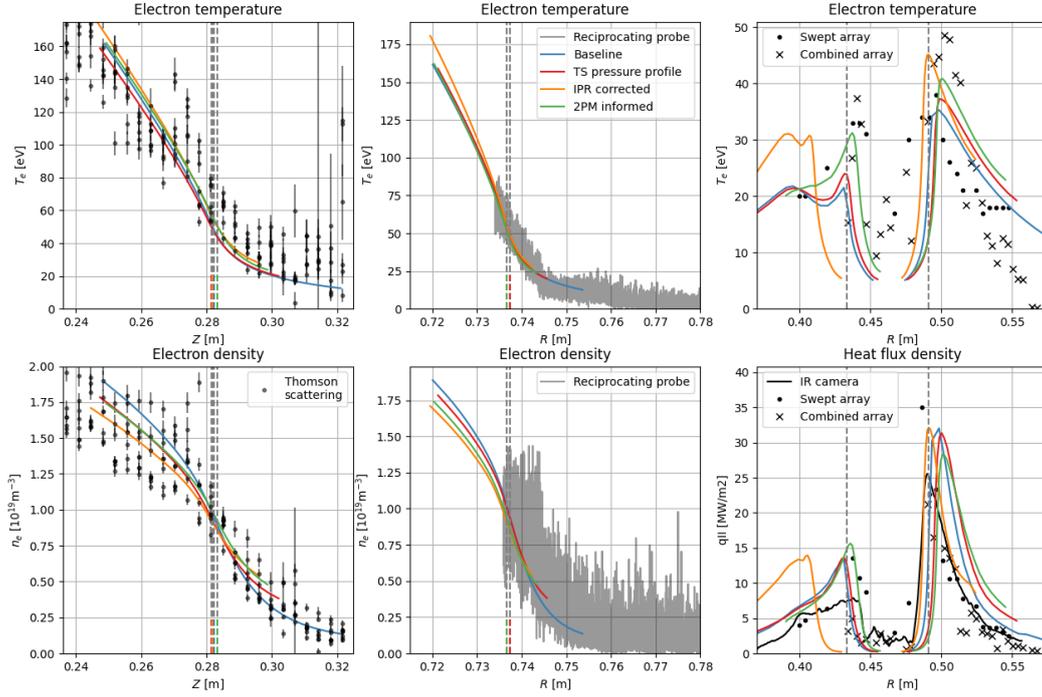


Figure 2: Comparison between SOLPS-ITER simulations and experimental profiles. Left column: plasma top, middle column: outer midplane, right column: divertor. Colored lines represent simulation profiles based on different magnetic equilibrium variants. The dashed lines represent the position of the separatrix.

The SOLPS-ITER simulation required no correction shift at the outer mid-plane and a 3 mm shift at the plasma top. The simulation required minimal corrections and again converged to a similar solution, see figure 3. Thus, we have validated the practice of ad hoc radial profile shifts in interpretative modelling, to our knowledge for the first time. Simulations based on erroneous equilibrium reconstructions but corrected with radial shifts have yielded the same results as a simulation based on an accurate equilibrium reconstruction requiring nearly no radial shifts. This means, with caveats discussed in the following sections, that an erroneous reconstruction is sufficient to perform a high-quality transport simulation, as long as there is enough experimental data to shift the radial profiles.

