Numerical modelling of detached plasma experiments with differential pumping in Magnum-PSI

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Introduction

The ion and heat flux in the scrape-off layer of a tokamak fusion reactor can cause excessive sputtering and melting of the divertor target tiles. A sufficient decrease is imperative to ensure the survival of these tiles. This specific condition called detachment occurs within low temperature, high density and highly recycling plasma. Detachment can be realized in linear plasma devices such as Magnum-PSI [1]. Magnum-PSI can generate plasma beams with high flux (up to 10^{24} particles m^{-2} s^{-1}), high density (10^{20} m^{-3}) and low temperature (< 5 eV), which are the typical plasma parameters in the divertor region of ITER. Based on the experimental data, numerical modelling is carried out to help gain further insights regarding the physics behind detachment. Any knowledge gain from the model can be translated to ITER or other tokamak geometries.

Modelling: B2.5-Eunomia

The model encompasses the three vacuum chambers of Magnum-PSI separated by skimmers. Each chamber is pumped with different pumping speeds. Additionally, gas puffing is realized in the target chamber to have the sufficient gas pressure for detachment. Two Thomson scattering (TS, see Figure 1 measurement locations are available 10 cm in front of the source hole, and 2 cm in front of the target.

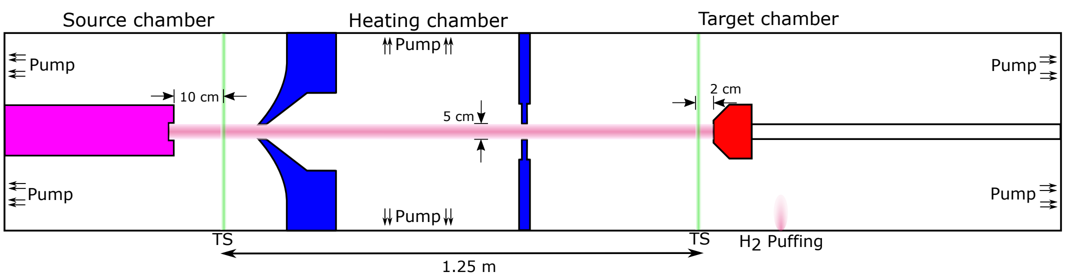

Figure 1: *Diagram of Magnum-PSI experimental domain. The vacuum vessel is separated by skimmers (blue) into three. The plasma beam (pink) extends from the source(purple) to target (red). Two Thomson scattering measurement location (green) are available.*

The experiment is modelled using two codes, based on a fluid model for the plasma and a kinetic model for the neutral species. The multi-fluid code B2.5 [3] solves the Braginskii equations for density, flow velocity, and temperature for every plasma species, and the electric potential of the domain. The B2.5 domain is a quadrilateral grid aligned to the magnetic field. The entire domain has four boundaries: source, target, symmetry axis, and plasma-neutral interface. Within each boundary the quantities (value, gradient, etc.) for every plasma species are specified as boundary condition for each of the equations. For B2.5 the domain only encompasses the plasma beam.

EUNOMIA [2] is a Markov chain Monte Carlo code for neutral species in 3D. It solves the static, force-free Boltzmann equation by following the random walks of many test-particles. The domain consists of tetrahedral cells generated by rotating the 2D triangular grid on the z-axis. Once all test-particles have been followed, the neutral species density, flow velocity and temperature are approximated by the residence time of the test-particles within each cell. All quantities are then averaged back to the 2D triangular grid.

The coupling between the two codes works as follows: First, based on the prescribed boundary conditions, B2.5 solves the steady-state plasma solution. This step generates the plasma quantities (density, flow velocity, temperature) for EUNOMIA to use as background information. Next, neutral test-particles are launched from prescribed input sources in EUNOMIA. These particles interact via collision with random particles drawn from the background plasma information. The collision events result in particle and energy sources (or sinks) for the plasma species. Finally, these sources are fed back to B2.5 for a new steady-state plasma solution.

