Benchmarking DIV1D on SOLPS-ITER simulations of TCV plasmas

G L Derks[1,2,3], J P K W Frankemölle[1,3], J T W Koenders[1,2],

M van Berkel[1], H Reimerdes[4], M Wensing[4], E Westerhof[1]

[1] *DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands*

[2] *Eindhoven University of Technology, Control Systems Technology, Eindhoven, The Netherlands*

[3] *Eindhoven University of Technology, Science and Technology of Nuclear Fusion, Eindhoven, The Netherlands*

[4] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland*

Introduction

In this paper we present DIV1D [1], a new 1D dynamic physics-based model of the divertor plasma that is specifically being developed to study the dynamics of detached plasmas. We benchmark DIV1D on 2D SOLPS-ITER simulations that scan gas puff magnitudes and are based on a TCV plasma equilibrium. The goal of this benchmark is to test if DIV1D can self-consistently match 2D SOLPS-ITER static solutions of TCV plasmas and dynamically transition between these solutions. We present a novel 1D mapping of static 2D SOLPS-ITER divertor plasmas that captures the heat as it flows from a region below the X-point (upstream) to the target plates. The 1D mapped SOLPS-ITER profiles are compared with DIV1D profiles.

The DIV1D model

The DIV1D model is detailed in [1]. The main assumption is that the behavior of the divertor plasma is dominated by the 1D dynamics along the magnetic field lines. In addition the plasma is assumed to be quasi-neutral and the ion and electron fluids are assumed to be strongly coupled resulting in equal ion and electron temperatures. The resulting set of balance equations for the plasma density, momentum, and energy as well as for the neutral density is very similar to equations as implemented by various authors in their 1D codes [2, 3].

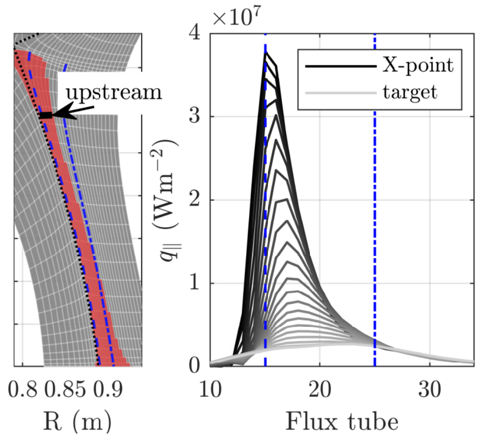

Figure 1: *(left) Poloidal overview of the region where the full width at half the maximum of the heat flux flows in red and two flux tubes in blue. (right) Radial distributions for the heat flux. Profiles change color from X-point in black to the target in lightest gray.*

SOLPS-ITER settings

The SOLPS-ITER code [4] simulations used in this contribution represent a gas puff scan and are based on TCV discharge #62807. The assumptions and settings used in SOLPS-ITER are similar to those in [5] and account for electric currents, drifts and kinetic neutrals.

Mapping SOLPS-ITER solutions to 1D

The single flux tube represents a convenient 1D solution of SOLPS-ITER because the grid is aligned with the magnetic field. However, the plasma profiles in single flux tubes of SOLPS-ITER depend to a great extend on cross-field transport and do not reflect macroscopic plasma behavior in the divertor. This can be seen in Figure 1, where flux tube 15 slightly underestimates the target heat flux while tube 25 clearly underestimates the upstream heat flux. In this work we consider a FWHM heat flux channel in order to map 2D SOLPS-ITER equilibria to 1D profiles. Following the experimental methodology in [6], the FWHM heat flux channel is bounded by the full width of the heat flux distributions at half the maximum values. The cells that roughly cover the full width at half the maximum (FWHM) of the heat flux are selected from the B2.5 grid (see left red area in figure 1), containing approximately 70% of the heat flux. Quantities are averaged on the red area to obtain 1D profiles along the leg while minimum and maximum values provide a distribution interval. The mapped 1D profiles are presented in figure 2.

