

Two-dimensional Particle-In-Cell model of the extraction region of the PEGASES ion-ion plasma source

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L. Garrigues^{1,2,a}, G. J. M. Hagelaar^{1,2,b}, D. Levko^{1,2,c}, and A. Aanesland^{3,d}

¹LAPLACE (Laboratoire Plasma et Conversion d'Energie),

Université de Toulouse, UPS, INPT Toulouse

118, route de Narbonne, F-31062 Toulouse cedex 9, France

²CNRS; LAPLACE; F-31062 Toulouse, France

³Laboratoire de Physique des Plasmas, CNRS, École Polytechnique,
91128 Palaiseau cedex, France

We have developed a two-dimensional Particle-In-Cell of the PEGASES thruster extraction region. Our simulation domain consists in a zoom of the one of the grid system. We consider one negative and one positive ion species with same mass and temperature, and electrons. The electronegativity is considered as a fixed parameter that has been changed from 1 to 10000 in the calculations. Because the main channel of particle losses is the collisions with walls, we have used a 0D global model to define an effective ionization source term to generate the plasma. We also propose and validate a method to control the electron temperature in the system. Results show that the electronegativity must reach very high value (on the order of 10000) to neglect the effect of electrons. In this regime, and for a square waveform applied on the biased electrode, calculations show that positive and negative ions can be collected alternatively by the grounded electrode, as far as the time passes by the ions between the two grids is shorter than the inverse of the signal frequency.

Nomenclature

roman characters

A	=	Surface of the electrodes (m^2)
e	=	electron charge constant (1.6×10^{-19} C)
E_x	=	axial electric field (V.m^{-1})
h	=	center-to-edge density ratio
I	=	current (A)
$I_{e,BE}$, $I_{i,BE}$	=	electron, ion current on the biased electrode (A)
$I_{i,GE}$	=	ion current on the grounded electrode (A)
k_B	=	Boltzmann constant (1.38×10^{-23} JK ⁻¹)
K_{iz} , K_{att} and K_{rec}	=	ionization, attachment and recombination rate ($\text{m}^3.\text{s}^{-1}$)
m_e , m_i	=	electron, ion mass (kg)
n_{e0} , n_{+0} , n_{-0}	=	averaged electron, positive and negative ion density (m^{-3})
n_{es} , n_{+s} , n_{-s}	=	electron, positive and negative ion density at the sheath edge (m^{-3})

^a Research Scientist at CNRS, laurent.garrigues@laplace.univ-tlse.fr

^b Research Scientist at CNRS, gerjan.hagelaar@laplace.univ-tlse.fr

^c Post-doctorate, dimitry.levko@laplace.univ-tlse.fr

^d Research Scientist at CNRS, ane.aanesland@lpp.polytechnique.fr

n_g	= gas density (m^{-3})
n_0	= bulk plasma density (m^{-3})
P, P_{abs}	= deposited, absorbed power (W)
S_{ion}	= ionization source term ($m^{-3}.s^{-1}$)
T_e, T_i	= electron, ion temperature (K)
$u_{Bohm}, u_{Bohm,*}$	= Bohm velocity, modified Bohm velocity ($m.s^{-1}$)
v_e	= electron velocity ($m.s^{-1}$)
V, V_{rec}	= bulk plasma, recombination volume (V)
W	= weight of particles
x	= x-direction (m)
y	= y-direction (m)

greek characters

α, α_s	= electronegativity in the bulk plasma, at the sheath edge
χ	= correcting factor for Bohm velocity
Δt	= time step (s)
Γ_{+s}	= positive ion flux on the surface ($m^2.s^{-1}$)
$\Gamma_{e,BE}, \Gamma_{i,BE}, \Gamma_{n,BE}$	= electron, positive and negative ions flux on the biased electrode ($m^2.s^{-1}$)
$\phi_{BE}, \phi_p, \phi_{ps}, \phi_s$	= biased, plasma, presheath, sheath potential (V)
$\gamma, \gamma_+, \gamma_-$	= ratio between electron and ion temperature, and positive ions, and negative ions

