PROCEEDINGS OF SCIENCE

Simulating an Ion Energy Analyzer using the Particle-in-Cell technique

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1. Introduction

The code XPDP1 simulates a bounded plasma within planar electrodes and an external circuit in one dimension. XPDP1 is an 1d3v electrostatic code, with an imposed external homogeneous constant magnetic field. The code uses Particle-in-Cell technique for simulating ions and electrons, the leap-frog method for integrating motion and field equations and Monte Carlo collision model for simulating collisions between charged and neutral particles. The external circuit includes R, L and C elements and both AC and DC. Also ramped current and voltage sources are included. The characteristics of the external circuit, charged particles and electrostatic fields are specified for each simulation separately in form of an input file [1].

An Ion Energy Analyzer is a simple probe consisting of parallel grids and a collector plate behind them. The probe separates electrons and positive ions. It is used in plasma devices for obtaining plasma parameters of the ions. The simulations are used for researching an impact of the analyzer on a plasma and the importance of various probe characteristics.

XPDP1 was modified in order to simulate the Ion Energy Analyzer. The new version, XPDP1_rfa, includes two conductive grids with adjustable opacity as shown in *Fig. 3*. The first grid (deflector) is set to be on a floating potential (U_1) and since average electron speed is much greater than average ion speed, the grid will become negatively charged according to the *Eq. 1*.

$$\Phi = \frac{k_B T_e}{e_0} \ln\left(\sqrt{\frac{2\pi m_e}{m_i}}\right), \qquad (1)$$

where Φ is the floating grid potential, T_e and m_e are the temperature and the mass of electrons and m_i is the mass of ions.

The second grid is an ion discriminator. The potential on this grid (U_2) is directly driven and only the ions with sufficient energy can pass through the grid. The potential on the collector (U_3) should be low enough (about -100 V) to repulse the remaining high-energy electrons [2].

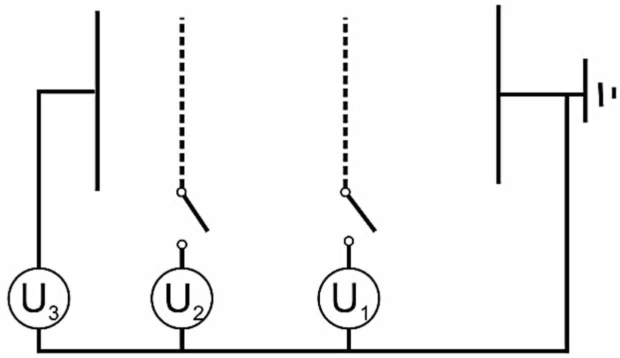

Figure 1: Circuit used for XPDP1_rfa. A planar source of charged particles was simulated on the right side of the system. On the left side, there was a collector grid (U3). The dashed lines represent conductive grids added to the system [2].

The main result of the simulation is the current-voltage characteristic, where the current on the collector plate is proportional to the number of ions that passed the discriminator grid. Since the velocity of the ions is distributed according to the Maxwell distribution, the equation for current density can be written as

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$$I(U) = I_s \exp\left(-\frac{e_0 U}{k_B T_i}\right), \tag{2}$$

where I_s is the saturated ion current, T_i is the ion temperature and U is the discriminator voltage. Using the I-U characteristics the ion temperature can be calculated and compared to the set ion temperature to determine the impact of the probe on a plasma.

2. Simulations

The gas used in the simulation was argon, with only single ionization allowed. On the right side of the system, shown in *Fig.1*, there was a planar source of charged particles. The temperature of the electrons was 1.0 eV and the temperature of the ions was in range from 0.1 eV to 5 eV. Both ion and electron current densities were set to 0.628 A/m^2. The distance between the source and the deflector grid was 4 mm and the distance between the discriminator grid and the collector plate was 3 mm. The ration between real particles and superparticles was 10^9 and the time step was $4 \cdot 10^{-11}$ s.