Settings for DIV1D simulations

The settings for DIV1D are chosen to match the mapped 1D SOLPS profiles as follows: connection length $L = 5$ m, upstream heat flux $q_{\parallel,u} = 22$ MWm^{-2}, carbon fraction $f_C = 3\%$, incident angle $\sin(\theta) = 0.06$ and *effective* flux expansion factor $\varepsilon_f = 2.3$. The recycling coefficient R is set to 99%, equal to SOLPS-ITER. The redistribution factor f_r is not used and set to zero. The neutral exchange time is chosen as $\tau_n = 3$ μs. The upstream density $n_{e,u}$ and neutral

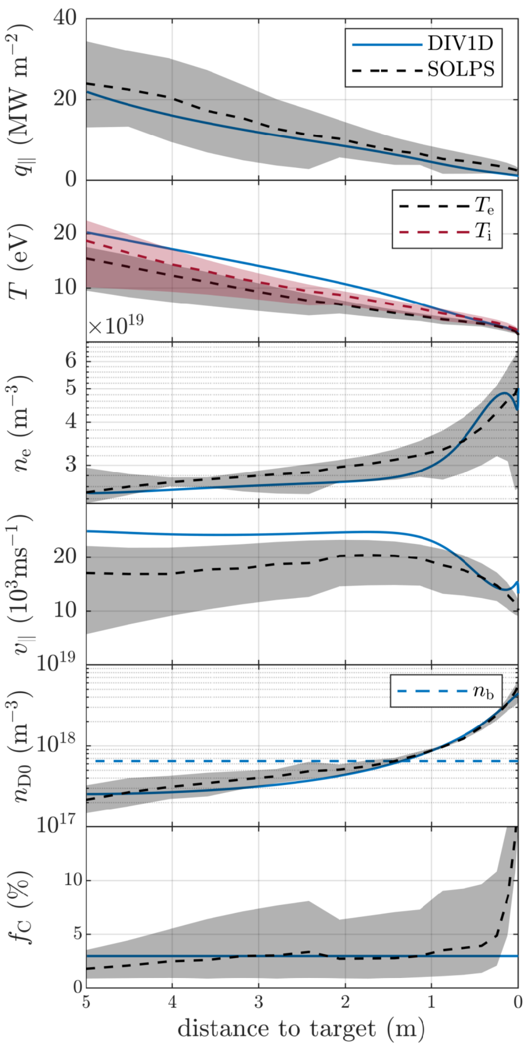

Figure 2: *Comparison of DIV1D with SOLPS-ITER profiles of simulation 150683 showing parallel heat flux $q_{\parallel}$, temperature T, electron density n_e, ion velocity $v_{\parallel}$, neutral density n_{D0}, background density n_b.*

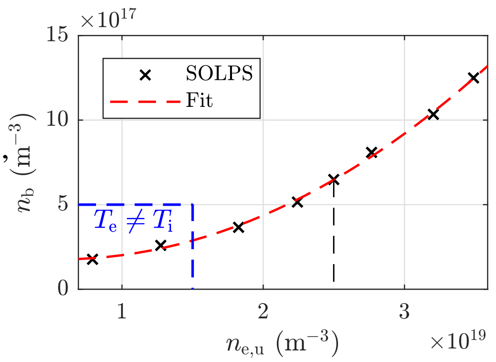

Figure 3: *The background neutral gas density and upstream plasma density extracted from mapped 1D SOLPS-ITER profiles.*

gas background density n_b are not constant but varied as function of 1D mapped SOLPS-ITER simulations, their functional dependence is depicted in figure 3. The two SOLPS-ITER simulations in the blue box are excluded from the comparison because the ion and electron temperatures are discrepant.

Comparing DIV1D and SOLPS-ITER

A simulation of DIV1D with good correspondence to 1D mapped SOLPS-ITER profiles is depicted in figure 2. The simulation has an upstream electron density of $2.5 \cdot 10^{19}$ m^{-3} and corresponds to the dashed black vertical line in figure 3. From the profiles in figure 2 it can be seen that the profiles of DIV1D for the parallel heat flux $q_{\parallel}$, electron density n_e, and neutral density n_{D0} are close to the averaged SOLPS-ITER profiles and within the shaded areas. The temperature profile of DIV1D is very similar to SOLPS-ITER but a few eV higher around a distance of two to three meters to the target. The velocity profile of DIV1D is higher than for SOLPS-ITER. Following analysis in , we compared with SOLPS-ITER simulation 150684 without drifts and found that the discrepancy reduces as the radial electric field no longer exerts a force on the ions towards the X-point. The remaining discrepancy might be due to ExB drifts or to the particle balance in DIV1D, indicating that more ions are lost in the divertor compared to SOLPS. These observations and discrepancies are similar across simulations with upstream densities in the range of $n_{e,u} = 1.8 - 2.8 \cdot 10^{19}$ m^{-3}. Next we present solutions of DIV1D and 1D mapped SOLPS-ITER as function of upstream and background density. The target ion flux is visible in figure 4, where it can be seen that the target flux of DIV1D lies within the interval of the 1D mapped SOLPS-ITER profiles and does not produce a roll-over with upstream density that was observed in experiments [5].

