ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-WEB2

PLASMA MODELIZATION AND STUDY FOR THE PHOENIX V3 ECR ION SOURCE

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Abstract

In the framework of the Spiral2 project, the PHOENIX V3 Electron Cyclotron Resonance Ion Source (ECRIS) (upgraded version from the previous PHOENIX V2) has been developed to optimize the production of ion beams with charge over mass Q/A=1/3. The ion source aims to produce mainly metallic ions. For such beams, the atoms are, for a majority of them, trapped into the plasma wall of the plasma chamber leading to a poor global ionization efficiency. A hybrid particle in cells (PIC) code is under development to study and reproduce the experimental spectrum from ion source PHOENIX V3. The simulation is 3D and focuses on the propagation of the ion. The simulation have several free parameters to adjust the distribution of the ion charge stat at the exit of the ion source. The simulation has already given some encouraging preliminary results.

INTRODUCTION

For plasma modelization, like for the ion thruster, the simulation are done using Particle-In-Cell (PIC) code method. Traditional PIC codes propagate neutral atoms, ions, and electrons in electromagnetic fields. It also includes computation of collisions between particles (neutrals and charged) as well as the resolution of the Poisson equation to, dynamically, take into account the electric field generated by the charged particles. To be confident into the results coming up from the simulation, PIC code must meet specific conditions. The time step of the particles propagation must be less than half of the lowest chara-cteristic time. It is the same for the space discretization, which must be thin enough for the Poisson equation resolution.

In the case of a PIC code applied to an ECR ion source plasma, the characteristic time is the electron rotation period around a magnetic flux line while the Debye length defines the spatial mesh. The ECR ion source plasma contains high-energy electrons; the minimum time step is of the order of picosecond, and the Debye length about micrometer. The aims of the simulation is to reproduce the ionization evolution of charged particles in the ECR ion source for different species and magnetic configuration in order to understand their dynamics of with the final goal to improve the global ionization efficiency. It is necessary to simulate the ion source operation for a duration greater than one milli-second at least in order to reach the equilibrium of the plasma. Propagation of charged particles during a millisecond within these conditions would require too much computing time. It has been decided to approximate some.

HYPOTHESIS

To shrink the computing time, it is necessary to reduce the number of mathematical operations done by the simulation does, while meeting the Physics hypothesis.

Electron Simplification

The first assumption is to consider that the electrons, more energetic than the ions, adapt their movements to those of the ions. Hence, it is possible to increase the time step imposed to the simulation by a factor of one thousand but also to reduce the number of particles moving into the simulation.

As the electrons follow the ions, the major electric charged are screened, and the plasma in the ion source is globally neutral. The Poisson equation resolution is no longer needed and neither the ion source mesh with one micrometer side cell. The plasma neutrality and the screening effect of the charged particles involve the nonexistence of plasma sheath and extraction meniscus.

Macroparticles Method

The PHOENIX V3 ion source has a volume of 1.45 liters, and operates with a pressure of 10^{-7} millibar. A rough estimation gives 10^{10} particles. The simulation cannot handle as many particles. The neutral atoms and the ions are injected and propagated, as macroparticle for the simulation. The particle number, and at the same time the macroparticle number, is not constant during the simulation.

It's extremely tough to estimate what value of particles belonging to a macroparticles the system evolves. However, it is important that the macroparticle numberpresent in the simulation doesn't increase too much. For this, it is necessary to establish a maximum for the macroparticle value and modify the particle number per macroparticle during the simulation. The charge exchange involves two macroparticles, whose charges and species may differ. To maintain the global charge and keep an equal charge for the particles in the same macroparticle, all macroparticles must have the same weight. The macroparticles weight variation must hold the charge and the number of particles.

SIMULATION

Propagation in Magnetic Field

The ion source is immersed in a intense magnetic field. The use of the "Leap Frog" method with a magnetic field produces a particles energy divergence. Propagation of charged particles is done with the Boris method [1], and the neutral particles are propagated in a straight line to reduce the computation time. In addition to the magnetic field, some

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experimental studies have highlighted the existence of a potential dip inside the plasma, but its position is not well known yet.

The potential dip keeps the ions confined in the plasma center between the axial magnetic field maximums. This trap enhance the multicharged ion production rate. In order to reproduce the experimental spectrum, from the PHOENIX V3 source, the simulation integrates a potential dip model. The potential dip is modelled by a local potential barrier, and located at the level of the ECR resonance.

