Impact of transport models on local measurements in W7-X using synthetic diagnostics with EMC3-EIRENE and comparison to experimental observations in the W7-X island scrape-off layer

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19 January 2022

Abstract. Modelling the scrape-off layer of a stellarator is challenging due to the complex magnetic 3D geometry. The here presented study analyses simulations of the scrape-off layer (SOL) of the stellarator Wendelstein 7-X (W7-X) using the EMC3-EIRENE code for the magnetic standard configuration. Comparing with experimental observations, the transport model is validated. Based on the experimentally observed strike line width, the anomalous transport coefficients, used as input to the code are determined to around 0.2 m\textsuperscript{2}/s. This is however in disagreement with upstream measurements, where such small cross-field transport leads to temperatures higher than measured experimentally. Agreement can be improved by using spatially varying transport coefficients. Various differences remain, even with spatially varying transport coefficients. The future implementation of drifts into the transport model are expected to help overcome the discrepancies, and thus the development of SOL transport models including drifts is a necessary next step to study the SOL transport of the W7-X stellarator.

1. Introduction

In order to operate fusion power plants based on the magnetic confinement concept the power flux on the plasma-facing surfaces needs to be controlled to prevent the overloading of the structures. Predictive modelling, necessary for design of next-step fusion devices, requires successful validation via comparison to existing experimental devices to ensure all important underlying physics is included in the code. One of these devices is Wendelstein 7-X (W7-X), an advanced stellarator with reduced neoclassical transport [1–4], which had its first divertor operational campaign in 2017 - 2018.

In contrast to tokamaks, the scrape-off layer (SOL) of W7-X is inherently three dimensional. W7-X features a 5-fold toroidal symmetry. Each of the 5 modules is in itself stellarator symmetric and can be split into two half modules. The SOL of W7-X features an island divertor, where in the standard configuration the 5 resonant islands are intersected by 10 divertor modules [5–7]. A plot of the islands and the intersection with the divertor is shown in fig. 1. The upper halves of the modules have...
even numbers, namely 18, 28, 38, 48, 58, and the lower half-modules have uneven numbers, 19 to 59. The half-modules $x8$ and $x9$ are in the $x$-th module. The divertors carry the numbers of the respective half-modules they are located within.

The lack of toroidal symmetry makes connection and comparison of experimental measurements at different toroidal locations extremely complex. As such, there is great demand for 3D modelling, where synthetic diagnostics can be implemented to help understand whether differing diagnostic measurements are truly in disagreement or if differences are due purely to spatial variations in the plasma. However, before such an analysis can be performed, it is critical to first validate the simulations, which itself requires diagnostic input covering as much of the SOL plasma domain as possible.

The anomalous cross-field transport in the SOL of fusion plasmas is often considered to be dominated by turbulence. In W7-X experiments, SOL turbulence and turbulent transport has been observed [8–11]. As fully turbulent simulations of the full SOL are computationally extremely challenging, simpler models are generally used, such as fluid transport codes [12]. There the turbulence is effectively represented by anomalous diffusion coefficients. The simplest diffusion model features a spatially constant diffusion coefficient. Spatially varying diffusion coefficients give significantly more freedom in matching data and have been used in tokamak simulations in the past [13–15]. However, finding appropriate distributions of the diffusion coefficient is challenging due to the large parameter space. To limit the parameter space, the coefficients can for example be motivated by experimental observations, theoretical predictions or turbulence simulations [15]. Even for non-local transport, for example the case where the transport is caused by filaments, the transport can be modelled as diffusive, using the appropriate diffusion coefficients [16]. As such diffusion coefficients can emulate hidden physics, and thus allow analysis of experimental data. In order to gain predictive capabilities, the underlying physics need to be understood, to predict the diffusion coefficients [8, 9, 17].

This work validates the diffusion-based anomalous transport of EMC3-EIRENE
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2. Method

2.1. W7-X diagnostics

In this work, two diagnostics are used for comparison to simulation data: one is located downstream at the divertor targets and the other upstream. Both downstream and upstream parameter comparisons are important to determine if the EMC3-EIRENE simulations successfully reproduce features across the entire SOL. The downstream measurement used is the infra-red (IR) camera system [20], which fully covered the area of 9 out of 10 divertors in the previous experimental campaign.

The temperature is derived from the spatial distribution of the IR radiation. The heat-flux is calculated by the evolution of the temperature profiles using the two-dimensional thermal model THEODOR [21]. This heat-flux is used to assess the validity of the employed SOL transport model in EMC3-EIRENE as the heat-flux in the absence of drifts in the model [18, 19] by using both spatially constant and spatially varying transport coefficients with experimental data from W7-X from the infra-red heat flux diagnostic and the reciprocating electric probes. This work extends previous work using constant diffusion coefficients and especially addresses remaining discrepancies between simulations and experiments. The here presented analysis is restricted to the magnetic standard configuration.

The current paper is organized as follows: Section 2 the newly developed methods for comparing the heat-fluxes from experiments and simulations is presented. Additionally the spatially non-constant diffusion profiles are introduced and motivated. In section 3 the experimental data is presented, where the toroidal power distribution and the strike line width is seen. In the following section, the simulations are presented. Section 5 summarises and discusses the results, here it is seen that a spatially constant diffusion coefficient cannot simultaneously match downstream and upstream conditions in the selected magnetic configuration. The main conclusions are presented in the final section.
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Figure 3: Mapped view of the target. Highlighted are some fingers with their finger ID, that are also shown in fig. 2. The coordinates map_x and map_y are not directly related to physical quantities. map_x is roughly aligned with the magnetic field, while map_y is roughly orthogonal to the magnetic field. The pumping gap is around map_y ≈ 125. In the top right is an inset of fig. 2.

Figure 4: Position of the MPM diagnostic. Reproduced with kind permission from [23].

has a high spatial resolution. The spatial resolution is around 3 mm the noise level is around 0.25 MW/m².

The second diagnostic used for comparison is the multi-purpose manipulator (MPM). The MPM can be equipped with different probe heads to provide profiles of various plasma parameters such as $T_e$, $n_e$, poloidal mash number, etc [22, 23].

In the here presented analysis, the MPM was equipped with Langmuir probes, that have been used to measure the electron density and temperature in the SOL of W7-X. This provides plasma parameters upstream and thus complements the downstream comparison provided by the heat-flux measurements at the divertor.
Unlike the infra-red diagnostic the MPM is only present in one location, thus does not give a direct measurement of up-down asymmetries [7] or field errors [24]. The path of the MPM is shown in fig. 4.