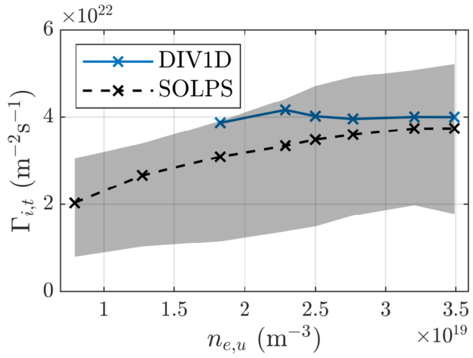

Figure 4: *Comparison of DIV1D and SOLPS-ITER for the target ion flux against upstream densities.*

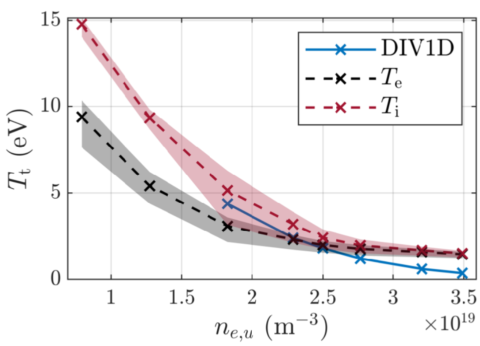

Figure 5: *Comparison of the target temperature for DIV1D and 1D mapped SOLPS-ITER simulations at various upstream densities.*

The target temperature is visible in figure 5 and shows that DIV1D follows the trend in ion temperature of SOLPS-ITER for $n_{e,u} = 1.8 - 2.8 \cdot 10^{19}$ m^{-3} and drops below at higher upstream densities. Finally, the momentum and power loss fractions are compared and calculated without volumetric integration using $f^{wovi}_{mom} = 1 - p_{tot,t}/p_{tot,u}$, $f^{wovi}_{pwr} = 1 - \varepsilon_f q_{\parallel,t}/q_{\parallel,u}$, with $p_{tot,u/t}$ the total target and upstream pressure, ε_f the effective flux expansion (taken as $\varepsilon_f = 2.3$ for presented power loss fractions) and $q_{\parallel,u}$ the upstream heat flux [7]. The target heat flux is calculated as $q_{\parallel,t} = T_{e,t}\Gamma_{\parallel,t}e\gamma$, where $T_{e,t}$ is the target temperature, e the electron charge, γ the heat transmission factor, and $\Gamma_{\parallel,t}$ the target ion flux parallel to the field magnetic field [7]. The ion flux is directly obtained from simulation data.

The power and momentum loss fractions are depicted in figure 6. There is a monotonic increase with upstream density in loss fractions for both DIV1D and SOLPS. The discrepancy in power losses might be a result of simplified carbon radiation functions [8], but could also result from the omission of plasma molecule interactions [9]. The larger momentum losses in DIV1D could be attributed to the omission of momentum conservation for the neutral population, losing all momentum from the plasma in charge-exchange collisions [3, 8].

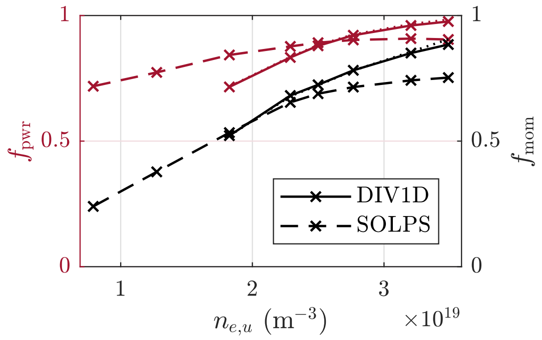

Figure 6: *Comparison of power and momentum loss fractions for DIV1D and 1D mapped SOLPS-ITER simulations at various upstream electron densities.*

Conclusions

The 2D equilibria of SOLPS-ITER were mapped to 1D by averaging over the full width at half the maximum of the heat flux distributions. It was shown that DIV1D reasonably agrees with SOLPS-ITER and can self-consistently transition between multiple solutions.

Acknowledgments 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.

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