Collisions

The simulation includes the interaction between the particles and the plasma chamber walls. The interaction with the wall is divided into three steps. First, the particle must go up to the contact of the wall, where it is thermalized [2]. The next action is a test to determine whether the particle sticks on the wall or not. If it doesn't stick, or after that the bond with the wall is broken, the particle is re-emitted. The particle reemission is done according to a hard sphere model [3].

To reproduce the spectrum at the source exit, the simulation must include collisions as electron impact ionization and coulomb collisions. For the collisions application, the plasma chamber is divided into cubic cells, henceforth the collisions are between particles existing in the same cell. The simulation integrates Coulomb collisions through K. Nanbu small-angle collision approximation [4]. This method allows to approximate Coulomb collisions induced by two particles in a plasma during a time step dt.

After Coulomb collisions, the particles are tested depending on the type of collisions: single and double ionizations, radiative recombination, and charge exchange. The cross sections is calculated using the Lotz formula [5] and Bélenger [6] respectively for single and double ionizations, Hahn [7] for radiative recombination, and Gallagher [8] for charge exchange. In order to avoid generating a random number for each possible collision at each time step, the simulation uses the null collision method [9] (Fig. 1).

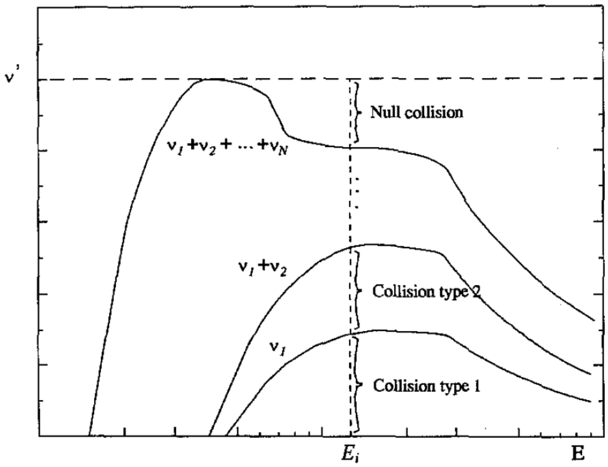

Figure 1: Null Collisions Principle Diagram

Electron Energy Distribution Function

Electrons do not propagate process in the simulation, but they are still needed for the ionization and recombination. Their interaction with atoms and ions is done thanks to the input electron energy distribution and density. The electron density is calculated to neutralize the ion charge density. The electron energy distribution is a combination of electron populations existing in the ion source. Three classes can be defined according to their energies:

- The cold electrons are generated by the ionization collisions or by emission from the wall. They have a low energy of tens electron volts.
- The warm electrons, with energies of the order of one to tens KeV, are derived from cold electrons. Successive interactions with the RF microwave at the ECR zone, they have gained stochastically energy and can actively participate in the ionizations for creating the high charge state ions.
- The hot electrons are very energetic, up to the MeV. This type of electrons have particularly weak ionization or recombination cross sections. The hot electrons participate mainly in the neutralization of the space charge of the ions =.

At first, the simulation is limited to use the of the two first electrons energy distribution components, the cold and warm electrons. They participate mainly to the ionization process, the cold electron act on low charge states while the warm electrons create higher charge states. As discussed in various papers [10–12], the electron energy distribution varies according to the magnetic configuration and the microwave power injected into the ion source.

Using an optimization function, the simulation modifies the electrons energy distribution such the source output spectrum is as close as possible to the experimental one. In addition, to being able to vary the average of the electron energy distribution, it is also possible to modify the energy distribution function that the electrons follow. Three functions of different distributions could be tested:

- A Gaussian distribution function has been chosen for the preliminary tests. However, knowing already that this function is too simple for representing the EEDF, each Gaussian function have two parameters: the center of the Gaussian, which corresponds to the average energy, and the σ that adjusts the energy dispersion.
- The second distribution function is a Maxwellian one. This distribution is more complex to compute but has only one free parameter allowing a faster optimization to fit to the desired spectrum [13].
- The third, and last, is the best to reproduces the electrons energy distribution function observed for ECR ion source. This is a non-Maxwellian function, which requires more time to implement and which request much more computing time [13].

PRELIMINARY RESULTS

The program is code around different function groups :

- A set of functions is used to initialize the simulation (reading of the magnetic field map, ionization energy, physical parameters ...)
- Set of functions is created for the atoms and ions propagation, as well as the particles localization in the ion source
- For the particles interacting at the wall, they can stick to the wall and can be re-evaporated
- The collisions between particles are applied on all the particles in the ion source and not trapped at the surface of the wall
- At the end of the simulation, a set of function are employed to get the particles information: position, impulsion, charge, specie)

The simulation structure, and all the functions involved can be summarized into a chart proposed on Fig. 2.