2.2. Heat-Flux distribution analysis

The strike-line width and amplitude is used in order to make the heat-flux profiles more comparable between modelling and experiments. The IR data is mapped onto the image format as shown in fig. 3. The divertor is split into smaller structures, called fingers, that extend mostly in poloidal direction. Some of the fingers are highlighted in fig. 3. 1D slices of the data are analysed, taking slices roughly perpendicular to the magnetic field lines, in the map_y direction from fig. 3. These 1D slices are then fitted to a function consisting of a constant background plus 2 Gaussian functions. The positions of the peaks are constrained to be within the data slice. The lower bounds for the peak is 3 times the grid spacing, to avoid fitting a single outlier, rather than the general shape of the data. For fitting the Trust Region Reflective algorithm (trf) from scipy.optimize.least_squares is used [25,26].

In order to decrease the computational cost as well as to decrease the impact of noise, 10 time frames are averaged for fitting. This gives a time resolution of 100 ms. The study is restricted to steady-state profiles as the EMC3-EIRENE code only provides steady-state solutions. Although the evolution of the toroidal plasma current throughout the discharge may change the location and width of the strike line, the movement is on the order of mm/s and does not significantly impact the result over a 100 ms time window [27].

For each averaged time slice, each pixel row of each finger is separately analysed. One should note, that for one map_x value there can be several data slices, as the low iota target and the vertical target are treated separately. Similarly, in the middle target, the data is split into two fingers, one close to the gap, and one further away. If the peak heat-flux is below the noise-level of 0.25 MW/m^2, no fit is attempted.

Examples of the fitted data are shown in fig 5 and fig. 6 for the low iota target and vertical target. Especially on the low iota target the fit is generally good. On the middle target, especially for the fingers distant from the pumping gap, the heat-flux is very low, and heat-fluxes above the 0.25 MW/m^2 limit are typically a single spike due to noise, giving a strike-line width of the lower bound $\leq 1$ cm. A problematic fit is shown in fig. 15 that will be discussed later.

On the vertical target, shown in fig. 6 the second structure at position 0.1 m is due to reflections, but as the the analysis is mostly concerned about the more narrow, higher peak, the reflection does not affect our analysis.

Fig. 7 shows on the left the connection length of some regions of the target regions. Regions of very long connection length $> 1000$ m indicate the location of the main strike line formed by the intersection of the island on the divertor target plates. It can be seen the main strike line is on the low iota target. Additionally, also on the vertical target long connection lengths are observed.

2.3. EMC3-EIRENE

EMC3-EIRENE is a Monte Carlo fluid transport and kinetic neutral code, that is capable of handling complex geometries, such as that commonly encountered in the SOL of stellarators. It has already been used in the past to model the edge.
Figure 5: Plot of the IR data for the low iota target and \texttt{map\_x=325}. It can be seen that the data consists of a narrow, high in amplitude peak, as well as a broader feature with a significantly smaller amplitude. The fitted background is in this case negligible.

Figure 6: Plot of the IR data for the vertical target and \texttt{map\_x=325}. The fit detects the main peak and the wide peak combined with the "Background" fits the background as well the reflection at 0.1 m.
Figure 7: Shown on the left is a plot of the connection length mapped on to the target. In grey shown is the target regions where no traced field line ended. On the right is a plot of the heat-flux on the divertor at $t = t_1 + 3.3$ s for shot #20180920.009. The main strike line is on the low iota target, roughly in agreement with the long connection lengths. Additional heat loads on the high iota target as well as the vertical target are visible.

of W7-X [12, 19]. While EMC3-EIRENE does captures some of the observations in experiments, especially global trends [12, 19], there is still disagreement in local parameters [28].

EMC3-EIRENE does include parallel transport in the form of advection as well as viscosity and parallel heat diffusivity. Perpendicular transport included in EMC3-EIRENE features anomalous diffusion based on some given particle and heat diffusion coefficients, that can be spatially varying [14, 18]. EMC3-EIRENE does not require nested flux-surfaces and is only aware of the local magnetic geometry. For this reason the perpendicular diffusion is uniform in radial and bi-normal direction, i.e. $D \propto I - \hat{b} \hat{b}$ with $\hat{b}$ the unit vector in the direction of the magnetic field and $I$ the identity matrix. Drifts, like the $E \times B$ drift, are not included in EMC3-EIRENE.

An analysis analogous to the one described in sec. 2.2 can be applied to simulated heat-flux data generated by EMC3-EIRENE. Thus, a direct comparison between experiment and modelling is performed. This allows to quantify the discrepancies and validate the modelling and the assumptions, for example the transport models, with experimental data.

2.4. Spatially varying diffusion

The here presented simulations use spatially varying diffusion coefficients, which is implemented in EMC3-EIRENE as discussed in sec. 2.3. In addition to scenario A: constant diffusion, two different spatial variation patterns were implemented in this work. Scenario B motivated by experimental observations and scenario C motivated by turbulence models. Scenario B is shown in fig. 8. In this scenario the transport is suppressed at the separatrix and enhanced towards the island centres. The distribution is motivated by experimental observations, as the narrow strike line requires a low transport coefficient at the separatrix, but for agreement with other diagnostics, such as the MPM, a larger transport coefficient is required [19]. Thus combining a small perpendicular transport value at the separatrix and a larger towards the centre of the island can satisfy both conditions. Fig. 8 on the right shows the coefficients at $z = 0$. The variation along the toroidal direction $\varphi$ is due to the poloidal contribution of the magnetic field, as the variation of $D$ is aligned with the magnetic field.
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Figure 8: Plot of scenario B: diffusion based on experimental data featuring radial-poloidal variation. On the left is a cut at $\phi = 0$, on the right top at $z = 0$ and on the right bottom $\phi = \pi/5 = 36^\circ$. The diffusion is set to $D = 1 \text{ m}^2/\text{s}$ in the core region for numerical stabilities of the boundary conditions. Further outside a background of $D = 0.1 \text{ m}^2/\text{s}$ is used, and enhanced towards the centre of the islands.

An alternative transport coefficient distribution, scenario C, motivated by turbulent transport drivers is shown in fig. 9. In this scenario the transport is enhanced in the outer bean shape, where a Gaussian perturbation has been added to $D$. The outer bean shape features the largest values of bad curvature, which is a significant driver for turbulent transport in the SOL [8, 29]. Thus this set of simulations mimics in a naive way the effect of turbulent transport and probes the impact of toroidally localized power flux into the SOL. The toroidal grid resolution can be seen in the radial outer guard cells, with $\Delta \phi = \frac{\pi}{180} = 1^\circ$. Further inward several cells contain a single value to reduce the computational cost, while retaining accurate results as the parallel variation, except close to targets, is small.