I. Introduction

Ion-ion (electronegative) plasmas differ from electropositive plasmas because the main negative charges are negative ions [1]. Only a few electrons are present in the discharge. One interesting application of this type of plasma could be for electric propulsion thrusters. In gridded ion engines, an external hollow cathode whose role is only to provide electrons not for thrust but to neutralize the ion beam in order to maintain the potential on the satellite close to the space plasma potential is necessary. In electric propulsion, the use of this external cathode leads of course to a more complex system. An electrostatic thruster with no external cathode called PEGASES (Plasma Propulsion with Electronegative Gases) has been proposed [2-4]. In the PEGASES thruster, an Inductive Coupling Plasma (ICP) discharge (RF antenna with a frequency at 4 MHz positioned upstream the source) is used to ignite the plasma (see Fig 1). A magnetic field barrier in the center of the discharge chamber is used to decrease the electron temperature to form an ion-ion plasma downstream the magnetic filter. At the end of the body, a system of grids is used to alternatively accelerate positive and negative ions. The injection of gas (SF_6) takes place through the walls of the source (see Fig. 2). The geometry of the source is rectangle with a cross section of 10 cm by 8 cm and 12 cm length [5].

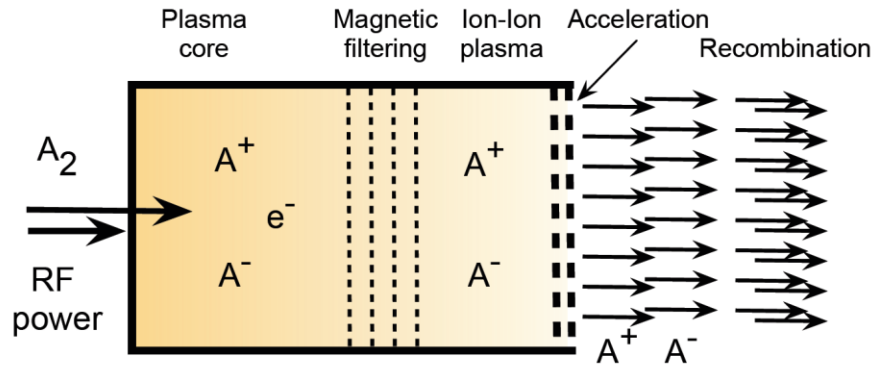


Figure 1: schematic view of the PEGASES concept.

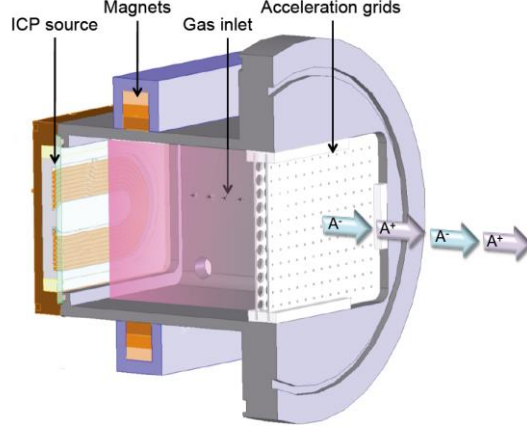


Figure 2: schematic view of the PEGASES prototype.

The problem of sheath formations in the case of alternate bias voltages to extract positive and negative ions is the one of the main issue of the PEGASES source. It has been studied for a simple one-dimensional case with plane electrodes for a pure ion-ion [6], and for a variable electronegativity [7], with Particle-In-Cell (PIC) simulations. The purpose of this work is to extend this work for geometry close to the accelerating grid system. We have developed a two-dimensional PIC model of the extraction region zooming on one hole of the grid system.

We describe the model based on the PIC approach we have developed in Section II. We use a heating technique to force the electron energy distribution to be a Maxwellian with a given temperature. The validation of the method for electropositive plasmas is shown in section III. The case of electronegative plasmas with a varying electronegativity is reported in section IV. We summarize our main results and draw the lines for future work in section IV.

