Radio-frequency sheaths in an oblique magnetic field

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Abstract

Radio-frequency(RF) sheaths occur in many processing plasmas and also occur in magnetically confined fusion devices. We are studying the sheath behaviour in a magnetized radio-frequency capacitively coupled (RF-CCP) discharge, with an oblique magnetic field via computational and experimental methods. In this paper, we present an inital investigation into the impact the magnetic field has on plasma properties, namely electron densities and temperatures, in a magnetized RF-CCP Argon discharge in comparison to an un-magnetized case as aswell as a brief discussion of simulation results for a magnetized RF-CCP discharge in the presence of an oblique field. This can be considered a benchmarking exercise for our code, MagPIC, as we compare our simulation results to experimental results provided by Institute for Plasma Research, Gandhinagar, Gujarat, India.

RF sheaths form in front of antennae in magnetic fusion devices during Ion Cyclotron Resonance Heating(ICRH) operation where the magnetic field often intersects surfaces at some oblique angle. These sheaths are thought to be responsible for numerous unwanted interactions such as impurity generation, hot spot formation, and power dissipation, all of which reduce the heating efficiency[1]. Therefore in order to optimize the performance of ICRH systems, these antenna-edge plasma interactions must be reduced. The solution to this problem begins with understanding the behaviour of magnetized RF sheaths. Our goal is that by studying their behaviour in a simple system (i.e RF-CCP discharge) this will help provide predictions of the behaviour of such sheaths in a larger more complex system (i.e RF sheaths near ICRH antennae in fusion devices) since magnetized RF-CCP discharges and antennae in magnetic fusion devices can experience similar RF processes[2].

MagPIC is an explicit 1d3v electrostatic PIC code, meaning it resolves one spatial but three velocity components and also includes the effect of an external magnetic field. It simulates a 1D plasma-sheath system in a symmetric parallel plate capacitive discharge where the plates are perpendicular to the x-axis. The space between the electrodes is filled with the working gas at a fixed density and temperature which determines the pressure of the system. The magnetic field is of constant strength but the angle, θ, is variable relative to the electric field which is directed perpendicular to the plates. Simulations can be chosen to be either voltage or current driven, starting with some set of initial conditions the system evolves to a steady state and the output data is averaged some sub-interval at the end of the calculation. MagPIC handles collisions via the Monte Carlo Collisions(MCC) method considering only collisions between the working gas and ion/electrons. Elastic, excitation, and ionization type electron-neutral collisions and elastic, and charge exchange type ion-neutral collisions are considered. It is also assumed that fluxes of charged particles reaching the electrodes are completely absorbed i.e no secondary particles are emitted.

Thus far we have simulated three cases: (a) an unmagnetized discharge, (b) a magnetized discharge with the field parallel to the plates and (c) a magnetized discharge with a range of oblique angles, at pressures of 1 Pa and 4 Pa. Simulations were driven with 100 V at RF frequency of 13.56 MHz with an electrode separation of 8 cm. T_e values were calculated for each case and compared with experimental results[3], which can be seen in the figures below.

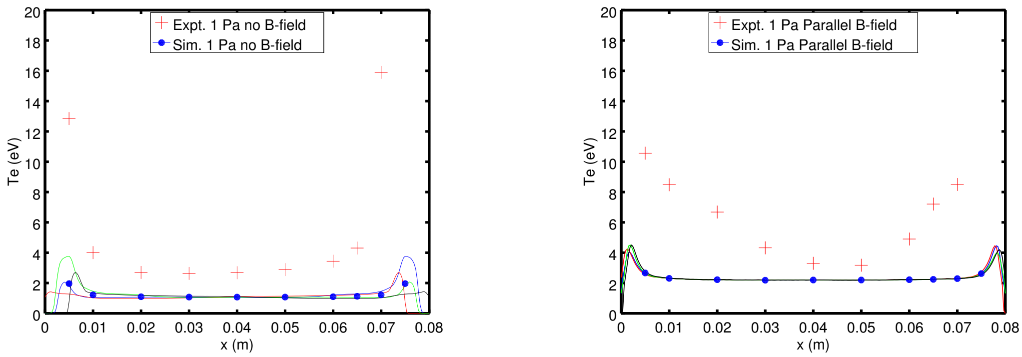

Figure 1: Comparison of T_e from simulation and experiment at 1 Pa for the un-magnetized case (left) and with application of a parallel magnetic field(right). Red points correspond to experimentally meansured values and blue points correspond to average T_e from simulations, while solid lines show variation of T_e over an RF cycle.