In all cases the heat diffusion coefficient $\chi$ is set to $\chi = 3 \cdot D$, i.e. scaled with the diffusion coefficient. Note that the resulting transport $q_\perp \propto n\chi$, i.e. has a density dependence even for constant $\chi$. Note that these scenarios are not intended to model the SOL of W7-X in a realistic way, but rather to measure the impact of the changes onto the synthetic diagnostics and if they can improve agreement, and what aspects are changed or not changed. A further question is whether the different transport models can be distinguished by the synthetic diagnostics. In addition, quantitative metrics are established for future studies.
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Figure 9: Plot of scenario C: diffusion based on turbulence metrics featuring a poloidal-toroidal variation. On the left is a cut at $\varphi = 0$, on the right top at $z = 0$ and on the right bottom $\varphi = \pi/5 = 36^\circ$. The diffusion is enhanced in the core region for numerical stabilities of the boundary conditions. Further outside a background of $D = 0.1 \text{m}^2/\text{s}$ is used and enhanced in the outer bean shape.

2.5. xemc3

The majority of the analysis has been carried out using the xarray framework [30,31]. For that the xemc3 [32] library has been implemented that reads the output of the EMC3-EIRENE routine into the xarray format. An extensive documentation, including documentation and online tutorials, is available online ‡.

3. Experimental data

For this analysis the W7-X experiments #20180920.009, #20180920.013 and #20180920.017 have been analysed. They are part of a density scan with an input power of 4.7 MW ECRH. They have been selected due to the low radiation fraction $f_{\text{rad}}$ of around 0.15…0.35. Low $f_{\text{rad}}$ avoids large effects of power dissipation in the volume. Thus transport is prominent and easier to study. The heat-flux on the divertor measured by IR was 3…4 MW, shown in fig. 10, with the time-averaged power per target between 330 kW and 496 kW. The peaks in the time evolution, shown in fig. 10, are due to CH$_4$ puffs and fuelling. The magnetic configuration used was the standard configuration. The toroidal plasma current increased over time and reached $\approx 5 \text{kA}$ after around 6 seconds towards the end of the discharge, with the exception of

‡ https://xemc3.readthedocs.io/
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Figure 10: Overview of the time evolution of the radiated power $P_{rad}$, the ECRH heating power, the power on the target measured by IR, the line integrated density $\int n_e$, the toroidal plasma current $I_{tor}$ and the strike line position from #20180920.009 on finger 24. For the target modules where no IR data was available, the average from the other targets was used to extrapolate to the total target power.

#20180920.017, where the maximal bootstrap current was around 2.5 kA. The SOL of W7-X is sensitive to plasma currents and the toroidal plasma current impacts the heat deposition [33–35]. For the current analysis, the strike-line width is not significantly impacted by the toroidal current, but the strike-line position is a function of plasma current [27], as shown in fig. 10.

The line integrated density was $4 \times 10^{19} \text{m}^{-2}$ to $8 \times 10^{19} \text{m}^{-2}$. These low to medium density cases were selected as they feature a low radiative fraction. This allows to focus on the heat transport effect on the target heat load distribution, reducing the additional impact of radiation, simplifying the required physics to model the dynamics and reducing the system complexity as $P_{rad}$ is a strong function of the electron temperature $T_e$. As the heat-flux is proportional to the density $q_\perp \propto n\chi$, a density scan was chosen for this study. The simulations do not feature the same densities, as in the simulations the separatrix density was set, while in the experiment the separatrix density is not well known. On the other hand the line integrated density is not known in the simulations, as the core region is not modelled.

Fig. 7 (right) shows an example of the spatial distribution of the target heat-flux in the projection described in fig. 3. Only the strike line on the low iota target is expected
Figure 11: Plot of the time averaged power per finger for the steady-state phase of #20180920.009. The error bars denote the standard deviation of the time evolution. The fingers are introduced in fig. 2 and fig. 3. Note that the alternating structure in the middle target is caused by the numbering, even numbers are close to the pumping gap, while the odd numbers are further away. The different half modules are shown separately. No data from half-module 58 is available.

from simple field line tracing. The load on the vertical target can be explained by field line tracing in the reverse direction, while other loads are only possible due to cross-field transport.

3.1. Toroidal distribution

Fig. 11 shows a plot of the toroidal distribution of the heat-flux, by showing the mean power on the respective fingers, as introduced in fig. 2 and fig. 3.

No strong variation for the different half modules is observed, only half-module 28 shows an increased heat-flux in the near end of the low iota target (around finger 20), as well as on the vertical target (around finger 120). For the lower divertors, most variation is observed at the far end of the low iota target (around finger 4) where module 59 shows an increased heat load and module 49 shows a decreased heat load. These variations might be explained by field errors [24]. The calibration of the absolute values of the IR diagnostic was incomplete in OP 1.2b. This limits the reliability of comparisons between the different IR cameras and thus between the different half modules. The simulations assume stellarator symmetry and therefore only one half-module is modelled. They are inherently up-down symmetric and no variation between different modules is included. For these reasons the following analysis will focus on averages of the different modules.

Fig. 12 shows the experimental power per finger that was measured in the steady state part of a density scan for the upper divertors (top) and the lower divertors (middle). In general, a decreasing trend of power on the target with increasing density is observed, which is expected in the experiments as with increasing density the radiation increases, and thus the target heat load is reduced. An exception to
Figure 12: Plot of the time and module averaged power per finger for the steady-state phase of #20180920.009, #20180920.013 and #20180920.017 on top for the upper divertors and in the middle for the lower divertors. On the bottom are results from EMC3-EIRENE simulations with $D = 0.2 \text{m}^2/\text{s}$ discussed in sec. 4. The error bars denote the standard deviation of the time evolution and inter module variation. See fig. 11 for further description. As the simulations don’t have a time component, only the experimental data has the error bars. The $P_{\text{rad}}$ for the simulations was 1 MW and for the experiments 0.68 MW to 1.7 MW, see fig. 10. The power on the divertor was 329 kW, 306 kW and 254 kW for the $n_{\text{e,sep}} = 1 \cdot 10^{19} \text{m}^{-3}$, $n_{\text{e,sep}} = 3 \cdot 10^{19} \text{m}^{-3}$ and $n_{\text{e,sep}} = 10 \cdot 10^{19} \text{m}^{-3}$ case respective. Note that simulations and experiments do not match in density, as for the experiments the separatrix density is not well known, and for the simulations, due to the lack of core profiles, the line integrated density is not known.

the decreasing trend is the load at the near end of the high iota target (around finger 80). The increased heat flux at this shadowed area is in agreement with an increased transport with increasing density. Consequently the load on the middle target is increased, at least on the upper divertors. At low densities the main heat load on the low iota target is mainly at the far end (finger $\approx 5$) and less pronounced on the near end (finger $\approx 25$). With increasing density the ratio of power on the far end and on the near end is reduced, suggesting an increased transport channel or a decrease in the losses from the transport channel to the near end of the low iota target. Especially on the upper divertors, this results in an increased heatflux on the near end of the low iota target. At the same time the heatflux at the far end decreases. Note that, as can be seen on fig. 7, the far end is shadowed while the near end is directly connected. As such this is in contrast to the expected behaviour.