II. Description of the model

The model we have developed is 2-dimensional and based on an explicit PIC description [8], [9]. Two-dimensional PIC models have already been developed in the context of the hydrogen neutral beam injection for the International Thermonuclear Experimental Reactor (ITER) program (e.g. [10], [11]). Extension to a three-dimensional PIC model has been already performed in the same context [12], [13]. The simulation domain is a zoom on one hole of the accelerating grid. It is a cartesian box that describes the sheath in front of extraction orifice (surrounded with a DC bias electrode with a voltage Φ_{BE}); the second grid electrode (plane) is grounded (see Fig. 3). Periodic boundary conditions are applied in the top and down simulation planes. The electric potential is fixed on the electrodes. The dimension of the simulation domain is 6 mm (x-direction) x 1.5 mm (y-direction). The distance between the biased electrode and the grounded one is 1.5 mm. The size of the grid aperture is 1.2 mm long and 2 mm in width. That corresponds to typical conditions of the PEGASES source.

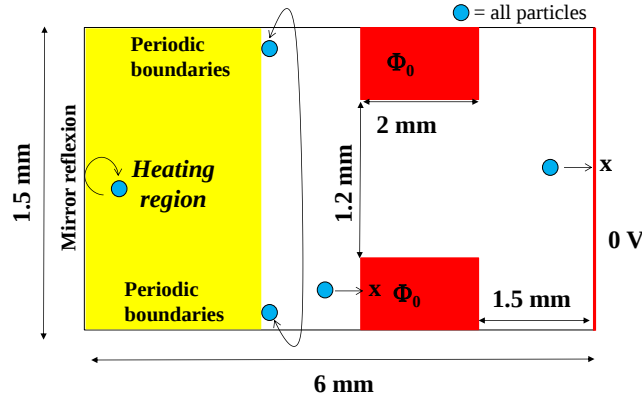


Figure 3: Computational domain.

We consider three different species (electrons, positive and negative ions). Charged particles are assumed unmagnetized. For particles, mirror conditions are applied on the left boundary (plane at $x = 0$) and periodic conditions are applied in the y -direction. All particles hitting the electrodes are eliminated from the system. To generate the plasma, we inject in the bulk plasma at each time step Δt a number of ions (each ion represents W real ions) that is proportional to a given source term of positive ions S_{ion} due to ionization and Δt and inversely proportional to W . For a positive bias voltage, the source term of positive ions can be fixed with a simple 0D global model, as in Ref. [14]:

$$K_{iz}n_{e0}n_gV - K_{rec}n_{+0}n_{-0}V_{rec} = \Gamma_{+s}A \quad (1),$$

$$K_{att}n_{e0}n_gV - K_{rec}n_{+0}n_{-0}V_{rec} \approx 0 \quad (2),$$

where K_{iz} , K_{att} and K_{rec} are the ionization, attachment and recombination rate constants respectively, n_{e0} , n_{+0} and n_{-0} are the averaged electron, positive and negative ion densities respectively. The gas density is noted n_g . V is the volume of the bulk plasma while V_{rec} is the volume where the recombination between positive and negative ions takes place. In our conditions, we can approximate V_{rec} by V . A is the surface of positive ions losses. The flux of positive ions impacting on the surface Γ_{+s} can be approximated by:

$$\Gamma_{+s} = hn_{+0}u_{Bohm} \quad (3),$$

where h is the center-to-edge density ratio and u_{Bohm} is the Bohm velocity of the ions at the sheath entrance. The h factor depends on the geometry of the source and plasma conditions [14]. In Ref. [15], a modified Bohm velocity is proposed for a given electronegativity α (ratio between negative ion and electron densities) and a given ratio between electron and ion temperatures γ (for same temperature for positive and negative ions). In this simple global model, we assume that the negative ions are trapped in the ambipolar electric field and the losses of negative ions are consequently negligible [Eq. (2)]. We also assume that electrons are collisionless.

Coupling Eqs. (1) and (2), we can define an effective ionization source term S_{ion} given by:

$$S_{ion} = \Gamma_{+s}A/V \quad (4),$$

in order that the positive ion density in the bulk plasma is n_{+0} . We have in parallel to inject negative charges in the bulk plasma to maintain quasineutrality. One solution could be to inject negative ions or electrons according to a probability proportional to the electronegativity $\alpha/(1+\alpha)$ and $1/(1+\alpha)$, respectively. This method is not suitable for very low and very large values of α . A more refine method consists to calculate the electronegativity α_c in the bulk plasma and to inject electrons when $\alpha_c > \alpha$ and negative ions when $\alpha_c < \alpha$. The same amount of negative charges as the positive charges is injected. When α tends to very large value, we use a lower weight for electrons to keep a sufficient electron number in the model. Particles are injected in the system according to the electron density profile.