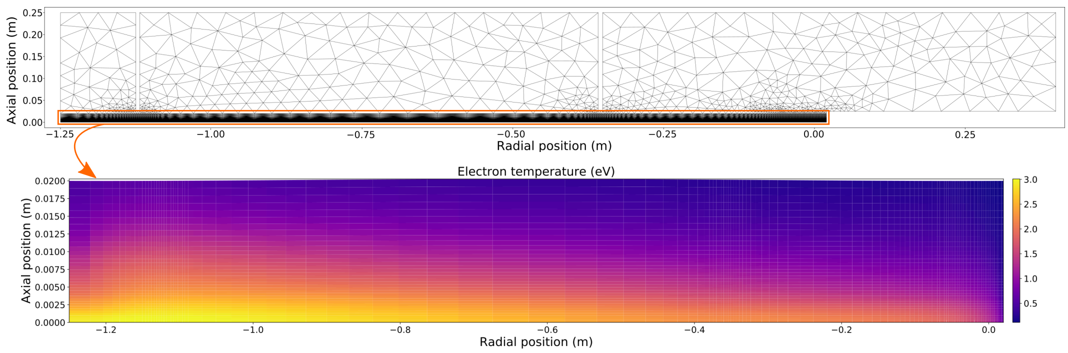

Figure 2: *Simulation domain for EUNOMIA (top) and B2.5 (bottom), with the source and target boundary on the left most and right most of the domain, respectively.*

Simulation: Boundary conditions and convergence

The boundary conditions for B2.5 are as follows: at the source boundary, the experimental profiles of electron density, electron temperature (with $T_e = T_i$ assumed) and electric potential are used as inputs. At the target boundary, sheath limits are imposed. At the plasma-neutral interface, a certain decay length is prescribed. Finally, at the symmetry axis, all quantities have zero flux. For EUNOMIA, the vessel walls have only two boundary conditions. Either the test-particle is absorbed (terminated) at the pump locations (see Figure 1) with a certain probability, or get thermally reflected everywhere else.

For a Monte Carlo simulation, a convergence criteria is needed. In this simulation, a convergence rule called *acceptable shifting convergence band rule* (ASCBR) [4] is used. The algorithm is as follows: first, a single standard deviation σ is calculated from the whole simulation cycles. Secondly, a confidence interval (CI) band is determined from the current mean μ_k of the quantity. This band has the length of 2σ, with $\mu_k + \sigma$ and $\mu_k - \sigma$ as the upper and lower thresholds respectively. When μ crosses the CI threshold, the band shifts following μ_{k+j}, with j as the number of cycles the band remained unshifted. If j is larger than a certain number ζ, convergence is concluded. This algorithm is then applied to all grid cells, and a coverage value is determined. For this simulation, the value $\zeta = 75$ is chosen.

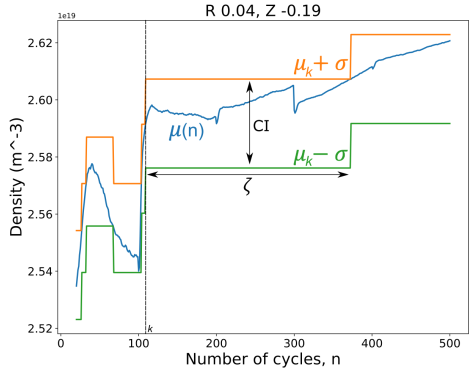

Figure 3: *ASCBR applied to the density of H in a cell at location R=0.04 m, Z=-0.19 m.*

Simulation: Results and discussion

Data from detachment experiments in Magnum-PSI are available for neutral gas pressures of 0.27, 0.53, 1.0, 2.0, and 4.4 Pa measured at the target chamber. These data are the Thomson scattering measurements near the target. Unfortunately, TS data are not available near the source. For simulation purposes, another experimental data is used, which has both TS measurements near the source and target. In this experiment the neutral gas pressure at the target chamber is 0.25 Pa. The source TS measurement profiles are used as input for B2.5 source boundary. The parameters at the other boundaries (except the symmetry axis) are adjusted such that the simulated profiles at the target TS location are similar to the target TS measurement profiles. After the parameters are established, the neutral gas pressure at the target chamber is increased to values 0.50, 1.0, 2.0, and 4.0 Pa following the detachment experiment. Comparisons between simulated profiles and experimental profiles are shown in Figure 4. All simulations are converged with coverage values of more than 95%, with the exception of the 2 Pa case (84%) due to time limitations. Both the simulated density and temperature profiles exhibit similar trend with the experimental profiles. With increasing neutral gas pressure, T_e decreases while N_e increases. The plasma pressure is defined as $2N_eT_e$ in the experiment and $(T_e + T_i)N_e$ in the