Simulations from scenario A with $D = 0.2 \text{m}^2/\text{s}$, shown in the bottom plot in fig. 12, do not see the same trends with density. Here the peak of the mean power appears on the near end of the low iota target at low density, while the far end of the low iota target generally sees lower power. As the separatrix density is increased, the mean power at the near end of the low iota target decreases, while the power at the far end increases slightly. This implies a missing transport channel in the simulations, which will be discussed further in sec. 4.
3.2. Strike-line

For the data shown in fig. 12 the strike-line has been analysed using the method discussed in sec. 2.4. Each module and time-slice has been analysed separately, to not broaden the strike line by averaging strike-lines at different positions due to the strike-line movement during the plasma discharge and e.g. camera misalignment and field errors [24] for different half modules.

The narrow feature identified is expected to be due to parallel plasma flow to the target. It is not yet clear what is causing the broad feature.

By integrating over the Gauss of the narrow feature, the power of the main strike line can be calculated. Fig. 13 shows the power observed in the narrow feature compared to the total observed power. Roughly 50\% of the power on the divertor is in the main strike line.

Fig. 14 shows the average of the width of the fitted narrow peak for the low and medium density cases #20180920.009 and #20180920.013. The average was calculated by taking for each finger the fits from all 1D slices, multiplying the fitted width in each slice with the power measured in that slice, and dividing the sum by the sum of power. It can be seen that the strike-line width is in the range of 2 cm to 4 cm.

Both density cases show a similar behaviour in their strike-width pattern on the upper and lower divertor target plates. Starting from the far end of the low iota target (fingers 0-2), both the upper and lower divertor targets see comparable strike line widths and heat flux magnitudes. For the remainder of the far end of the low iota target, on the lower divertor a narrow strike line is measured for the region of the high heat-flux, that stays constant towards the near end of the low iota target, where the power flux is reduced, while on the upper target the strike-line is broader at the far end, end gets more narrow towards the near end of the low iota target.

The strike-line width on the vertical target is comparable on the upper and lower divertors, at least for the points with significant power flux. The vertical targets of the upper and lower divertors mainly differ in their magnitude of the heat flux, as shown in fig. 12. The width on the high iota target is slightly wider on the lower divertor, however they are still the same within the standard deviation.

For the highest density case #20180920.017, the average strike line widths (not shown) across the divertor target could not be computed. Small-scale structures in the strike-line pattern keep the fits from converging reliably, with an example shown in fig. 15. The cause of these structures is not yet known. The small scale structures seem to be fixed in space, while the main strike line moves in time. As such it seems unlikely that the heat-flux of the plasma onto the target does contain such small-scale structures. It is currently hypothesized that these structures are caused by artefacts.
Figure 14: Plot of the time and module strike-line width per finger for the steady-state phase of #20180920.009 and #20180920.013. On the left hand side is the strike-line width for the upper divertor and on the right hand side for lower divertor. The points denote the average of the strike-line width for all fits, weighted by power, and the error-bars denote the standard deviation also weighted by power. Shown is the narrow strike-line, that has been identified by fitting. In addition, the average power on the finger is colour-coded. Only finger with at least 1 kW average power are shown. The grey lines show estimates for #20180920.009 for upper and lower divertors, that will later be used for comparison to simulations. The large variation in the lower target on the vertical target is due to significant variation in the time traces for some of the fingers.

Figure 15: Plot of the IR data for the low iota target and map_x=325. For #20180920.017 unlike fig. 5 for #20180920.009. Additional, smaller structures in the fit prevent the expected convergence of the fit, and the narrow peak is actually a smaller perturbation of the true main peak.
Figure 16: Poloidal position of the strike-line for the different slices, time averaged between 1 and 2 seconds. The different divertors are colour-coded based on the vertical position of the divertor, i.e. upper versus lower divertor. Note that the strike line position is not plotted as a function of time, but rather as a function of the finger number. Thus the jump around finger 15 is due to the definition of the local coordinate system. Also shown is the position of the long connection length from fig. 7 (left). Note that a deviation is expected due to the finite toroidal current, as shown in fig. 10.

4. Simulations

The scrape-off layer of W7-X has been modelled using EMC3-EIRENE. For this the upstream density was scanned. The simulation relies on the stellarator symmetry of W7-X, and therefore only one half-module is modelled. Ideal coils are used and thus no error field effects are included. Drifts are not included as they are not yet implemented in the code.

The input heating power within the simulation domain (one half-module) was set to be 470 kW, leading to a total of 4.7 MW for the whole device. The power was distributed evenly between ions and electrons, and enters the domain at the core boundary. The observed power on the divertor is up to 352 kW - giving a total power of $\approx 3.5$ MW on all divertors. The upstream density was set to be fixed $n_{e,sep} = 1 \ldots 10 \cdot 10^{19} \text{ m}^{-3}$. The cases $n_{e,sep} = 1 \cdot 10^{19} \text{ m}^{-3}$ and $n_{e,sep} = 3 \cdot 10^{19} \text{ m}^{-3}$ are roughly in the range of the experiments, while $n_{e,sep} = 10 \cdot 10^{19} \text{ m}^{-3}$ is a purely hypothetical case, as for such high densities the radiation fraction would be much higher. No pumping and fuelling is included in the simulations, and therefore particle balance is achieved via scaling the recycling flux to the amount needed for the fixed upstream density value. The radiation was fixed to 1 MW, achieved via carbon

in the IR diagnostic. For example surface layers could modulate the radiation. Future work includes understanding the origin of these structures as well as extending the current fitting mechanism to be more tolerant of these modulations, such that reliable results of the strike line features can still be obtained even with their presence.

Fig. 16 shows the poloidal position of the strike-line for the low iota target. For the two lower-density cases, shown in fig. 14, lower divertors tend to have the strike line located somewhat closer to the pumping gap as compared with the upper divertors.
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Figure 17: Density (top) and electron temperature (bottom) profiles for the \( n_{e,sep} = 1 \cdot 10^{19} \text{ m}^{-3} \) case with \( D = 0.2 \text{ m}^2/\text{s} \) at the bean shape, at \( \varphi = 0 \) (left) and the triangular shape, at \( \varphi = \pi/5 = 36^\circ \) (right).

impurity radiation, giving a radiation fraction \( \approx 21\% \). While in the experiment the radiation fraction varies from 0.15 to 0.35, this was done to study the density and diffusion coefficient rather than the influence of the radiation fraction, which was recently studied by Feng et al. [19]. In particular the low \( f_{\text{rad}} \) was selected to avoid a dominant effect of the radiation.

