Kinetic Simulations in Support of Probe Measurements of COMPASS scrape-off-layer

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ABSTRACT

We have constructed a 1.5d3v simulation model of a flux tube in the SOL layer of the COMPASS-D tokamak. The model is realized in the kinetic code BIT1h5. The model results were compared with the probe measurements results. Due to lack of CPU time available we were unable to make a complete study of the electron energy distribution functions near the separatrix.

1 INTRODUCTION

Electrical probes remain one of the important diagnostic tools for edge and SOL tokamak plasma, even as we steadily approach the era of big fusion reactors. The measured I-V characteristic of a simple Langmuir probe (LP) can provide a variety of plasma parameters with an excellent spatial and temporal resolution. However, interpretation of the obtained data is often a subject of oversimplification, leading to imprecise results. One such peculiarity in tokamak probe measurements is the use of the part of the I-V characteristic only below the floating potential $V_{fl}$ and assuming a Maxwellian electron energy distribution function (EEDF), without, in fact, measuring it. Such classical approach can therefore overestimate the overall temperature of the electron population due to small population of fast electrons, which can result in significant errors in e.g. plasma potential $\Phi_{pl}$ evaluation. An advanced method has been developed, which utilizes the electron part of the characteristic even in strongly magnetized plasma and has been applied in edge and SOL tokamak plasmas with success [1]. This progressive approach i.e., first-derivative technique (FDM), is used here to evaluate the real EEDF in the area of divertor probes close to the strike points, which - in return - significantly decreases the classically predicted density of high energy electrons.

In our work we then made use of a fully-kinetic code BIT1 [2] to simulate a single flux tube inside the SOL region during a D-shaped L-mode discharge. The flux tube is bounded between two divertor plates and volumetric injection of particles represents the cross-field diffusion as the plasma source. Injected electrons have high energy Maxwellian distribution that is “reshaped” through collision interactions and “measured” at the divertor sheath, where a high energy tail to the Maxwellian distribution is expected to still be present. In the first-
derivative method this is modelled via bi-Maxwellian EEDF configuration, which leads to the possibility of a direct comparison between the EEDF obtained from divertor probe measurements to the results from PIC simulation.

2 SIMULATIONS

2.1 Simulation model

The proposed task required us to convert the 3d nature of the SOL into a 1d simulation domain. The theoretical background lies in the onion-skin method of modelling a flux-tube, which is presented in [3]. A similar practical application of such model was up to now, to our knowledge, used only by the author of the code BIT1 [4]. The basic idea of straightening out the SOL and modelling of sources and sinks is shown below in Fig. 1.

As input parameters we take only the geometrical and magnetic configuration and the plasma parameters at approximately the stagnation point, which was in our case the outer midplane. Plasma parameters are obtained from the measurements made with the Langmuir probe head located on the horizontal midplane reciprocating manipulator. The length of the simulated system is calculated from the reconstruction of the magnetic configuration using EFIT [5] code and then artificially shortened in the code using enhanced collision factors. The simulation domain is terminated by two perfectly absorbing electrodes, presenting two divertor tiles, which are connected in short circuit. The magnetic field lines intersect with the two walls at 85°.

Figure 1: Transformation of a flux tube 2d to 1d.

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Figure 2: Magnetic surface reconstruction with EFIT for shot #3912.
Due to the 1d nature of the simulation system, the neo-classical properties of the SOL plasma are of course neglected, however, unlike the fluid modelling, here we take into account all relevant particle-particle and particle-surface interactions. Another advantage is the full resolution of the sheath, which is very important when EEDF modelling is in question.

Simulations are very demanding regarding the CPU time. We had obtained 300000 CPUh on the HPC-FF supercomputer, which proved to be far from enough to make a comprehensive study. Most importantly, in general we can make some crude calculations on the source strength to fit the measured parameters, but to reach the desired values of the density and temperature at the stagnation point we have to use the trial-and-error method.

To make a complete simulated profile, we would have to make individual simulations for each point of the measured profile, which was impossible. Therefore, we decided to simulate the flux tube close to separatrix, where we expected the high energy tail of the distribution.

2.2 Plasma input parameters

In this subsection we will just briefly present the method for obtaining input parameters. There are obviously only two plasma parameters needed to model the source, i.e. temperature and density. These parameters can be obtained either from electrical probe measurements or via some sort of spectroscopy method. Since Thomson scattering was unavailable at the outer midplane, we had to rely on the probe data. On Figure 3, the radial profile of the temperature and densities at the outer midplane are presented.

![Electron density n_e profile measured by the reciprocating probe](image)

![Electron temperature T_e profile measured by the reciprocating probe](image)

Figure 3: Density and temperature profiles from shot #3912 measured by LP.

These values are also reassessed via power the transport equation over the separatrix and balance with the sink, which is in short written as:

\[ P_{\text{SOL}} = \frac{n_u \chi_\perp k_B T_u A_\perp}{\lambda_{r_u}}. \]

Here \( n_u \) and \( T_u \) are upstream density and temperature, \( k_B \) is the Boltzmann constant, \( \chi_\perp \) is the radial anomalous heat conduction coefficient, \( A_\perp \) is the last-closed-field-surface (LCFS) surface area and \( \lambda_{r_u} \) is the radial upstream temperature decay length.
3 RESULTS

Measurement results are obtained from the divertor area probes. The presented results in Figure 4 show the discrepancy between the densities and temperatures measured by the classical method and the FDM at the divertor. We can see that the biggest discrepancy is in the vicinity of the striking points, which are presented as dashed lines. This is also the reason why we want to simulate the flux tube close to the separatrix.

![Figure 4: Measurement results from divertor area probes.](image)

On the other hand, the results obtained from the simulations are, in general, moments of distribution functions, which are obtained from averaging of subsequent phase spaces. From the results the points of entrance into the sheath are calculated from the equations following [6].

![Figure 5: Profile of the simulated flux tube.](image)

We take the values at the sheath entrance as the referential values to be compared with the probe measurement results, as they are unperturbed by the strong electric field in the sheath. The temperature calculated in the profile is reversely calculated following the classical method from the distribution functions in order to find comparable corresponding results, which then fit the measured values.

In Figure 6 we present the electron energy distribution functions obtained from the simulation at the sheath edge and a single-Maxwellian distribution for comparison. We can
see a strong deviation in the high-energy part of the distribution function leading to an error in the standard measuring method of the electron temperature and other plasma parameters.

![Normalized electron energy distribution functions at position $x = 9.722m$.](image)

Figure 6: Normalized electron energy distribution functions at position $x = 9.722m$.

4 CONCLUSIONS

We have tried to show, that the classical method has to be taken with precaution when it comes to the estimation of electron temperature data and parameters depending on the electron temperature. This is due to the fact, that the starting point of the classical method is the value of the floating potential, which is heavily influenced by fast electrons even if they are in small numbers. As measurements have predicted, this is often the case with the electron distribution function close to the separatrix or close to the striking points on the divertor.

We have used a kinetic code to simulate a single flux tube inside COMPASS-D tokamak. The Results have shown that at the sheath entrance there is a significant deviation from the Maxwellian distribution, leading to an overestimation of the “effective” temperature.

More CPUh will have to be obtained to make a comprehensive study of this issue.

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REFERENCES