2.1 Inter-grid distance

The simulations are used for researching an impact of the analyzer on a plasma and the importance of various probe characteristics.

One of the most important parameters of the probe is the distance between the deflector and the discriminator grid. Several I-U characteristics are shown in *Fig.2*, using various inter-grid distances. It can be seen, that a limit distance exists, where the I-U characteristics starts to differ. The reason for that is the potential in the area between the grids. If the distance is too large, the maximum potential between the grids exceeds the potential on the discriminator grid due to the excess of the ions between the grids.

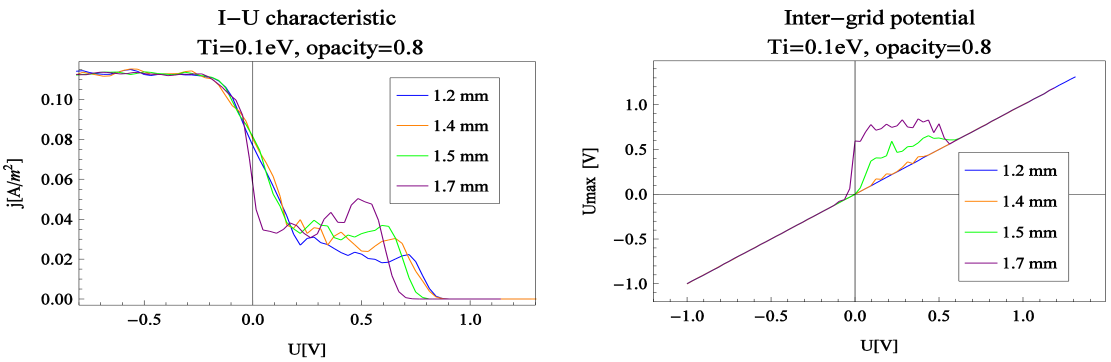

Figure 2: I-U characteristics for various inter-grid distances (left) and the maximum inter-grid potential versus the discriminator potential (right).

2.2 Opacity

The opacity can be set for each grid separately. For the discriminator grid, the opacity is set to 0.1 in order to reduce the statistical error. However, the opacity of the deflector grid represents the ratio between the surface of the real probe and the plasma vessel walls. In order to study the importance of this probe parameter, several simulations with different values were made.

It can be seen in *Fig.3* that the current density on the collector plate decreases with increasing opacity of the deflector grid as expected. However, the shape of the I-U characteristic does not

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change, which means that the size of the ion energy analyzer has no impact on the results of the measurements.

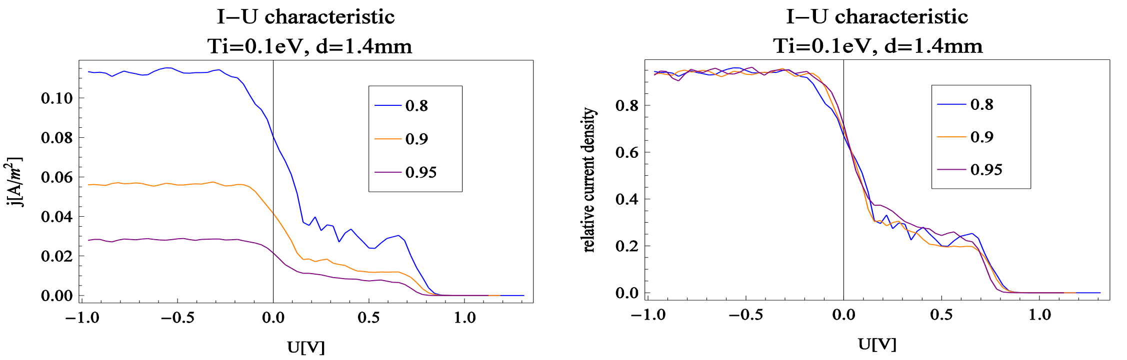

Figure 3: I-U characteristics with the opacity of the deflector grid set to 0.8, 0.9 and 0.95 (left) and the comparison of the shapes of the characteristics (right).