The same magnetic field configuration was used in simulation as in experiment: the standard magnetic field configuration. For each diffusion coefficient set-up described in sec. 2.3, a scan in density and magnitude of diffusion was performed. EMC3-EIRENE stores where and how many particles leave the plasma domain. These particles can then be mapped onto the target surfaces in a post-processing step. In a next step the data has been mapped to the representation introduced in fig. 3. From this step on the same analysis, described in sec. 2.2, has been used for the simulated data as for the experimental data.

Fig. 17 shows plots of the electron density and temperature distribution of a
Figure 18: Plot of the power per finger for simulations with different separatrix density and different diffusion coefficient. This plot extends the density scan in fig. 12 with a scan of the diffusion coefficient \( D \), with the heat diffusivity \( \chi = 3D \) and \( q_\perp \propto n_\chi \). The dotted results contain numerical issues as discussed.

Simulation, where the diffusion coefficient was spatially constant at \( D = 0.2 \text{ m}^2/\text{s} \) and the upstream density was set to \( n_{e, \text{sep}} = 1 \cdot 10^{19} \text{ m}^{-3} \). The density shows a peak just in front of the target, at toroidal angle \( \varphi = 0 \) at the upper and lower target plates. At the triangular shape (\( \varphi = \pi/5 = 36^\circ \)) no target plates are present and thus also the density is not strongly peaked in the SOL. The temperature drops of towards the target. While in this case the electron temperature at the separatrix is around 160 eV, the separatrix electron temperature is in all cases below 200 eV. Experimentally, separatrix electron temperatures were generally between 30 and 100 eV.

Similar to the experimental result, shown in fig. 7 (right), the main heat-flux is on the low iota target, with a strike line width and location similar to the experimental one. The main difference is that the main power is on the near end of the low iota target, while in the experimental figure the main heat-flux is on the far end of the low iota target.

4.1. Toroidal distribution

The toroidal distribution of the heat-flux, and how the change of the spatially constant diffusion parameter impacts it is shown in fig. 18.

For the non-constant diffusion coefficients the toroidal power distribution for each density level is shown in fig. 19 and fig. 20. The general trends are similar to the spatially constant diffusion case. For the low diffusion coefficients, with increasing density less power is deposited on the low iota target, and more on the high iota.
target. The power on the low iota target is for low density and low diffusion coefficients mostly at the near end, around finger 25, and only with higher density and diffusion a more flat distribution on the low iota target is observed. Peaking at the far end, as in experiments is in general not observed in the simulations.

4.2. Strike-line

Besides the question where the power is deposited, the width of the strike line is of interest, as that influences over what area the heat is distributed, and thus also the peak heat-flux that the divertor has to withstand. Besides this more practical question, the strike line width gives also insight into the transport. Fig. 21 shows the fitted strike line width for a separatrix density $n_{e,sep} = 1 \cdot 10^{19} \text{m}^{-3}$ with a diffusion coefficient scan in the range $D = 0.1 \ldots 0.5 \text{m}^2/\text{s}$ for scenario A: constant diffusion. As mentioned, $\chi$ is scaled as $3D$. The strike line width for the other two density cases of interest $n_{e,sep} = 3 \cdot 10^{19} \text{m}^{-3}$ and $n_{e,sep} = 10 \cdot 10^{19} \text{m}^{-3}$ are shown in fig. 22. The experimentally observed density are likely between $n_{e,sep} = 1 \cdot 10^{19} \text{m}^{-3}$ and $n_{e,sep} = 3 \cdot 10^{19} \text{m}^{-3}$, as will be later discussed based on MPM data in sec. 4.3.

For the smallest $D = 0.1 \text{m}^2/\text{s}$ the strike line width is $1 \ldots 2 \text{cm}$ on the low iota target, and thus smaller than the experimentally observed ones, shown before in fig. 14. For $D = 0.2 \text{m}^2/\text{s}$ the strike line width is $2 \ldots 3 \text{cm}$ matching most closely to the experiment, while for $D = 0.5 \text{m}^2/\text{s}$ the strike line width is in the range of $2 \ldots 5 \text{cm}$ and thus a bit larger than observed.

The peak at the near end of the high iota target, at finger 79 to 81, agrees
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Figure 20: Plot of the power per finger for simulations with different separatrix density and different diffusion coefficient. This plot is similar to fig. 18 but with enhanced transport in the outer bean plane.

Figure 21: Mean of the strike-line width as a function of the fingers, as introduced in fig. 3. Note that the error bars are expected to be smaller than in the experimental data, shown e.g. in fig. 14, as the experimental data includes variations in time and across the different modules. The power on the finger is colour coded. Simulation results for a constant diffusion $D = 0.1 \ldots 0.5 \text{ m}^2/\text{s}$ and $n_{e,\text{sep}} = 1 \cdot 10^{19} \text{ m}^{-3}$. The grey lines show the estimates for the low density case from fig. 14.
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**Figure 22:** Mean of the strike-line width as a function of the fingers. Like fig. 21 but for $n_e, \text{sep} = 3 \cdot 10^{19} \text{m}^{-3}$ on top and $n_e, \text{sep} = 10 \cdot 10^{19} \text{m}^{-3}$ on the bottom.

**Figure 23:** Mean of the strike-line width as a function of the fingers, as introduced in fig. 3. Note that the error bars are expected to be smaller than in the experimental data, shown e.g. in fig. 14, as the experimental data includes variations in time and across the different modules. The power on the finger is colour coded. Simulation results for scenario B introduced in fig. 8.

with experiment for all 3 spatially constant diffusion coefficient values. $D = 0.2 \text{m}^2/\text{s}$ matches most closely for the lower divertors. A good match for the upper divertors is $D = 0.5 \text{m}^2/\text{s}$ as well as the $D = 0.2 \text{m}^2/\text{s}$ for the $n_e, \text{sep} = 3 \cdot 10^{19} \text{m}^{-3}$ case.
The strike-line widths for the spatially varying diffusion coefficients are shown in fig. 23 for scenario B: diffusion motivated by experiment and in fig. 24 for scenario C: diffusion motivated by turbulent transport. In order to change the strike line width in the low iota target, a significant variation of $D$ is needed. In contrast, the strike line width on the vertical target is quite sensitive to an enhanced transport in the island. In addition of an increased strike line width, also the power is increased.

