EXPERIMENTAL TESTS OF NUMERICAL SIMULATION OF THE INTERACTION OF THE ROSETTA ORBITER WITH THE COMETARY PLASMA

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Abstract

Whenever this is possible, it is extremely valuable to compare results obtained by numerical simulation and modeling to experimental observations in order to check the validity and accuracy of the numerical methods and algorithms. In the course of a study of the electrical charging of the ROSETTA orbiter, we have thus undertaken an experiment in the JONAS facility at ONERA/DESP, a plasma chamber where it was possible to reproduce conditions scaled from the expected cometary environment and to deploy a simplified mock-up of the ROSETTA orbiter with its solar panels. In the following, we briefly discuss the methods which were used to define the range of adequate plasma parameters, describe the experimental set-up and the main results which are then compared to model calculations.

1- Experimental simulation of a cometary plasma: scaling laws and practical limitations

The JONAS plasma chamber aims at simulating the ionospheric environment sensed by LEO satellites and the plasma is obtained from a Kaufman ionization source followed by a neutralizing filament; the most commonly used gas is Argon. The densities and electron temperatures range respectively from a few 10^4 to 10^6 el/cm^{3}and from 2000 K to 6000 K while the ion drift velocity varies typically from ~ 3 to ~ 15 km/s. The plasma conditions which are expected in the inner coma of comet Wirtanen have been reviewed in a companion paper (Roussel and Berthelier, this volume) and are obtained from models (e.g. Mendis et al., 1985) since no direct measurement very close to a nucleus has ever been performed. For an active comet, the cometary densities in the model are in the range of ~ 10^3 to 10^5 el/cm^3 thus close to the densities obtained in the JONAS chamber. Plasma flow velocities in the inner coma range from a few hundreds meters/s to 1 km/s at most, significantly less than the values quoted above. The parameter showing the largest difference between cometary conditions and the plasma chamber is the temperature since the model temperatures of cometary thermal electron and ions vary typically from 50 K to 200 K. It is therefore not possible to reproduce in a plasma chamber such as the Jonas facility conditions identical to those expected during the ROSETTA mission. Simulating cometary conditions therefore leads to a similar situation as that encountered in experimental studies of gas dynamics: it is necessary to rely on similarity laws and determine properly scaled plasma conditions which can be achieved in practice and allow to perform a meaningful experiment.

1.1- Scaling laws

Let n, t_e, t_i, v_i, and m_i be the scaling parameters equal to the ratio between the plasma parameters (density, electron and ion temperatures, ion drift velocity, and ion mass) in the chamber and those in the coma. Similarly the ratio between the characteristic lengths, the electric potentials and the magnetic field in the chamber to those in the coma will be denoted by l, _, b.

We can safely assume that the cometary plasma is only composed of ions from the water group with masses 18 and 19 being the major species. During the tests in the JONAS chamber Argon has been used which thus gives a value of ~ 2.2 for the m_i parameter.

The determination of the scaling parameters can be addressed either by a physical approach or by a mathematical approach where one considers the dimensional equations derived from the physical equations which describe the physics of the system. Only the physical approach will be briefly reviewed here, a more detailed derivation of the scaling parameters can be found in Berthelier and Roussel (1999). In order to conserve the ion Mach number and the ratio of the ion and electron thermal velocities, the following relations must hold:

$$m_i\, v_i^2 = t_i \qquad (1)$$

$$t_e = t_i \qquad (2)$$

The kinetic and potential energies must scale similarly which can be achieved by keeping constant the ratio $e\Phi/kT$, hence the relation:

$$\varphi = t_e = t_i. \qquad (3)$$

As far as the geometrical dimensions are concerned, the ratio of the Debye length to the characteristic dimensions of the orbiter should be conserved, which writes as:

$$n\, l^2 = t_e. \qquad (4)$$

All together, the previous set of relations correspond to 4 constraints which can be expressed as:

$$\varphi = t_e = t_i = m\, v_i^{\ 2} = n\, l^2 \qquad (5)$$

and this leaves with 2 degrees of freedom for the total set of 6 parameters $n,\ t_e,,\ t_i,\ v_i,\ \varphi,\ l$. The condition on the magnetic field is rather simple: there is no magnetic field in the inner coma and laboratory simulations must be made in an unmagnetized plasma or at least under conditions where the magnetic forces are negligible compared to electric forces. In practice, the magnetic field in the JONAS chamber was controlled using a set of 3 Helmotz coils and made very small in the region of interest.

