SolEdge2D-Eirene simulations of Pilot-PSI plasmas

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The exhaust of power is a crucial issue for ITER and next step fusion devices [1]. Predictions for divertor operation are heavily dependent on edge plasma simulations typically utilizing a fluid plasma code in combination with a Monte Carlo code for neutral species. Therefore it is important to validate the codes using well-diagnosed experimental setups. The Pilot-PSI device offers a high density ($n_e \sim 10^{19} - 10^{21}$ m^{-3}), low temperature (T_e < 5.0 eV) plasma comparable to that expected in the ITER divertor region. In this work, hydrogen plasma discharges in Pilot-PSI have been modelled using the Soledge2D fluid plasma code [2] coupled to the Eirene neutral Monte Carlo code. In the model, the plasma is generated using external volumetric sources of plasma density and power in the region of the cascaded arc plasma source and a constant H_2 gas inflow rate. The external power source is found to be the main control parameter of the simulations and is set in order to match experimental n_e, T_e profiles from Thomson scattering (TS) 4 cm downstream of the cascaded arc nozzle. The total injected power is typically 2 – 3 kW. The simulation results are compared to TS measurements 56 cm downstream from the source nozzle (2 cm in front of the Pilot-PSI target) and a Langmuir probe embedded in the target.

Introduction

The Pilot-PSI linear plasma device was designed as a forerunner of Magnum-PSI, in order to confirm the ability of a cascaded arc plasma source to deliver high plasma fluxes for testing of plasma facing components for ITER and next generation fusion devices. The plasma generated by a cascaded arc source of Pilot-PSI is similar to an expected ITER detached divertor plasma, with $n_e \sim 10^{19} - 10^{21}$ m^{-3} and T_e below 5 eV. Good diagnostic access and the simple cylindrical geometry of the device have attracted our attention for modelling using the SolEdge2D-Eirene tokamak edge transport code for two reasons, (a) interpretation of code results for a simple, yet real physical case, and (b) benchmarking of the code using experimental data from Pilot-PSI.

Simulation setup

Pilot-PSI has been modelled using the Soledge2D fluid code coupled to the Eirene neutral Monte Carlo code. The simulation grid is field aligned, rectangular and with high resolution (smallest grid element ~0.5 mm) close to the axis of symmetry, the target and the cascaded arc source, visible in figure (1). Cylindrical coordinates (r, z) are used. Drifts and electric currents were switched off for this case, so self-consistent description of plasma generation via the arc discharge current was not possible. However, our interest here was not in the details of operation of the cascaded arc, it was rather the interaction of the plasma with background with neutral species. Therefore, the plasma was generated using fixed external sources of ion-electron pairs $S_{\mathrm{n}}^{(\mathrm{ext})}$, and electron/ion energy, $S_{\mathrm{E,e/i}}^{(\mathrm{ext})}$ injected in the arc source region with a Gaussian profile in both r and z, e.g. $S_{\mathrm{n}}^{(\mathrm{ext})} = \frac{S_{\mathrm{n,tot}}^{(\mathrm{ext})}}{C} \exp\left(-\frac{(r-r_c)^2}{\lambda_r^2}\right) \exp\left(-\frac{(z-z_c)^2}{\lambda_z^2}\right)$, where $S_{\mathrm{n,tot}}^{(\mathrm{ext})}$ is the total amount of particles injected into the volume and C is a normalization. In this case, the plasma is generated on axis, i.e. r_c=0 and $\lambda_r \ll R_{\mathrm{arc}}$ and $\lambda_z \ll L$ (R_{arc} and L are the diameter of the arc discharge channel and length of the device, respectively) and thus $C \approx \frac{\pi^{\frac{3}{2}}}{2} \lambda_z \lambda_r^2$. A similar expression applies for the electron and ion energy sources $S_{\mathrm{E,e}}^{(\mathrm{ext})}$, $S_{\mathrm{E,i}}^{(\mathrm{ext})}$ The boundary conditions are the following: On the axis of symmetry, vanishing radial gradients are imposed whereas on the walls, the penalization technique [2] is used. The neutrals (H_2 and H) are treated by the Eirene MC code. H_2 molecules are injected at the source to mimic the constant gas puff. Additional sources include wall recycling and volumetric recombination (these are calculated self-consistently by Eirene). Saturated surfaces are assumed. i.e. recyling coefficient R=1 and one pumping surface with R<1 is defined at the back of the vessel (see

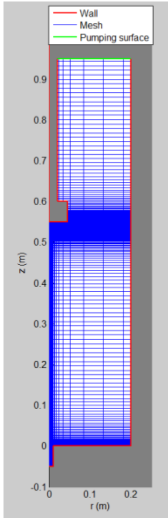

Figure 1 - Non-uniform, rectangular, field aligned grid in place for the simulations. External source terms are situated in (R, z)=(0, -0.05 m)

reaction #	reaction description
1	$H + e \rightarrow H^+ + 2e$ (EI)
2	$H + H^+ \rightarrow H^+ + H$ (CX)
3	$H_2 + e \rightarrow H_2^+ + 2e$ (EI)
4	$H_2 + e \rightarrow 2H + e$ (EI)
5	$H_2 + e \rightarrow H + H^+ + 2e$ (DI)
6	**$H_2 + H^+ \rightarrow H_2 + H^+$ (EC)**
7	**$H_2 + H^+ \rightarrow H_2^+ + H$ (IC)**
8	$H_2^+ + e \rightarrow H^+ + H^+ + e$ (DI)
9	$H_2^+ + e \rightarrow H + H^+ + 2e$ (DS)
10	$H_2^+ + e \rightarrow 2H$ (DR)
11	1. $H^+ + e \rightarrow H$ (RC)

Table 1 – List of reactions used in Eirene. Reactions in bold were added only recently to the SolEdge2D-Eirene suite.