From the strike line width on the low iota target, in scenario B motivated by experimental observations, shown in fig. 23, the $D = 0.1 \ldots 2.5 \text{ m}^2/\text{s}$ case agrees with the experimental observations. For scenario C, the $D = 0.1 \ldots 1.0 \text{ m}^2/\text{s}$ and $D = 0.1 \ldots 5.0 \text{ m}^2/\text{s}$ cases agree best with the experimental strike line width in the low iota target. Thus for all scenarios we can find cases that give similar strike line widths than observed in experiments.

4.3. Upstream data

To further compare the output of the models to experimental data, upstream data is beneficial as it is separated from the location that was optimised for. As introduced, the MPM can measure the density and temperature in the SOL, outside of the separatrix. Due to the separation from the targets, this can further ensure a matching transport model is chosen.

Figure 25 shows the density and temperature of a line of sight measured by the MPM diagnostic. Although no experimental MPM data is available for program #20180920.009, #20180920.013 and #20180920.017, similar programs with MPM data exist and are used as an upstream comparison to simulation. These programs have similar heating power, the same magnetic configuration and line integrated densities are in the range $4 \ldots 6 \cdot 10^{19} \text{ m}^{-2}$. The simulation results, for both spatially constant and spatially varying diffusion coefficients, are plotted as lines in fig. 25. The simulations matching best the strike line width are plotted as lines, smaller $D$ distributions are dotted and large ones are dashed, for all three scenarios.

All simulations show essentially monotonic behaviour in the temperature and the density. This is in contrast to the experimental data. The density behaviour is not
Figure 25: Plot of electron density and temperature as a function of the radial position. Shown is a 1D cut along the path of the MPM diagnostic [22, 23]. The experimental data from the MPM diagnostic is shown as symbols. The lines are the simulations with $n_{e, sep} = 1 \cdot 10^{19} \text{m}^{-3}$ and the best matching diffusion based on strike line width for the given spatial distribution. Dotted lines denote smaller diffusion, i.e. more narrow strike line width and dashed lines denote larger diffusion values. For scenario A: constant diffusion $D = 0.1 \text{m}^2/\text{s}$ is plotted as green dotted, $D = 0.2 \text{m}^2/\text{s}$ as green line (best match based on strike line width) and $D = 0.5 \text{m}^2/\text{s}$ as green dashed. Note that the temperature for $D = 0.1 \text{m}^2/\text{s}$ is lower in the plotted regime, the gradient is higher and the separatrix temperature is the highest for the low diffusion value. For scenario B: diffusion motivated by experiment, $D = 0.1 \ldots 0.4 \text{m}^2/\text{s}$ is shown as magenta dotted, $D = 0.1 \ldots 2.5 \text{m}^2/\text{s}$ as magenta line (best match based on strike line width) and $D = 0.1 \ldots 10 \text{m}^2/\text{s}$ as magenta dashed. For scenario C: diffusion motivated by turbulence, $D = 0.1 \ldots 1 \text{m}^2/\text{s}$ as black dotted and $D = 0.1 \ldots 5 \text{m}^2/\text{s}$ as black line (best match based on strike line width). The point magnetically closest to the O-point is around $R = 6.05 \text{m}$ while the shadowed area is around $R > 6.075 \text{m}$.

Quantifying which case matches best, or which density would match best, is not well defined as the profiles do not match. For scenario A, $n_{e, sep} = 3 \cdot 10^{19} \text{m}^{-3}$ matches clear, and varies between the different experimental measurements. The temperature profile however shows a clearly monotonic trend in the shadowed region $R > 6.075 \text{m}$, in contrast to the data in the longer connection length, where a hollow temperature profile is observed. The hollow temperature is observed in none of the simulations.

The separatrix density is an input parameter for the simulations. As such we can freely choose a density, to best match the experimental results. For all diffusion cases, the best match is between $n_{e, sep} = 1 \cdot 10^{19} \text{m}^{-3}$ and $n_{e, sep} = 3 \cdot 10^{19} \text{m}^{-3}$.

Quantifying which case matches best, or which density would match best, is not well defined as the profiles do not match. For scenario A, $n_{e, sep} = 3 \cdot 10^{19} \text{m}^{-3}$ matches
very well in the target shadow, while, depending on the experimental measurement, the $n_{e,\text{sep}} = 1 \cdot 10^{19} \text{ m}^{-3}$ case matches reasonably good around $R = 6.06 \text{ m}$. Scenario B shows, like the experimental data, a drop in the profile. For $R < 6.10 \text{ m}$ the profile is roughly linear, while further outside an exponential profile is measured. For the experiments, the drop is $R \approx 6.08 \text{ m}$, with an exponential behaviour outside, but towards the island the behaviour is more complicated.

For the temperature, all simulations feature a to high temperature towards the island centre. Not shown here is the separatrix, where the temperature in all simulations is further increased. Scenario B shows the lowest separatrix temperature. Due to the large fall-off length, the temperature is further out higher then observed by the other simulations. $D = 0.1 \text{ m}^2/\text{s}$ for scenario A might seem to show good agreement with the MPM temperature measurement, but the temperature at the separatrix is the highest of all shown simulations. Similar to the density profiles does the temperature profile of scenario B show a kink, featuring a stronger fall off outside. In general with increasing $D$ the separatrix temperature decreases, and the fall-off-length increases.

5. Discussion

The experimental heat-flux data from W7-X has been analysed determining the toroidal distribution as well as using fits of the strike line. The fits allowed to determine the position and the width of the strike line, with the exception of the higher density case #20180920.017 where the fit did not converge reliably, as smaller structures where present.

Determining the shape of the strike line allows to determine how much of the power is deposited on the main strike line versus how much in total is deposited on the divertor. A significant amount of power is observed by the IR cameras to be deposited outside of the main strike-line ($\sim 1 \text{ MW}$). This power is seen as a broad feature and its cause is not yet known. Surface layers, which have been observed to build up on certain areas of the divertor over the campaign [36], may increase the IR emissivity of the targets, thus possibly creating an artefact of higher heat flux. Another possible explanation is power load by plasma radiation close to the divertor. Initial calculation seem to agree with the radiation hypothesis, however an in-depth study is outside of the scope of this paper. Future work is planned to investigate this feature.