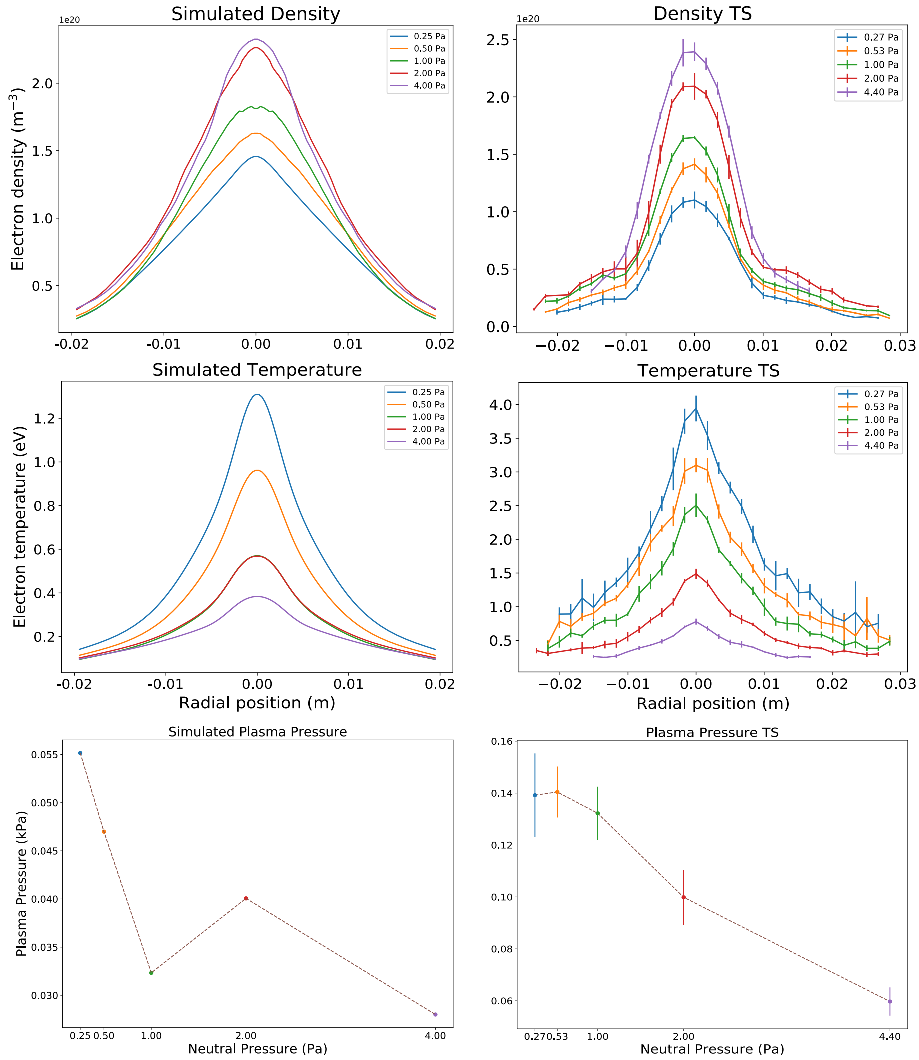

Figure 4: *Profiles of electron density and temperature from the simulations and experimental measurements at the TS location near the target. The bottom two graphs are the plasma pressure calculated using the maximum value of the profiles. Both indicated a reduction in plasma pressure with increasing gas pressure.*

simulation. The maximum values of N_e and T_e profiles are used in the pressure calculation. Both indicate a reduction in plasma pressure with increasing gas pressure, which is the key feature of detachment. To analyze which transport channels contribute to this pressure reduction, future simulations will be carried out with the same plasma parameters as the detachment experiment.

References

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