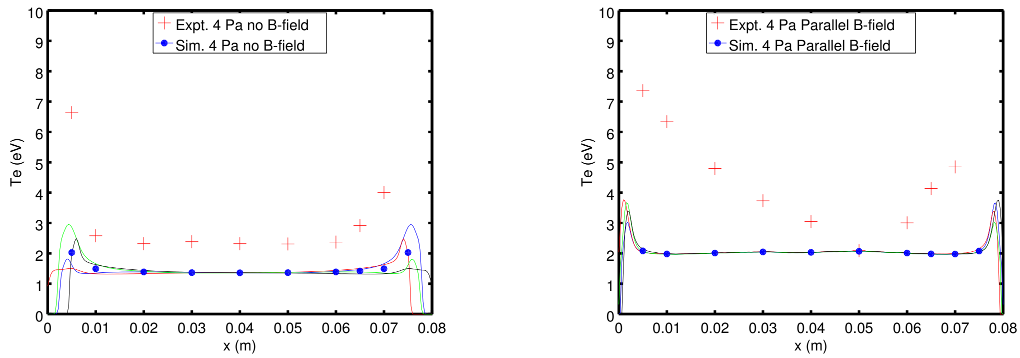

Figure 2: Comparison of T_e from simulation and experiment at 4 Pa for the un-magnetized case (left) and with application of a parallel magnetic field(right). Red points correspond to experimentally meansured values and blue points correspond to average T_e from simulations, while solid lines show variation of T_e over an RF cycle.

For the unmagnetized case, at both 1 Pa and 4 Pa, the simulation and experimental data show similar trends of an almost constant electron temperature throughout the bulk plasma and an increase towards the plates near the sheath region. This is to be expected due to stochastic heating due to the sheath, which is the dominant heating mechanism at low pressures[4]. The solid lines show the evolution of T_e during an RF cycle while the points correspond to an average T_e.

When the parallel magnetic field is applied, an increase in bulk T_e is observed in both experiment and simulations, compared to the un-magnetized case. In the simulations the trend seems to be consistent with the un-magnetized case showing a constant bulk T_e where as in the experimental case a linear gradient appears to form creating an increase in T_e from the centre of the discharge towards the plates.

One possible explaination for this inconsistency between the experimental and simulation data with the parallel magnetic field is interactions in the $E \times B$ field as the 1D simulation cannot completely take this effect into account. Therefore a 2D code is already being developed, which will include these interactions and will be benchmarked against experiments for further investigation.

For the oblique magnetic field, simulations were performed from angles ranging 10 to 80 degrees with the plates, and electron denisty and temperature values were calculated, at both 1 Pa and 4 Pa and are shown in the figures below. Experimental work on these oblique cases have not yet been completed and simulation results are still to be benchmarked.

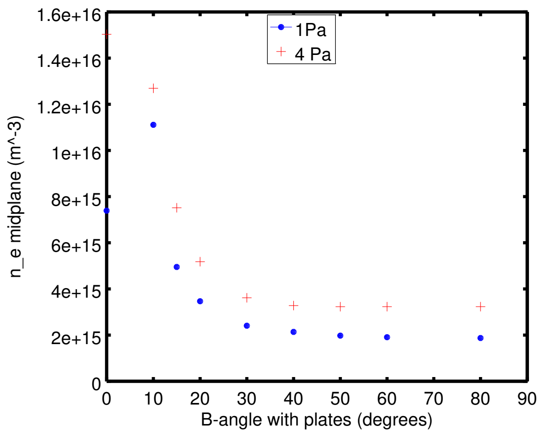

Figure 3: Simulation results showing the variation of midplane n_e with oblique angle with plates for 1 Pa and 4 Pa.

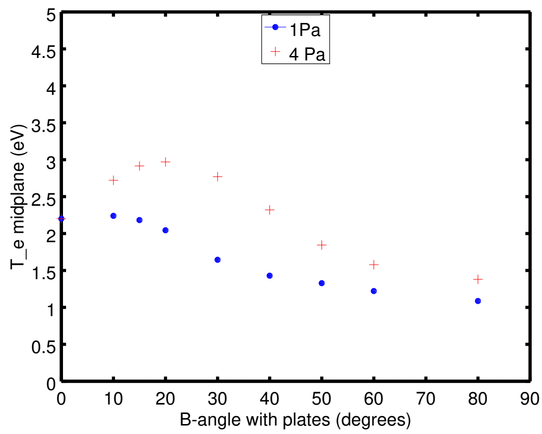

Figure 4: Simulation results showing the variation of midplane T_e with oblique angle with plates for 1 Pa and 4 Pa.

A sharp increase in electron density can be seen below 20 degrees, as the field approaches parallel alligment with the plates. The electron temperature in the bulk plasma increases with smaller incident field angles, see Figure 3. When the angle with plates is varied between perpendicular to almost parallel, the sheath width is found to be decreasing. For the larger angles of intersection, electron diffusion towards the plate is greater and the probability of electron-neutral collisions increases which can give rise to energy dissipation. While for small angles the electron flow is reduced therefore electron-neutral collisons also decrease, resulting in a higher electron temperature[5] as was observed in the simulations.

Future work will entail benchmarking our 1d3v oblique simulation results against the experimental results when complete, and a full comparison of the 2D code against experiments in both parallel and oblique fields. The results from these investigations will be used in an attempt to scale the behaviour of magnetized RF sheaths in these small simple systems to large fusion devices.

References

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