We inject particles uniformly with a Maxwellian distribution function with a given temperature in the bulk plasma. The role of the electrons especially at low electronegativity is of course crucial because it controls the plasma potential. Previous studies in the context of the hydrogen neutral beam injection source [10-13] did not take care about that. We want to insist here that injecting electrons with a given temperature does not mean that the electron temperature in the system is equal to the initial temperature because high energetic electrons whose energy is large enough to pass sheath voltage drop are not trapped by the ambipolar electric field and escape from the system. The first consequence is that the electron temperature will be lower than the chosen initial one. The second consequence is that the electron energy distribution becomes non-Maxwellian. The electron temperature in the system is the result of the balance between the ionization in the volume and the losses of charges particles on the surfaces. We propose a method that has already been successfully used in the context of magnetized low-temperature plasmas [16]-[17]. We impose a given power that is absorbed by the electrons in a given region (called "heating region" that starts at $x = 0$ and ends at $x = 1.5$ mm – see the yellow zone in Fig. 3) and assume that this absorbed power P_{abs} leads to a Maxwellian electron energy distribution function. We first determine a number of electrons N that will be heated (that corresponds to around one third of the electrons positioned in the heating

region). We write that during one time step of the simulation Δt the total energy of these electrons is increased by $P_{abs}\Delta t$. The total new energy then can be expressed as a function of a given Maxwellian temperature T_e :

$$\frac{3}{2}Nk_B T_e = \sum_N \frac{1}{2}m_e v_e^2 + P_{abs}\Delta t \quad (5).$$

For the chosen N particles, we replace the previous velocity components with new components chosen from a Maxwellian at a temperature T_e . We adjust the absorbed power in order to obtain a temperature of 1 eV in the bulk plasma, close to measurements [3], [4]. For typical plasma density of 10^{16} m^{-3} , the Debye length is on the order of $7 \times 10^{-5} \text{ m}$ and plasma frequency $6 \times 10^9 \text{ s}^{-1}$. To respect the constraints on grid spacing and time step as for explicit method, 270×70 grid points and $\Delta t = 2 \times 10^{-11} \text{ s}$ are used. To reduce the computational time, we use a larger time step for heavy species that corresponds to $10 \times \Delta t$ (subcycling method – see Ref. [8]). We have also reduced the computational time by employing a hybrid parallel programming technique that combines OpenMP (Open Multi-processing) and MPI (Message Passing Interface). The elliptic Poisson equation has been solved using the PARDISO software package [18-20]. Computational time varies from 4 to 6 hours on Dual Six-Core Intel processor at 2.66 GHz.

III. Validation for electropositive plasmas

We first have performed calculations for an ideal one-dimensional problem, where the biased electrode has been removed and only positive ions of mass m_i and temperature T_i and electrons are considered in the case of a collisionless plasma. For Maxwellian electrons for electron temperature T_e , the plasma potential ϕ_p is therefore given by [14]:

$$\phi_p = \frac{1}{2} \frac{k_B T_e}{e} + \phi_s = \frac{k_B T_e}{e} \left(\frac{1}{2} + \ln \sqrt{m_i / 2\pi m_e} \right) \quad (6),$$

where ϕ_s is the sheath potential. We also calculate the power deposited on the grounded electrode. For collisionless plasma, the deposited power P is simply the product of the current impacting the surface I time the total energy lost (kinetic energy losses for electrons and ions at the surface) [14]:

$$P = I \left(2 \frac{k_B T_e}{e} + \phi_p \right) \quad (7).$$

We have performed calculations for different ion masses to validate the heating method we propose. Results are reported in Table 1. We notice a good agreement between the calculations and the results from the analytical theory.

Ion mass (a.u.m.)	T_e (eV)	ϕ_p – calculations (V)	ϕ_p – theory (V)	Power - calculations (W)	Power - theory (W)
4	1.4	5.5	5.6	0.105	0.11
18	1.67	7.8	7.9	0.07	0.08
73	1.8	9.5	9.7	0.044	0.046
146	1.8	10.2	10.5	0.031	0.035

Table 1: Comparisons between calculated and theoretical plasma potential and deposited power on the grounded electrode for a one-dimensional geometry.