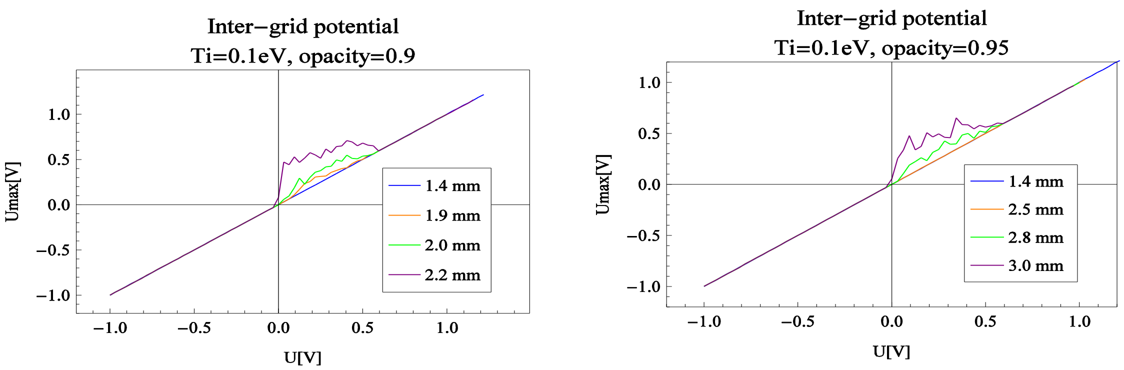

Figure 4: The maximum inter-grid potential versus the discriminator potential for opacity of the deflector set to 0.9 (left) and 0.95 (right).

The higher opacity of the deflector grid means lower number density of the ions in the area between the grids. Since the maximum inter-grid potential depends on the number density of the ions, the limit inter-grid distance depends on the opacity of the deflector grid. Some of the values are written in *Table 1*.

In all the following simulations the opacity of the deflector grid was set to be 0.9.

Table 1: The limit inter-grid distance for different opacities of the deflector grid. The temperature of the ions was 0.1 eV.

opacity	0.8	0.9	0.95
limit distance	1.4 mm	1.8 mm	2.6 mm

2.3 Ion temperature

Using the I-U characteristics, the ion temperature can be calculated and compared to the set ion temperature, in order to determine the impact of the probe on a plasma. The set ion temperatures were in range from 0.1 eV to 5.0 eV, the inter-grid distance was 1.4 mm and the opacity was 0.9.

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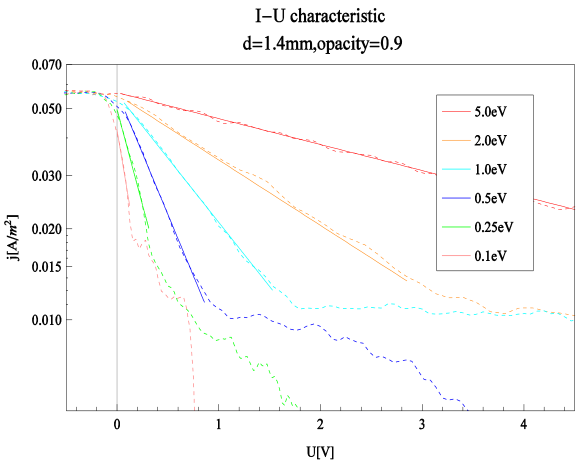

Figure 5: I-U characteristics for several ion temperatures. The dotted lines represent simulations and the solid lines represent the fitted curves.

The *Eq.2* was fitted on the I-U characteristics in order to calculate the ion temperatures. In *Fig. 5*, the solid lines represent the fitted curves and the intervals in which the characteristics correspond to the equation. The results are presented in *Table 2*.

Table 2: Comparison between the set and the calculated ion temperatures and the intervals of correspondence between the I-U characteristics and the equation.