1.2- Practical limitations

The major limitation comes from the impossibility to scale the photo-electron distribution and current using the same scaling parameters as those adopted for the plasma parameters: the characteristic energy of the photo-electrons in the laboratory cannot be made different from that in space. We have thus not simulated the photo-electron emission in the laboratory. Nevertheless, and as will be shown later we have tested the effect of positive floating potentials on the plasma sheath structure by applying positive potentials on the mock-up.

Another limitation come from the limited range of velocities that can be achieved in practice in the chamber. Finally the comparison between the values of the main parameters in JONAS and the cometary conditions is as follows:

- Mach numbers of 8 to 10 compared to values of 3 to 6 in the coma,
- ratio of electron to ion temperature from 1 to 2, close to the ratio of 1 in the coma.
- l/λ_D from 5 to 700, very similar to the range from 10 to 1000 in the coma

2- Description of the experiment.

A schematic illustration of the experimental set-up in the JONAS plasma chamber is shown in figure 1. In a preliminary experiment we have determined the range of positive voltages which can be applied to the mock-up without exceedingly disturbing the plasma in the chamber. This was done using a simple plate 1 meter long and 20 cm wide simulating the solar panel. For the more complete 3D tests, the mock-up of the ROSETTA spacecraft was composed of a cube 20 cm in dimension representing the orbiter body and two truncated solar panels 50 cm long and 20 cm wide. As examplified by numerical simulations, what happens at the edge of the solar panels at more than ~20 λ_D has little effect on the plasma sheath in front of the cube which makes possible to reduce the length of the solar panels in the mock-up. The two sides of the solar panels are electrically insulated and can be biased separately. Similarly the face of the cube opposite to the plasma source, which corresponds to the face of the orbiter looking towards the Sun, is electrically insulated from the other five faces. Such a design aims at simulating the electrical configuration which was shown by numerical simulation to provide a way to reduce the positive equilibrium potential of the orbiter body which is detrimental to charged particle measurements. The mock-ups were placed near to the center of the chamber in the region where the earth s magnetic field can be compensated and reduced to less than 10 to 20 mG. Currents collected by all electrically insulated surfaces of solar panels or orbiter body can be measured independently. In addition, the face of the cube facing the plasma source has a circular hole in its center through which particles can access the entrance area of a plasma spectrometer which was designed to measure the angular and energy distribution of the incoming ions.

3- Experimental results.

3.1- 2D measurements. The main idea of this first series of measurement was to check the operation of a positively charged body with quite large dimensions in the JONAS chamber because, from past experience, we were aware of the likely disturbances induced in the operation of the ion source itself due to the collection of a large electron current by a positively charged probe. To check the plasma behavior we performed conventional Langmuir probe measurements at a number of locations both in front and in the wake of the plate. A typical current/voltage characteristic is shown in figure 2. It was obtained in the case of a plasma with undisturbed electron density and temperature of 5.5 10^5 el/cm^3 and ~3000 K respectively, corresponding to a Debye length of 5 mm, and an ion drift energy of 5.5 eV equivalent to a drift velocity of 5 km/s. The probe was located at 50 cm upstream of a plate biased with a 20 V positive potential. Although this characteristic displays some differences with respect to that obtained in an undisturbed plasma, it is still possible to determine the plasma potential at about 1.7 V as well as the electron and ion densities. As exemplified by figure 2, the main conclusion from this initial experiment was to ascertain that operation of a mock-up of such size was possible up to positive bias voltages of 10 to 20 V. In addition, some of the data show an increase in the ion density at some distance from a positively biased object, an effect which was already observed in numerical simulation and was assigned to the deceleration of drifting ions at the edge of the plasma sheath.