We secondly have performed calculations for the geometry of Fig. 3. We have fixed the potential on the bias electrode ϕ_{BE} to a positive value. Of course the validation with analytical formulation of the problem is more complex due the grid aperture. In the situation where ϕ_p is positive and large, the grounded electrode will collect positive ions, and the biased electrode will collect electrons and positive ions. Of course, the total current is conserved in our system; therefore, the electron current is larger than the ion current on the biased electrode. In the following, our reference potential is the bias electrode potential. In front of the biased electrode, the electron flux in the Maxwell-Boltzmann approximation can be written as [14]:

$$\Gamma_{e,BE} = \frac{1}{4} h n_0 e^{-\phi_s/T_e} \sqrt{\frac{8k_B T_e}{\pi m_e}} \quad (8),$$

Where n_0 is the plasma density in the bulk plasma. The ion flux can be expressed as:

$$\Gamma_{i,BE} = h n_0 \sqrt{\frac{k_B T_e}{m_i}} \quad (9).$$

Combining Eqs. (8) and (9) gives the electric potential in front of the sheath ϕ_s :

$$\phi_s = \frac{k_B T_e}{e} \ln \left[\sqrt{\frac{m_i}{2\pi m_e}} \frac{\Gamma_{i,BE}}{\Gamma_{e,BE}} \right] \quad (10).$$

The ratio of ion over electron flux is calculated with the PIC model to compare analytical sheath voltage given by Eq. (10) and calculations.

We can also calculate the power deposited on the surfaces of the system:

$$P = I_{e,BE} 2 \frac{k_B T_e}{e} + I_{i,BE} \phi_p + I_{i,GE} (\phi_p + \phi_{BE}) \quad (11),$$

where $I_{e,BE}$, $I_{i,BE}$, and $I_{i,GE}$ are the electron and ion current on the biased electrode, and ion current on the grounded electrode, respectively. In the case where $\phi_{BE} > \phi_p$, and for low electron temperature, the deposited power can be approximated by:

$$P \sim I_{i,GE} \phi_{BE} \quad (12),$$

We have summarized comparisons between analytical results and calculations in Table 2. For same plasma condition, we notice that as the potential on the biased electrode decreases, the ion flux on the biased electrode increases and the sheath potential increases. At the opposite, the ion current collected on the grounded electrode decreases, so does the power deposited on the surfaces of the system. Increasing the ion mass keeping constant the biased voltage leads to an increase of plasma potential and a decrease of deposited power. Again, the calculations and the results from the Maxwell-Boltzmann theory are comparable. All these comparisons for simple case where only electrons and positive ions are taken into account show that we can properly control the electron temperature and maintain a Maxwellian distribution for electrons in the system.

Ion mass (a.u.m.)	ϕ_{BE} (V)	T_e (eV)	ϕ_s – calculations (V)	ϕ_s – theory (V)	Power - calculations (W)	Power - theory (W)
18	2000	1.8	1.2	1.4	14.28	14.2
18	500	1.75	5.2	4.8	2.85	2.75
18	200	1.7	6.5	6	0.8	0.78
73	200	1.85	8.2	7.9	0.41	0.39

Table 2: Comparisons between calculated and theoretical sheath potential and deposited power on the electrodes for the one-hole geometry.

IV. Calculations for electronegative plasmas

We have performed calculations for the geometry of Fig. 3 in the case of positive and negative biased voltage $\phi_{BE} = \pm 200$ V. Temperature of charges species is fixed ($T_e \sim 1$ eV, $T_i = 0.07$ eV). The mass of ions (same for positive and negative) is fixed to 18 a.u.m. Only recombination between positive and negative ions will be considered. The recombination rate is fixed to $K_{rec} = 5 \times 10^{-14} \text{ m}^3 \cdot \text{s}^{-1}$ [14]. The electronegativity α will be considered as a free parameter.