T_{set} (eV)	0.10	0.25	0.50	1.00	2.00	5.00
T_{calc} (eV)	0.22	0.35	0.54	1.02	2.06	5.05
$(T_{calc} - T_{set}) / T_{set}$	1.16	0.38	0.07	0.02	0.03	0.01
interval (V)	0.0 - 0.13	0.0 - 0.31	0.0 - 0.86	0.0 - 1.53	0.0 - 2.85	0.0 - 7.73

The differences between the set ion temperatures and the calculated temperatures are in range from 0.03 to 0.12 eV. The relative difference decreases with increasing ion temperature. The interval of correspondence between the I-U characteristics and the equation increases almost linearly with the set ion temperature.

Higher ion temperature also results in larger limit inter-grid distance, since more ions crosses the discriminator grid and the number density of the ions in the inter-grid area is lower.

Table 3: The limit inter-grid distance for different ion temperatures.

T_i (eV)	0.10	0.25	0.50	1.0	2.0	5.0
limit distance (mm)	1.8	1.9	2.0	2.2	2.4	3.0

2.4 Secondary emission

In the second part of the research the secondary electron emission was included to the code. The secondary electrons can be emitted due to the impact of the electrons or the ions. However, the secondary electron emission coefficient is much smaller in case of an ion impact. Therefore only the secondary emission with electrons was studied.

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In the simulations, the secondary electron emission coefficient is set at constant value, even though the coefficient depends on the energy of the electrons. *Fig.6* shows several I-U characteristics using different secondary electron emission coefficients.

The emitted electrons are typically low-energy electrons. The energy of the emitted electrons is set to 0.025 eV. The minimum electron energy required for causing secondary emission is set to 0.050 eV, which is twice the energy of the emitted electrons.

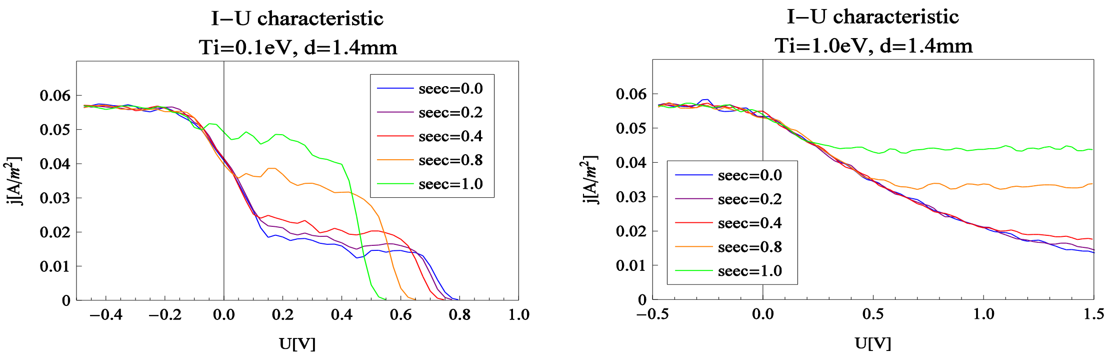

Figure 6: I-U characteristics for several secondary electron emission coefficients. The ion temperature is 0.1 eV (left) and 1.0 eV (right).

It can be seen in *Fig.6* that the secondary electron emission affect the results of the measurements with the ion energy analyzer. The inclinations of the upper part of the curves do not change. Therefore the calculated ion temperatures also do not change. With increasing secondary electron emission coefficient the interval of the correspondence between the I-U characteristics and the *Eq.2* decreases. Also, the current density reaches zero at lower discriminator voltage.

2.5 Conclusion

The XPDP1 code was modified in order to simulate the ion energy analyzer. The simulations show that one of the most important probe parameters is the distance between the deflector and the discriminator grid. The limit inter-grid distance depends on the deflector grid opacity, the ion temperature and probably also on other probe and plasma parameters. The correspondence between the set and calculated ion temperature shows the effect of the analyzer on plasma.

The secondary electron emission affect the measurements by shortening the interval of the correspondence between the I-U characteristics and the *Eq.2*. However, it does not affect the inclination of the curve and the calculated ion temperature.

References

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