Fig. 1) at the place of the pumping duct. A pump albedo is adjusted in order to match typical experimental neutral pressures in the vessel of several Pa. The atomic physics model is depicted in Tab. 1 and taken from Ref. [3]. Reactions in bold (6, 7) were added only recently to the SolEdge2D-Eirene suite. The source terms were adjusted in order to match experimental Thomson scattering (TS) profiles measured at z=4cm from the source nozzle. The total (volume integrated) external power and particle sources are 3 kW and 1.0×10^{20} s^{-1}, respectively. Perpendicular diffusion coefficients for particles (D), parallel momentum (ν) and energy (χ) are all set to 0.3 m^2s^{-1}.

Results and Discussion In Fig. 3 axial profiles of main plasma parameters at a radius of 1.7 mm are shown for two cases: case (1) is a run without ion-molecule elastic collisions (EC, reaction 6 in Tab. 1), case (2) includes these collisions. Monotonic profiles, with strong axial gradients of n, T, ion flux (Γ), total pressure (Π) are observed. Supersonic flows are observed for the case (1) atomic physics model, while inclusion of EC in the case (2) model suppresses supersonic flows. Moreover, with EC the local reduction of flux is more pronounced. It was found that this strong reduction of local target flux is caused exclusively by radial transport. Fig. 3 shows an axial profile of ion flux integrated over a full surface normal to the magnetic field.

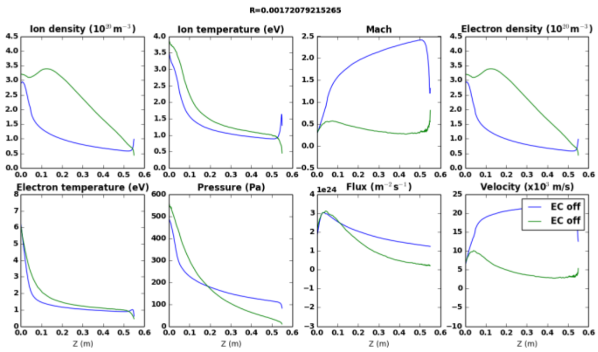

Figure 2 - Axial profiles of plasma parameters for the two cases with elastic collisions on and off.

This integrated flux is constant (apart from a small area at the source region, where all the ionization takes place), indicating that there are no net volumetric plasma sources or sinks in a large region of the plasma beam. Further evidence is the broadening of the typical width (FWHM) of the radial Γ profile along the field lines (Fig. 3). Next, the SolEdge2D-Eirene simulations are compared to a target-embedded Langmuir probe (LP) and Thomson scattering (TS) measurements 2 cm at the source. The ion flux was determined

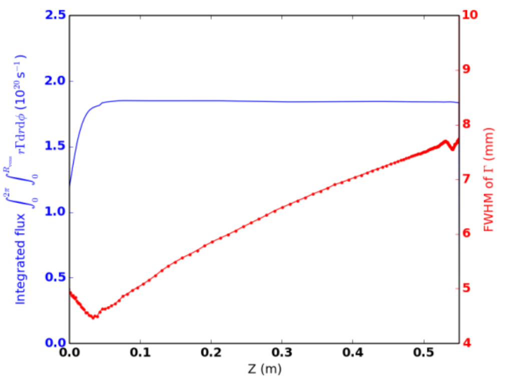

Figure 3 – Axial profile of integrated ion flux and FWHM of the ion flux radial profile.

from the LP ion saturation current and indirectly from n_e and T_e measurements from TS, for more details see [4]. Within the experiment, the background neutral pressure (P_n) was varied by changing the pumping speed. In the simulations, the external source terms were kept the same as described above and the pump recycling coefficient was changed in order to obtain a scan on P_n, The experimental trend (exponential reduction of target ion flux) is clearly recovered in the simulations. However, numerically stable solutions for high P_n cases (>5 Pa) with very low target T_e and possibly strong recombination were not obtained so far (while keeping upstream parameters constant) and thus remain the topic of future investigations.

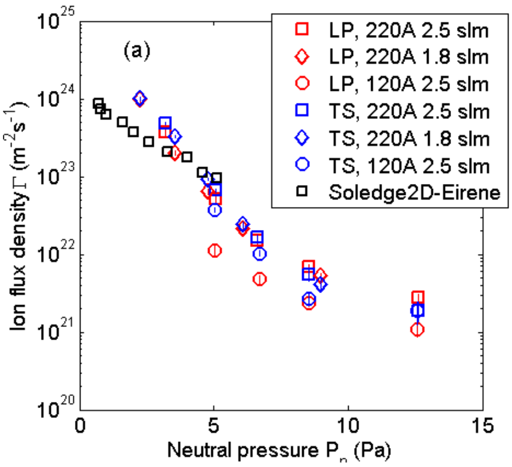

Figure 4 – Target ion flux density measured by a Langmuir probe and TS for several experimental cases and comparison with SolEdge2D-Eirene simulations.

Conclusion

It has been demonstrated that SolEdge2D-Eirene can be used with success to model a linear plasma device, proving the flexibility of the code. The experimental trend (exponential reduction of ion flux density with background pressure) can be reproduced in the simulations. It has been found that for cases converged so far, local reduction of target ion flux is driven by radial transport, while strong volumetric recombination was not observed in the simulated cases. High background pressure (>5 Pa), low T_e cases could not be accessed so far and will be investigated in continuation of this work. Moreover, results are sensitive to the atomic physics model: e.g. adding elastic collisions of plasma with H_2 molecules indirectly reduces local target flux by increasing time available for perpendicular diffusion.

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