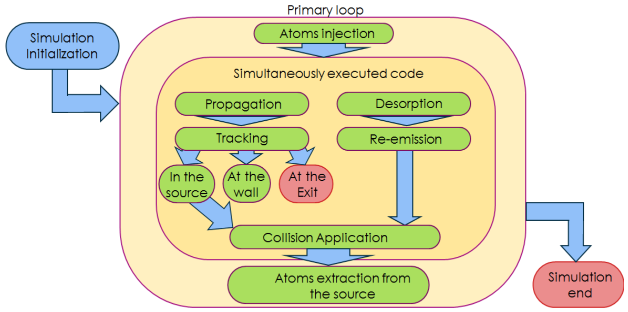

Figure 2: Organization Chart of the Simulation

To find the electron energy distribution function for the cold and the warm electrons which latches the experimental spectrum, an optimization program is used [14]. The optimization code varies the several parameters to reduce a certain value. In our case, the value ($V_{criteria}$ (Eq. (1))) is the gap between the total intensity of the experimental spectrum and the total intensity from the spectrum of the simulation.

$$V_{criteria} = \sqrt{\sum_i \left(I_{exp}(q=i) - \frac{I_{simu}(q=i)}{I_{simu}(q=1)} I_{exp}(q=1) \right)^2} \tag{1}$$

After the preliminary tests, the simulation was able to reproduce an experimental ion spectrum from the ECR Ion Source PHEONIX V3. The first spectrum to recoded is a simple one involving as less as poissble ion source parameters. It was produced using only Argon injection, and a very low voltage applied on the bias disc of the source.

To reduce the computing time, the simulation doesn't solve the Poisson equation and considers the plasma sheath as non-existent. At the walls, the approximation doesn't induce a significant error. However, at the extraction, the sheath is deformed into a meniscus that acts strongly on the ions leaving the ECRIS and traveling through the extraction system. Without the electric field of the meniscus, a lot of ions of the simulation miss the exit of the source and go up to the wall; leading to an extraction not very effective.

To overcome this problem, it was decided to study the ions charge state distribution inside the source between the ECR zone and the Ion source exit [15]. Doing that, it is possible to increase the statistics of the different charge states, and hence to reduce the relative intensities uncertainties of the ion mass spectrum.

For the first spectrum, the minimum value is found for $E_{out} = 220eV$, with E_{out} the cold electron energy, and $E_{in} = 2700eV$, E_{in} the warm electron energy.

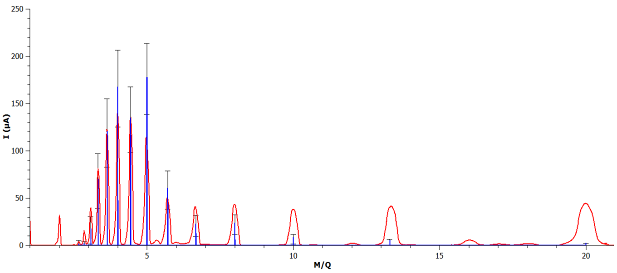

Figure 3: Preliminary Simulation Results

The Fig. 3 shows the experimental spectrum (in blue) and the one from the simulation (in red). There is a difference between the experimental values and the values from the simulation. These differences can be explained in different ways:

- During the experiment, only argon was injected in the ion source. However, the experimental spectrum shows H, H_2, O and C traces. The presence of different species in the plasma varies the charge states distribution.
- The simulation doesn't reproduce the electric field produce by the bias disk. The experimental spectrum was obtained with a low voltage on the bias disk but not zero. The bias disc has the effect of promote the production of high charge stat. The difference between the experimental voltage (not zero) and the simulated voltage (zero) can explain the spectrum difference.

CONCLUSIONS

The simulation gave some preliminary results, and at the same time proved its effective running. As this first spectrum is encouraging, several improvements were planed :

- The potential dip, and the plasma sheath can be integrated into the simulation through an additional map field. The plasma sheath would have then an effect on charged particles, and the potential dip would be continuous

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- The density of electrons can be pre-calculated in a way that electrons follow more the magnetic flux line. The ionizations would occur along the magnetic flux line, and the ions would be confined in the plasma more easily.

In the next months, the PHOENIX V3 ion source will be used to test the production of Ca ion beam with and without liner. Besides various possible improvement, the simulation will also be requested to reproduce the Calcium ion mass spectrum observed experimentally.

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