A. Fixed bias voltage

We show in Fig. 4 the current fractions collected by the biased electrode (BE) and grounded electrode (GE) for a wide range of electronegativity variation. In our system the total current is conserved. The sum of the negative charge current (electrons plus negative ion species) collected by both electrodes is equal to the positive charge current. For positive and negative bias voltage, we observe three different regimes. For $\alpha < 10$, the negative ions effect is negligible. For positive biased voltage, the ion current extracted from the source is not compensated by the electron current collected by the bias electrode and a non-negligible fraction of ion current is also lost on the bias electrode. For intermediate value of α (between 10 and 1000), the negative ions start to play a role in the current contribution. Finally, we have to wait very large electronegativity ($\alpha > 1000$) to consider that the effect of the electrons becomes negligible. In this latest regime, when $\phi_{BE} > 0$ (respectively < 0), the grounded electrode collects positive ions (respectively negative ions) and the biased electrode collects negative ions (respectively positive ions).

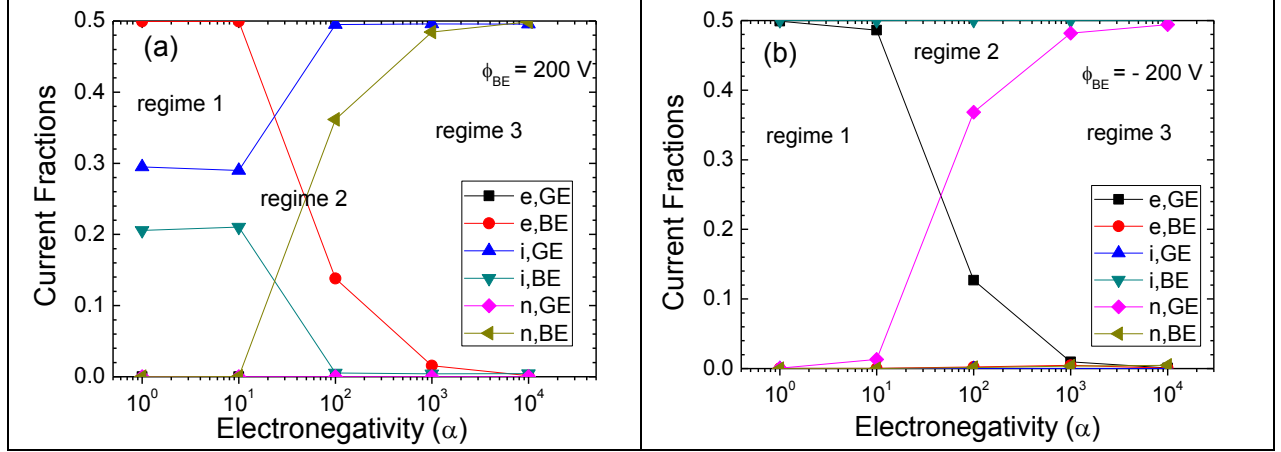


Figure 4: Collected currents by (a) the biased electrode (BE), (b) grounded electrode (GE) for a positive and a negative bias voltage ϕ_{BE} . The subscripts e, i and n indicate electron, positive and negative ions.

We have analyzed the evolution of plasma potential as a function of electronegativity. For a reference potential taken on the biased electrode, the plasma potential defined as the difference of electric potential between the bulk and the biased electrode, can be written as:

$$\phi_p = \phi_{ps} + \phi_s \quad (13),$$

Where the first term corresponds to the presheath potential given by [14]:

$$\phi_{ps} = \frac{1}{2} \frac{k_B T_e}{e} \left[\frac{1 + \alpha_s}{1 + \gamma \alpha_s} \right] \quad (14).$$

Remark that α_s is the electronegativity at the sheath edge. As far as α (and α_s) increases, the presheath potential reduces to:

$$\phi_{ps} = \frac{1}{2} \frac{k_B T_e}{\gamma e} \quad (15),$$

and ϕ_p tends to be equal to ϕ_s for large ratio between electron and ion temperature, as in our problem ($\gamma \sim 15$).