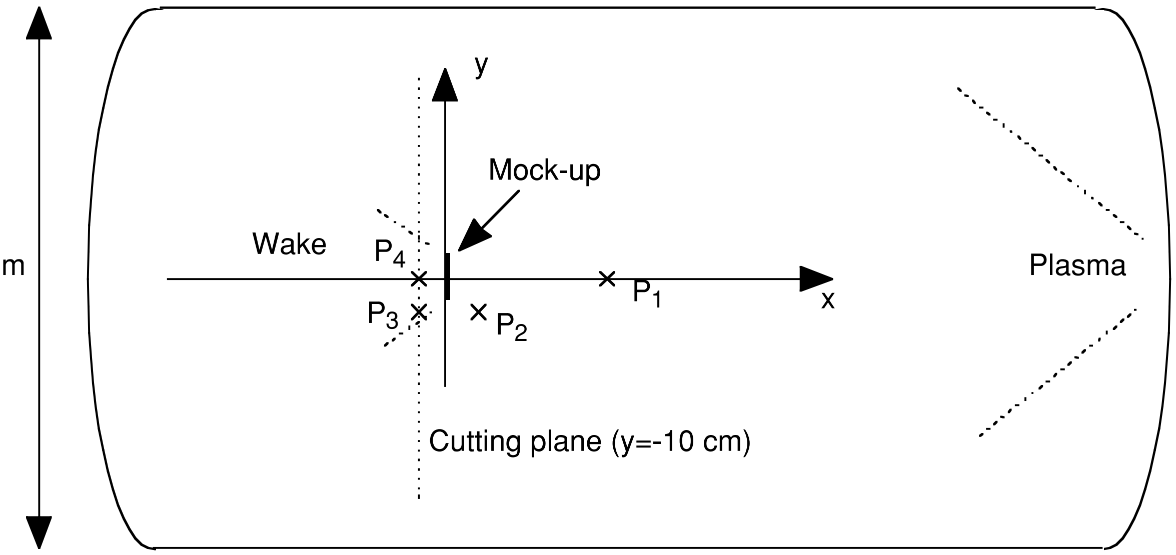


Figure 1. Schematic view of the JONAS chamber, 2D or 3D ROSETTA mock-up and location of Langmuir probe measurements.

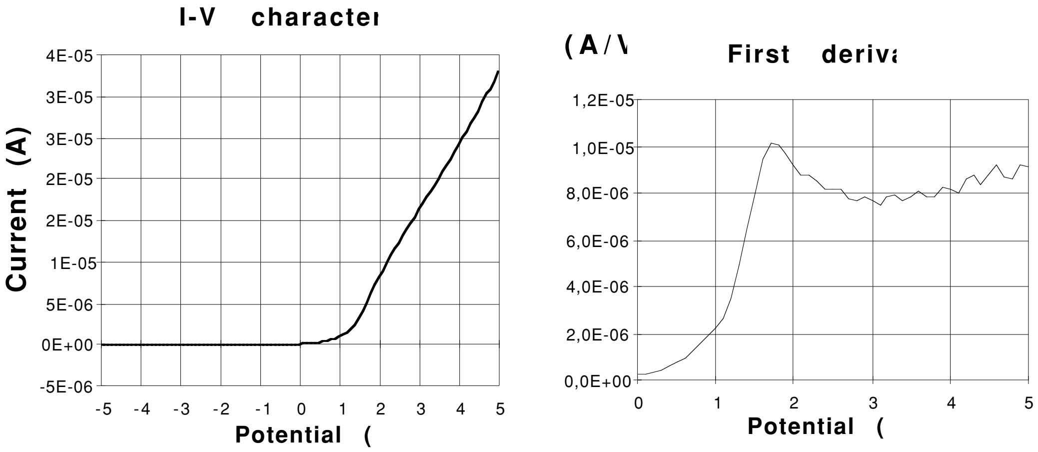


Figure 2. Current/Voltage characteristic of a Langmuir probe at 50 cm upwind of the 2D mock-up.

3.2- 3D measurements

In this series of measurements, the undisturbed plasma parameters were the following: electron density 1.4 10^5 el/cm^3, electron temperature ~4000 K, ion drift energy $E_{c\ \mathrm{ions}}$ = 5.5 eV – 1 eV, ion temperature parallel to the flow $T_{//}$ ~ 800 K, perpendicular to the flow $T_\perp$~ 300K as deduced from the ion flow divergence of ~3¡. These values were used for the numerical simulations to which the measurements were compared.

Global current measurements.