Two different spatially varying diffusion coefficient distributions have been tested in EMC3-EIRENE. Besides scenario A with constant diffusion, scenario B based on experimental observations features enhanced transport towards the centre of the islands. This is motivated by the need for a small $D$ to match the experimental observed strike line width and a larger $D$ to feature low enough upstream temperature. Figure 26 scatches the simplified transport through the island in the island divertor on a single island. The heat from the confined region enters the island through the separatrix, which separates the island from the confined region, depicted as a red arrow. Of course this is not localised, but spread out over the whole separatrix. In terms of connection length, it does not have a large impact where the heat crosses the separatrix, as close to the x-points, the field is mostly toroidal, while in between the x-point a larger poloidal contribution is present, giving the area close to the x-point a dominant contribution to the parallel connection length. From the region where the heat enters the island, there are, simplified speaking, two channels to the target. The parallel channel, depicted as green arrows. This is in tokamaks, neglecting detachment,
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**Figure 26:** Sketch of the heatflux in the SOL of W7-X. Depicted is the cross section of an island. The target is on the bottom. The heatflux is entering at the top (red arrow). The channel via parallel transport around the island is shown as green arrows, while the transport through the island, relying on diffusion, is shown as blue arrows.

The main channel of transport and can be described by the two-point-model [37–39]. The two-point-model gives the heatflux, and the scaling with temperature can be given as $q \propto T^{7/2}$, i.e. as a strong function of temperature. We can therefore assume that the parallel transport is only important as long as the upstream temperature is still high. Thus only a width of the order of the temperature decay length $\lambda$ contribute to the parallel channel. The width in turn is determined by the perpendicular heat transport $\lambda \propto \chi_s$ at the separatrix. This gives a total power going through the parallel channel as $P_{\parallel} \propto \chi_s \times T_s^{7/2}$, with $T_s$ the separatrix temperature. The transport through the island, depicted in blue, is in turn depending on the temperature at the separatrix, or excluding the region dominated by parallel transport, the temperature after the distance $\lambda$: $T(R_{sep} + \lambda)$. After the initial $\lambda$, a change in $\chi$ does not directly impact the parallel heatflux anymore. Indirect impacts, such as additional heatflux, and thus for a given heatflux resulting in a lower separatrix temperature, do exist. The heatflux for a single perpendicular channel is proportional to the “integrated heatconductiviy”: $X = 1/\int_{sep}^{tar} \chi dr$ and $T(R_{sep} + \lambda) = T_s/e \propto T$. The total heatflux through the island $P_\perp$ is given by the sum over all possible channels $P_\perp \propto T_s \int X da$. Thus increasing $D$ towards the island centre, increases $X$ and $P_\perp$ without a direct impact on $\lambda$.

Scenario C is based on the scaling of turbulent transport with bad curvature, which is in W7-X largest at the outer bean plane. The three scenarios have been used for a scan in both density as well as magnitude of the diffusion coefficient using the EMC3-EIRENE code. A one-to-one comparison of the heat flux from experiment and simulation was performed.

The strike line width from the experiments has been determined to be around 2 to 4 cm in the magnetic standard configuration. This is true for the low iota target, the high iota target as well as the vertical target, independent of the connection length. This observation is reproduced in the simulations, where for a given density and diffusion the strike line width is roughly constant for all significantly loaded areas. As also the toroidal distribution features similar feature for all scenarios, it is difficult to distinguish the appropriate transport model purely based on the target profiles. With the inclusion of the upstream measurements from the MPM, the different scenarios could be distinguished by the virtual diagnostics. However, none of the cases showed good agreement with the measured profile. Besides additional upstream measurements, in the future a scan in separatrix density and magnitude of the diffusion coefficients with more intermediate values could help increase the agreement to experiments.

The fact that $D = 0.2 \text{ m}^2/\text{s}$ and $n_{e,sep} = 1 \cdot 10^{19} \text{ m}^{-3}$ from scenario A matches the lower cases, but the upper divertor is better matched by an increased diffusion of
$D = 0.5 \, \text{m}^2/\text{s}$ or an increased density $n_{e,\text{sep}} = 3 \cdot 10^{19} \, \text{m}^{-3}$, is in agreement up-down asymmetry as observed by field reversal experiments [40], in agreement with the effects of drifts. The variation of $D$ could be emulated in full module simulations. Using full module simulation it might also be possible to choose boundary conditions, that result in up-down asymmetric densities, similar to the ones observed by Zhang et al. [40] and check whether that introduces up-down asymmetries on the targets.

The strike line width varied in the high-iota target between upper and lower divertor, as shown in fig. 14. If one assumes that this is based on drifts, one can make a rough estimate on the effective parallel drift velocity using a simple model. The parallel velocity is assumed to be the sound speed $c_s$, modified by the drift velocity, with the sign of the drift depending on upper or lower divertor. Rather then the actual drift velocity, the effective parallel drift velocity $v_D$, projection of $v_{\text{pol}}$ on $v_\parallel$ is used. The estimated parallel transport time is then based on the parallel connection length $L_\parallel$ and given by $L_\parallel/(c_s \pm v_D)$. This gives a strike line width of around

$$\lambda_\pm \approx \sqrt{\frac{D L_\parallel}{c_s \pm v_D}} \tag{1}$$

which in turn gives an effective drift speed of

$$v_D \approx D L_\parallel \frac{\lambda_-^2 - \lambda_+^2}{\lambda_+^2 \lambda_-^2} \tag{2}$$

Using $\lambda_- = 3 \, \text{cm}$ and $\lambda_+ = 2 \, \text{cm}$, and assuming $L_\parallel \approx 100 \, \text{m}$ and $D = 0.1 \, \text{m}^2/\text{s}$ this gives an effective parallel contribution of the drifts on the order of $v_D \approx 14 \, \text{km/s}$, and thus in the range of the expected parallel velocity. Thus drifts would have to significantly contribute to the transport to cause such variations.

Field errors could cause the variations between half-modules, but the variation between upper versus lower half modules seems rather systematic. Drifts are expected to cause up-down asymmetries as depicted in fig. 27 [7]. Experiments with reversed field can be used to test this hypothesis and are suggested for the next experimental campaign.

The location of the strike line, as shown in fig. 16 is in agreement with Hammond et al. [7] where in the low iota forward configuration the strike line on the low iota target was a few cm closer to the pumping gap, an effect that was attributed to drifts.

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**Figure 27:** Sketch of the $\vec{E} \times \vec{B}$ drifts in W7-X. Reproduced with kind permission from Hammond et al. [7].
Note that drifts could also cause toroidal transport, not shown in the figure, which is in contrast to tokamaks where due to toroidal symmetry this can be neglected. Other potential reasons include a systematic misalignment of the divertors or vertical misplacement of the entire plasma. This hypothesis could be tested by field reversal experiments. Experiments of field reversal in low iota configuration [7] and standard configuration [40] imply drifts are responsible for the up-down asymmetries. The experiments include error field correction, i.e. the magnetic field has been optimised to minimise differences between the different target heat loads [24].