In the case of electronegative plasmas, positive ions enter in the sheath with a modified Bohm velocity according to Ref. [15] and the ion flux impacting on the biased electrode can be written as

$$\Gamma_{i,BE} = n_{s+} \sqrt{\frac{k_B T_e}{m_i}} \sqrt{\frac{1 + \alpha_s}{1 + \gamma_+ \alpha_s} + \frac{1}{\gamma_-}} = n_{s+} \sqrt{\frac{\chi k_B T_e}{m_i}} \quad (16).$$

γ_+ and γ_- are ratio between electron and positive ion temperature, and electron and negative ion temperature. The positive ion density at the sheath edge is noticed n_{s+} . Remark that when $\gamma_+ = \gamma_-$ and when $\alpha \gg 1$, the modified ion Bohm velocity $u_{Bohm,*}$ is:

$$u_{Bohm,*} = \sqrt{\frac{2k_B T_i}{m_i}} \quad (17).$$

This velocity is larger by a factor $\sqrt{2}$ than the modified ion Bohm velocity proposed in Ref. [14]. Calculations have confirmed that at large electronegativity the positive ions enter in the sheath with a velocity given by Eq. (17), as in Reference [7].

For electrons in a Maxwellian-Boltzmann equilibrium, the electron flux at the walls is given by [as Eq. (8)]:

$$\Gamma_{e,BE} = \frac{1}{4} n_{es} e^{-\phi_s/T_e} \sqrt{\frac{8k_B T_e}{\pi m_e}} \quad (18),$$

Where the electron density at the sheath edge is noticed n_{e+} .

We have tried to analyse the sheath potential strength with simple analytical analysis by estimating the current collection on the biased electrode.

In regime 1, the negative ions are repelled by the sheath potential. The situation is very close to electropositive plasmas. We have calculated the gradient of the pressure term $\nabla(n_e k_B T_e)$ and force term $en_e E_x$ – where E_x is the axial electric field. The two terms are on the same order, we consequently can write a Maxwell-Boltzmann relation for the electrons and Eq. (8) is still valid. Because the ion density is equal to electron density at the sheath entrance, the sheath potential can be deduced by combining Eqs. (16) and (18):

$$\phi_s = \frac{k_B T_e}{e} \ln \left[\sqrt{\frac{m_i}{\chi 2\pi m_e}} \frac{\Gamma_{i,BE}}{\Gamma_{e,BE}} \right] \quad (19).$$

When $\alpha = 1$, α_s tends to 0.5, and the positive ions enter in the sheath with a modified Bohm velocity very close to the Bohm velocity for electropositive plasmas. For positive bias voltage, ϕ_s given by Eq. (18) is 3.2 V very close to 3.5 V. For negative bias voltage, the calculated sheath potential is 17.5 V near the calculated one (17 V). Notice that the large difference between the two cases is simply due to difference of positive ion and electron fluxes collected by the biased electrode.

For others regime, comparisons with analytical seem difficult. In regime 2, the current collection is composed by positive and negative ions, plus electrons. Moreover, we do not observe a Maxwell-Boltzmann equilibrium for negative charged particles. In regime 3, when $\phi_{BE} > 0$, positive ions are collected on the grounded electrode, while negative ions are collected on the biased electrode. To repel positive ions from the biased electrode, the sheath potential is reversed and negative ions can be accelerated towards the biased electrode. In this situation, the maximum of plasma potential is the biased electrode. For $\phi_{BE} < 0$, when negative ions are extracted from the source, the sheath potential is now positive to accelerate positive ions towards the biased electrode. Further investigations are needed to estimate sheath potential drop.

B. Alternate bias voltage

We have run calculations in the case of large electronegativity and the plasma is composed by positive and negative ions ($\alpha = 10000$). The biased voltage is alternatively positive and negative (with a magnitude of 200 V). The voltage waveform is a square whose frequency varies from 1 MHz to 100 kHz. We have observed an alternate extraction of positive and negative ions on the grounded electrode. This is due to fact that the time passed by the ions in the sheath in front of the grounded electrode is shorter than the inverse of the frequency.

V. Conclusions and future works

We have developed a two-dimensional PIC of the extraction region of the PEGASES ion thruster. We have considered one positive and one negative ion species of same mass (18 u.m.a) and same temperature, and electrons. Our computational domain is a zoom on one hole of the source. Periodic boundary conditions are used on the top and down frontiers. Mirror conditions are used on the left boundary. Since collisions do not dominate and the main losses of charged particles are on the walls, we have shown that we can define an ionization effective source term to generate the plasma. Derived from previous work, we have proposed a method to force a Maxwellian energy distribution for the electron and that is able to control the electron temperature.