The most easily measured experimental variables are the currents collected by the 4 independently polarized areas of the external surfaces of the mock-up. Several different potential configurations were imposed on these 4 elements. The two first reported here correspond to the standard electrical configuration of the equipotential ROSETTA spacecraft with all external surfaces at the same potential, one case with a moderate negative voltage of —2 V, the second with a larger positive voltage of + 6 V. The third one corresponds to the insulator electrical configuration where the front faces of the mock-up looking towards the plasma source (i.e. towards the comet nucleus) are disconnected from the rear faces (i.e. looking towards the Sun); a large positive potential of +15 V is applied to the rear faces while the front faces are biased at — 2 V. The measured currents and the currents computed from a numerical simulation using the actual plasma parameters measured during the experimental tests are summarized in Table 1 and a graphical example is given in figure 3 for the second case with a bias of + 6 V applied to the entire mock-up. The agreement between experimental and modeled current is very good with discrepancies less than ~20% in all cases except for the ion current collected by the sunward face when it is negatively biased (first line of table 1). No ions are collected by this face in the simulation, since it is facing the wake. In the experiment, a small current is collected on the wake side, 0.4 A compared to ~13 A on the ram side. This wake current arises from the collection of the slow ions created in the chamber by charge exchange of drifting ions with the background neutrals (Coggiola, 1988; Roussel et al., 1997). Since this current is very small we simply have chosen to neglect it and not to take into account the slow ions in the numerical simulation since this implies a significant increase of the run time. One must note that the agreement is as good for a negatively or positively biased mock-up which demonstrates that the numerical simulation correctly models the ion as well as the electron dynamics which is important to guarantee the validity of the calculation of floating potentials.

Imposed potentials (V)		Collected currents (A)							
		Solar array				Main body			
Comet side	Sun side	comet side		sun side		comet side		sun side	
		simulation	experiment	simulation	experiment	simulation	experiment	simulation	experiment
-2	-2	13	12	0.00	0.40	9	10	0.00	0.00
6	6	-1522	-1530	-581	-610	-1895	-2170	-116	-94
-2	15	16	15	-1951	-1570	13	13	-641	-400

Table 1. Comparison of measured and computed currents collected by the 4 electrically isolated areas of the mock-up

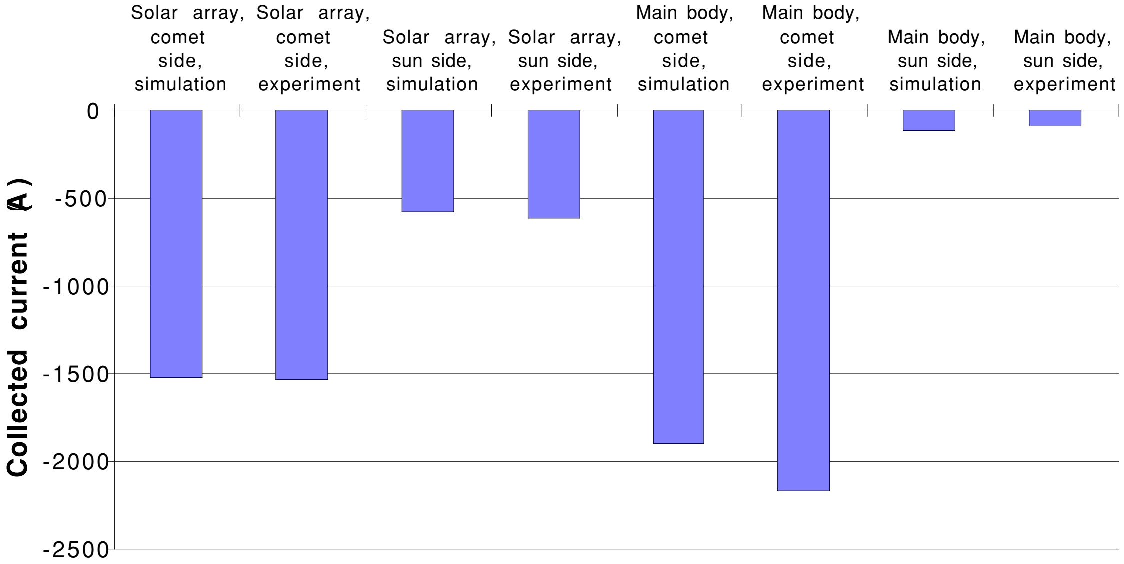


Figure 3. Measured and computed collected currents for an equipotential mock-up at + 6 Volts.

Ion analyzer measurements

One of the objective of the experimental tests in the JONAS chamber was to operate under conditions as close as possible to those encountered in the coma when the orbiter floats at a positive potential larger than both the thermal and drift energies of the ions. Under such conditions, practically no ion can reach the spectrometer if its entrance face is at the positive ground potential of the orbiter and measurements are meaningless. In order to try to overcome the repulsive effect of the positive mock-up potential we have made a series of tests with the entrance face of the spectrometer biased at a negative potential with respect to the orbiter ground. Such a configuration allows a detailed validation of the numerical model and, moreover, simulates the actual configuration of the ROSINA ion mass spectrometers on board ROSETTA which will have a negatively biased entrance area to attract ambient ions. In the experimental setup, the diameter of the hole in the face of the orbiter mock-up looking towards the plasma source (i.e; the comet nucleus) has been varied from 20 to 40 mm. The entrance area of the ion spectrometer which can be polarized is located just behind this hole at a distance of ~3.5 mm and its diameter is about 60 mm, so that the polarized area is always greater than the hole diameter.