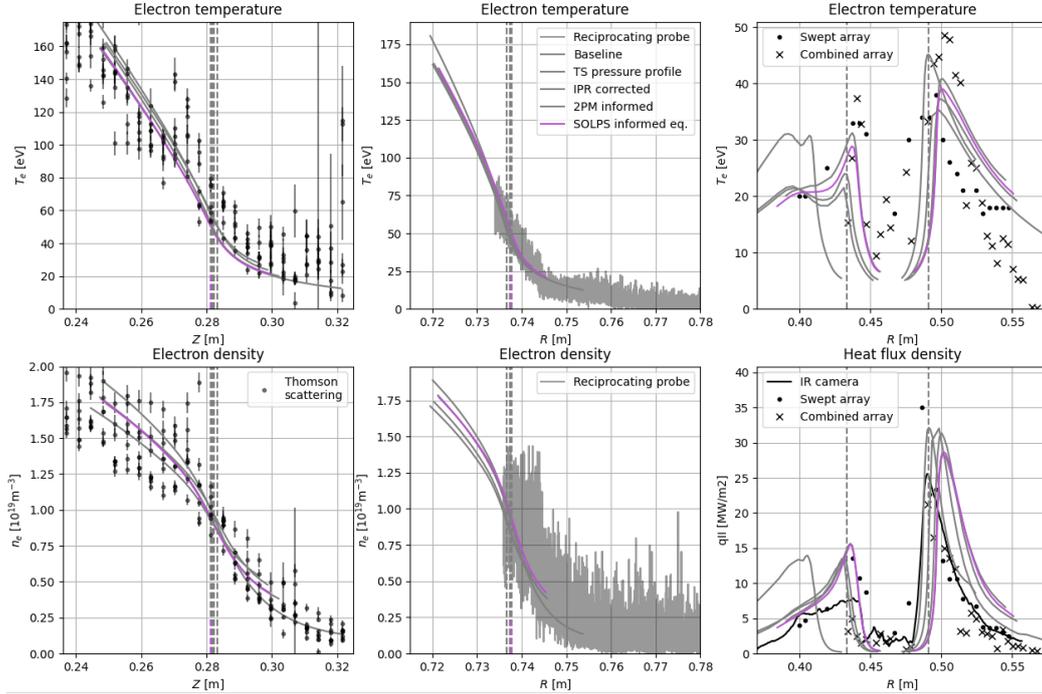


Figure 3: Comparison between SOLPS-ITER simulations and experimental profiles. Left column: plasma top, middle column: outer midplane, right column: divertor. The simulated profiles based on different magnetic equilibrium variants are shown with the simulation based on SOLPS-ITER informed equilibrium being highlighted. The dashed lines represent the position of the separatrix.

6 Discussion and conclusion

This study demonstrates that radial profile shifts are a robust method to compensate for magnetic equilibrium reconstruction errors in interpretative edge plasma modelling. Despite substantial initial separatrix position discrepancies across the four investigated reconstruction variants, applying shifts reduced these differences to within a few millimeters (Table 1). This outcome suggests that aligning simulation profiles with experimental measurements yields a more accurate estimate of the true separatrix position.

The 3 mm shift at the plasma top for the final simulation is due to the Thomson scattering diagnostic having a significant measurement uncertainty in the edge and low spatial resolution. This makes the calculated shift sensitive to small changes in profile shape even when using the uncertainty-weighted least squares algorithm and averaging over multiple flat-top measurements.

An important insight is that the magnitude of the necessary profile shift serves as an indicator of reconstruction quality. Smaller shifts suggest a closer agreement between the reconstructed and actual separatrix positions. In this study, the two-point model reconstruction required the smallest adjustments, implying that the basic two-point model, even without momentum and energy loss factors, can describe the SOL physics on COMPASS accurately.

The results further indicate that SOLPS-ITER simulations are relatively resilient to errors of equilibrium reconstruction, provided appropriate corrections are applied. This robustness simplifies interpretative modelling by ensuring that even suboptimal equilibrium reconstructions can be corrected to provide accurate simulation results. It should be noted that the COMPASS tokamak has a simple, open divertor and the plasma remains in a sheath-limited regime in all simulations. In tokamaks with more complex divertor geometry the reconstructed strike point position and angle may significantly affect the transport regime and therefore the conditions in the SOL. Such cases may be more prone to reconstruction errors.

We establish that radial separatrix shifts can systematically reconcile SOLPS-ITER simulations with diagnostics, constraining the separatrix to within a few millimetres despite initial centimetre-scale discrepancies. This finding underpins the credibility of edge modelling and provides a way to improve the accuracy of magnetic equilibrium reconstructions.

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