We have first have validate the method in the case of electropositive plasmas in a one-dimensional plane to plane geometry and for a one-hole geometry by comparisons of plasma potential and power between calculations and simple analytical (or semi-analytical) formulation.

We have then have performed calculations for varying the electronegativity by 4 orders of magnitude. Results show that we can define three different regimes. At low electronegativity, electrons still play a major role on the plasma potential and current extraction. In an intermediate regime, both negative charges play a role, and finally for very large electronegativity, the electron effect becomes negligible. In this latter regime, for a square waveform of biased potential, positive and negative ion currents can be collected on the grounded electrode as far the frequency of change of the biased voltage is larger than the time for the ions to pass the region between the two grids.

Because the plasma composition in the case of SF_6 is rather complex [21] and different ion mass can be generated inside the plasma and extracted from the source, more works are now needed for different ion masses. The effect of the shape of the biased electrode waveform applied on the current extraction then can be more deeply analyzed. Even if we have seen that at high electronegativity the role of the electrons is reduced, the effect of the magnetic field has also to be investigated. Finally, this model of the extraction region can furnish initial ion energy distributions to another model that will be able to carefully look at the acceleration and the role of space charged limitations on longer distance, as well as recombination effect.

Acknowledgments

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References

- [1] D. J. Economou, *Applied Surface Science* **253**, 6672 (2007).
- [2] A. Aanesland, A. Meige, and P. Chabert, *Journal of Physics: Conference Series* **162**, 012009 (2009).
- [3] A. Aanesland, J. Bredin, P. Chabert, and V. Godyak, *Applied Physics Letters* **100**, 044102 (2012).
- [4] J. Bredin, P. Chabert, and A. Aanesland, *Applied Physics Letters* **102**, 154107 (2013).
- [5] A. Aanesland, D. Rafalskyi, J. Bredin, P. Grondein, N. Oudini, P. Chabert, L. Garrigues, and G. J. M. Hagelaar, “The PEGASES Gridded Ion-Ion Thruster Performance and Predictions”, 33rd *International Electric Propulsion Conference*, October 2013, Washington, D.C., paper IEPC-2013-259.
- [6] N. Oudini, L. Garrigues, A. Meige, J. L. Raimbault, P. Chabert, and A. Aanesland, *Physics of Plasmas* **19**, 103501 (2012).
- [7] N. Oudini, J.L. Raimbault, P. Chabert, A. Meige, and A. Aanesland, *Physics of Plasmas* **20**, 043501 (2013).
- [8] R. Hockney and J. Eastwood, *Computer Simulation Using Particles* (Mac Graw-Hill, 1981).
- [9] C. Birdsall and A. Langdon, *Plasma Physics Via Computer Simulation* (IOP, 1998).
- [10] K. Miyamoto, S. Okuda, and A. Hatayama, *Applied Physics Letters* **100**, 233507 (2012).
- [11] F. Taccogna, P. Minelli, S. Longo, M. Capitelli, and R. Schneider, *Physics of Plasmas* **17**, 063502 (2010).
- [12] S. Mochalsky, A. Lifschitz, and T. Minea, *Journal of Applied Physics* **111**, 113303 (2012).
- [13] S. Mochalsky, A. Lifschitz, and T. Minea, *Nuclear Fusion* **50**, 105011 (2013).
- [14] M.A. Lieberman and A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, 2nd ed (Wiley-Intersciences, New York, 2005).
- [15] H. Ghoumo and M. Khotamabadi, *Journal of Fusion Energy* **30**, 481 (2011).
- [16] G. Fubiani, G. J. M. Hagelaar, J. P. Boeuf, and S. Kolev, *Physics of Plasmas* **19**, 043506 (2012).

- [17] J.P. Boeuf, B. Chaudhury, and L. Garrigues, *Physics of Plasmas* **19**, 113509 (2012).
- [18] <http://www.pardiso-project.org/>
- [19] O. Schenk, A. Wächter, and M. Hagemann, *Computational Optimization and Application* **36**, 321 (2007).
- [20] O. Schenk, M. Bollhofer, R.A. Romer, *Society for Industrial and Applied Mathematics Review* **50**, 91 (2008).
- [21] D. Levko, L. Garrigues, and G. J. M. Hagelaar, *submitted to Journal of Physics D: Applied Physics* (2013).