Total current measurement at the entrance of the spectrometer.

In a first series of measurements we were interested in the total ion current collected by this entrance area which was compared with the similar quantity deduced from the numerical simulation. A sample of the results is given in figure 4 which displays a comparison in a graphical form of the measured and computed currents in the case of a hole with a 20 mm diameter. All current intensities were normalized with respect to the current collected when both the mock-up and the entrance aperture of the spectrometer are at the ground potential of the plasma chamber, practically within less than 1 volt from plasma potential.

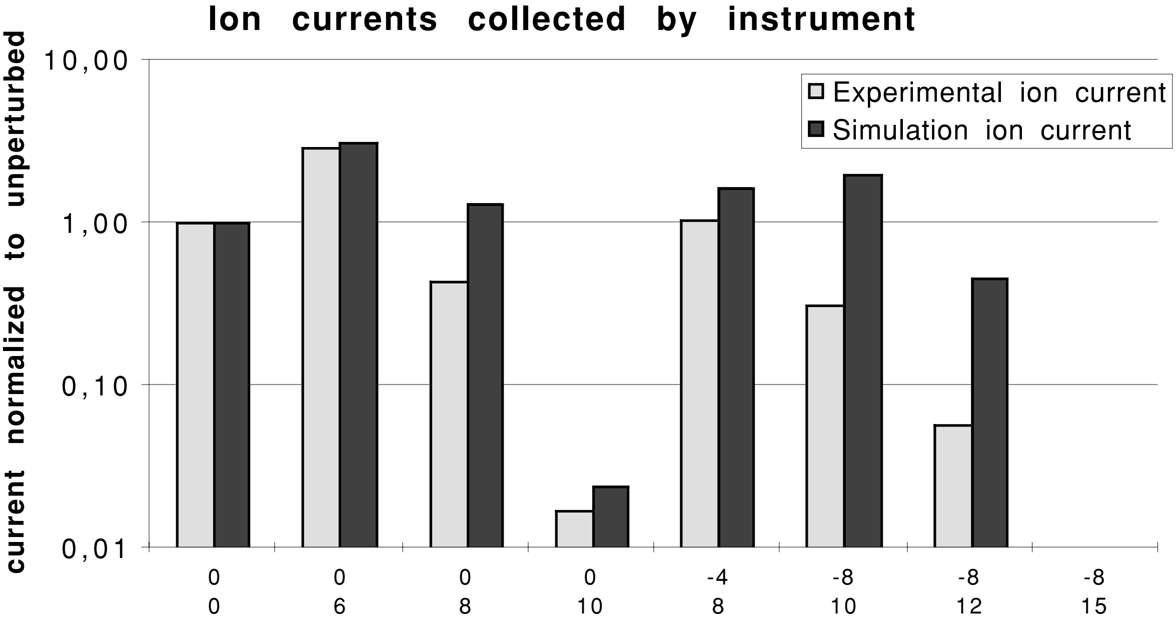


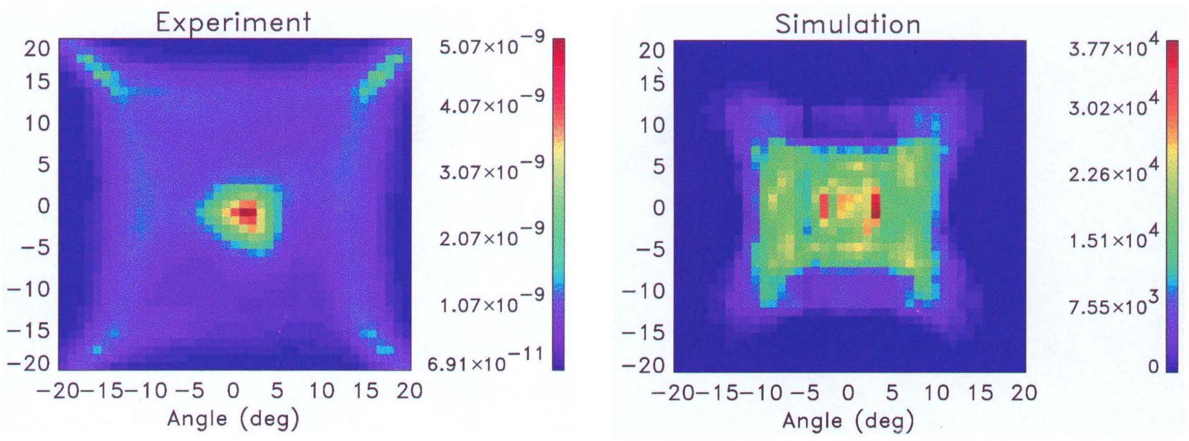
Figure 4. Comparison of measured and computed ion currents collected on the entrance area of the spectrometer. The various potentials applied to the mock-up (lower line) and to the entrance area relative to the mock-up (upper line) are indicated below the horizontal axis. Hole diameter in the face of the mock-up: 20mm