For the experimental data no clear trend of the strike line width with density is observed. For the simulations a clear trend of increasing strike line width with increasing density is observed. In the simulations the density variation was however much larger. Killer et al. [9] show that the transport is local in nature, i.e. depends on the local gradients, which is in contrast to the far SOL in tokamaks, where the transport is dominated by filaments, and thus non-local [41]. Even though the transport is local, Killer et al. [9] shows it is non-diffusive, as it is proportional to the pressure gradient, rather then the density gradient [9]. Even for non diffusiv transport, following the approach from Manz et al. [16] would still allow to use a diffusive model to simulate the effective transport. In the case of a pressure driven transport, a scaling of $D = D(T)$ could be used, requiring an iterative process for the simulation.

While it is possible to match the strike line width to the experimental ones, none of the simulations matched the toroidal distribution on the low iota target. Scenario B matched best the upstream temperature measured by the MPM. Experimental measurement of the required high diffusion coefficient in the island centre would support the scenario B model. Especially the hollow temperature profile, as measured by the MPM in the island has not been reproduced by any of the simulations and cannot using a diffusive model with $D > 0$ and no dominant sources or sinks, with the current topology. Changing the topology, for example by including error fields, could introduce a short, parallel connection from further upstream and thus cause an hollow SOL profile. The density profiles measured by the MPM agree better with the non-constant diffusion coefficients, selected from the simulation with a matching strike line width. However, the non-monotonic behaviour is in no case reproduced. The hollow temperature profile and the associated non-monotonic density profile in the island have been repeatedly experimentally observed in the past [9,22,23,42–44]. Other EMC3-EIRENE simulations are also missing this feature, and a hollow temperature island due to radiation losses at the O-point has so far only been observed for very low density cases in simulations. However, outside of the non-monotonic region, scenario A and scenario B agree reasonably well with the density profile measured by the MPM. For the temperature profile, scenario A underestimates and scenario B and C overestimate the profile. Scenario B is the most promising scenario, as scenario A shows disagreement in both density and temperature, and scenario C does not drop sufficiently for larger radius.

Non-isotropic diffusion in the perpendicular plane could help reproducing the hollow island. In EMC3-EIRENE the diffusion is already non-isotropic, as the parallel diffusion is independent of the perpendicular plane. However, within the perpendicular plane, the transport is diffusive. A non-isotropic transport in the perpendicular plane would require to have flux surfaces in the island, so that the diffusion within the surface could be higher then the diffusion across the surfaces. Effectively 3 diffusion coefficients would be used, a parallel one, one for within flux surfaces and one across flux surfaces. Such a diffusion model would allow to increase the transport around the
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island, and thus give enough transport away from upstream, while at the same time avoiding a significant heat-flux into the island. This would need significant changes in EMC3-EIRENE, as the code only needs the local magnetic field, and is not aware of the global topology, such as flux surfaces. Alternatively convective transport in bi-normal direction, around the island, could help reproduce the hollow temperature profile. As the convective transport is expected from drifts, including drift terms is an important and promising route to better understand the transport in the SOL of W7-X.

To help elucidate how important drifts may be, we assume drifts are solely responsible for the convective transport. An estimate of the velocity can then be given. This assumes that the transport time is given by the diffusion coefficient over the square of the fall-off-length $\lambda$.

$$v_{pol} \gtrapprox L_{pol} \chi \left( \frac{\nabla T}{T} \right)^2 \approx L_{pol} \chi \frac{1}{\lambda^2}$$  \hspace{1cm} (3)

Using a falloff length of $\lambda \approx 3$ cm, consistent with the data here presented, the island size on the order of one meter, and $\chi \approx 0.3 \text{ m}^2/\text{s}$ gives $v_{pol} \gtrapprox 300 \text{ m/s}$. Parallel flow velocities observed by experiments and EMC3-EIRENE are typically in the range of 30 km/s. As the field line pitch is around 0.001, this gives a perpendicular contribution of 300 m/s, thus the drifts could be comparable to the parallel flows. The drift velocity measured by the MPM are consistent with this estimate [42]. This can also be accompanied into the two-channel model shown in fig. 26. Assuming a fast enough drift velocity, the $\chi$ can be increased ($\rightarrow \infty$) by the part of the path that is governed by fast poloidal rotation, and thus giving an effectively increased $X$.

It is not clear whether drifts could be responsible for such an effect. Besides simulations including drifts, also post processing routines could give some insights into the impact of drifts [45,46]. Another proposed explanation is an angle-dependent sheath transmission coefficient, as the incident angle decreases from near end of the low iota target towards the far end of the low iota target. However, this hypothesis cannot explain the heat flux in the shadowed area at the far end. It should however be possible to tune the sheath transmission factors in the model, to test this hypothesis.

6. Conclusion and Summary

For comparing experimental and simulation data of the target heat-fluxes, a fitting routine has been implemented, which works reliably for well-behaved IR heat-flux data. Future work will make the fitting more robust to counteract any possible artefacts in the heat-flux analysis.

In the past some qualitative comparison between experiments and simulations have been attempted for the SOL of W7-X. The here performed quantitative comparison shows that, in order to reproduce the experimentally observed strike line width of the range 2 to 4 cm, diffusion coefficients in the range of 0.2 m$^2$/s are needed in the magnetic standard configuration for low to medium density cases. In addition to constant diffusion coefficients spatially varying diffusion coefficients can be used to reproduce the experimentally observed strike-line width. The spatially varying diffusion coefficients can reduce the simulated upstream temperature and are in better agreement with the experimental observation, as shown here by comparing to MPM.
There are significant differences between simulations and experiments, that could not be reproduced by the simulation. Some differences are expected to be due to a lack of drifts in EMC3-EIRENE: e.g. the up-down asymmetry on the divertor target plates. Additionally, small toroidal asymmetries are observed in experiment, which are expected due to the non-perfect error field correction. Due to the inherent symmetry of the simulation, they are, like drifts, not expected to be reproduced. However, other discrepancies remain which are not expected, such as the difference in the toroidal distribution of the heat flux on the low iota target. One hypothesis is that this, too, could be an affect of drifts. Additionally hollow temperature profiles in the islands are measured by the MPM diagnostic, which has not been reproduced by the simulations. Non-isotropic transport in the perpendicular plane could help to reproduce this. Drifts are one of the mechanisms that could cause this.

Altogether, these observations show that spatially varying diffusion coefficients can improve agreement to experimental measurements. They further indicate that drifts could contribute substantially to the transport in W7-X, which cannot be captured with the present version EMC3-EIRENE. Thus, implementation of the drifts are a priority for future work, in order to fully capture the physics seen in experiment.

7. Acknowledgement

This work has been carried out using the xarray framework [30, 31]. Some task have been paralellised using GNU parallel [47].

The simulation presented here are available at: DOI: 10.5281/zenodo.5762079

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