With + 6V on the mock-up and 0V on the spectrometer, the (6,0) case, the collected current is larger than in the reference case where both the mock-up and the entrance area are at the chamber floating potential, the (0,0) case. The negatively biased entrance area builds a potential structure in the nearby plasma sheath which focuses and attracts quite efficiently the incoming ions. However, this effect only exists as far as the potential on the mock-up does not exceed a threshold which is a function of the ion drift energy. When the potential applied to the mock-up increases (+ 8V and + 10V), the ion current decreases, for instance down to ~ 2 % of the (0,0) reference current in the case (+ 10,0). This indicates that a potential barrier at some distance in front of the spectrometer aperture prevents practically all ions to reach the spectrometer. As anticipated when the spectrometer aperture bias goes more negative with respect to the mock-up, the current collection is enhanced : for example with $V_{\text{mock-up}}$= + 10V, the current increases from 2% to 31% of the reference current when the spectrometer entrance bias goes from 0V to — 8V, in good agreement with the numerical simulation. The comparison between numerical and experimental currents show that the current collection is numerically overestimated by a factor of ~2 for most of the cases. One reason at least is certainly due to the difference between the actual geometry, where the spectrometer aperture plane is 3.5 mm behind the mock-up face, and the geometry used in the numerical simulation where the spectrometer aperture is supposed to lie in the plane of the mock-up face. In the real situation the actual voltage in the plane of the mock-up face is less negative than the spectrometer bias which thus reduces the ion current collection.

When the hole diameter is increased to 40 mm, the behavior of the currents and the agreement between simulation and experiment are rather similar. As can be expected the effect of the negatively biased entrance area is more sensitive.

Ion angular distribution measurement

The ion spectrometer was also used to determine the angular distribution function of the impinging ions. An example of the data and of the numerical results is presented in figure 5 for $V_{mock\text{-}up} = +8$ V and $V_{instr} = -4$ V. The selected ion energy was equal to the energy of flowing ions accelerated by the potential on the aperture of the spectrometer. The data from the spectrometer are output current measured on the detector as a function of the direction of sight of the instrument given by the 2 angles in vertical and horizontal planes. The X shape of the of the resulting angular distribution is due to the transfer function of the spectrometer with an enhanced sensitivity for directions of arrivals at 45¡ with respect to the main axis of the spectrometer. The main difference lies in the width of the measured, ~8¡, and computed, ~18¡, angular distribution. Two reasons can explain at least in part this difference. As mentioned above, the actual position of the entrance plane in the experiment is behind the face of the mock-up, contrary to the geometry used in the numerical model, and this can entail a more efficient converging lens effect which decreases the angle of incidence of the incoming ions. The second reason is linked to the 5 mm resolution of the numerical grid, too large to properly reproduce the exact potential variation in regions with small scale structures as is the case in the vicinity of the entrance area.



Conclusion

Using the JONAS plasma simulation chamber we have performed a series of tests in order to compare the experimental results to the results provided by a numerical modeling. Scaling laws were used to determine the range of experimental plasma conditions which can simulate the conditions anticipated in the inner coma of a comet. Within the limitations imposed on the plasma parameters by the operation of the plasma chamber itself and by the impossibility to experimentally reproduce a scaled photo-electron distribution, we have been able to achieve a number of tests in particular to describe the effects of the large positive floating potential of the ROSETTA orbiter which was obtained from the numerical simulation. The experimental measurements and the corresponding model results have been shown to be in good agreement, demonstrating the validity of the numerical modeling. The outcomes of this model can thus be used to predict the conditions which are likely to be encountered during the ROSETTA mission.

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