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Self-consistent Monte Carlo model for ECRIS plasma simulation

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Abstract. A self-consistent iterative Monte Carlo model to simulate electron cyclotron resonance ion source (ECRIS) plasma is presented. It computes the species' spatial and energy distribution in the whole plasma chamber in a three-dimensional mesh. A number of electrons and ions are propagated independently considering the static magnetic field, injected microwave field and local electrical potential field. The species trajectories populate the mesh allowing to compute their local density and velocity. Each species is pushed until it undergoes a destructive collision or after a fixed time limit. After each propagation phase, the local plasma potential and the heating electromagnetic microwave field are updated. This process is then iterated until convergence of species distributions and fields is reached. This method is intended to be a faster alternative to other methods to characterise the species distributions in the plasma for a specified ECRIS design and aid with their conception. The model and software development status are presented, along with prospects.

1. Introduction

The simulation of electron cyclotron ion sources (ECRIS) is of great interest for their design and development of such devices. This self consistent 3D Monte-Carlo method for simulating ECR plasma is intended to be a fast and reliable tool for predicting the plasma species' distributions. A Monte-Carlo method was chosen as it allows for easy parallelization of the code and a PIC simulation is not viable given the large volume simulated and predicted scale of the plasma's Debye length (λ_d), which constrains the simulation resolution. A similar, while not identical, method has been studied and is also under development by a team at INFN, Italy [1, 2, 3].

1.1. The PHOENIX V2 ECRIS

Helium plasma in the PHOENIX V2 ECR ion source [4] is simulated as a proof of concept. Helium beam production is chosen given that it has a maximum of two ionic species, further reducing computation requirements for the tests. The PHOENIX V2 ion source was developed at "Laboratoire de Physique Subatomique & Cosmologie" (LPSC), Grenoble. Then it was in operation until 2019 at the SPIRAL 2 accelerator at the "Grand Accelerateur National d'Ions Lourds" (GANIL), Caen. This ion source is now back at LPSC, where experimental measurements of its extracted ion beam will be performed, and compared with simulation.

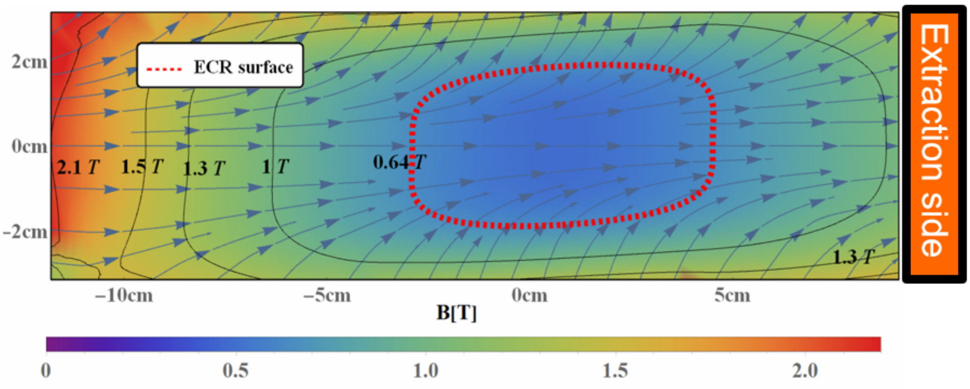

Figure 1: Minimum-B confining magnetic field of the PHOENIX V2 ECRIS

Table 1: Main characteristics of the PHOENIX V2 ECRIS

Dimensions	$L204mm \times \phi 63mm$
Operation frequency	$18\,GHz$
Maximum extraction potential	$60\,kV$
$\{B_{inj},\, B_{min},\, B_{ECR},\, B_{ext}\}$	$\{2.1\,T,\, 0.4\,T,\, 0.64\,T,\, 1.3\,T\}$

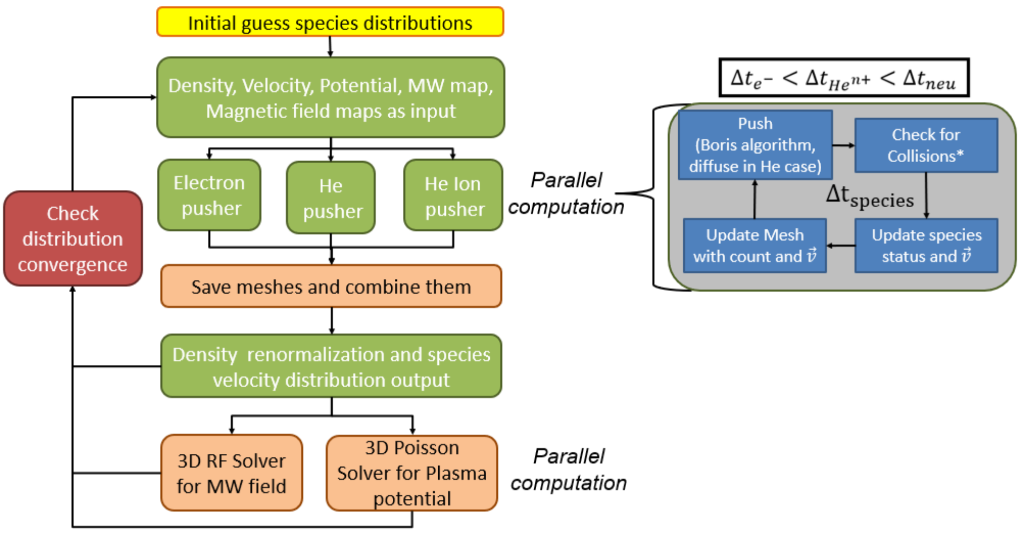

Figure 2: Flowchart of the ECR helium plasma Monte-Carlo simulation

Axial electron confinement is provided by solenoids and radial confinement by a permanent magnet hexapole. This provides a magnetic field configuration called "Minimum-B", see figure 1, and its main characteristics are listed in table 1 [4].

2. Simulation Overview

In its current state this code propagates both ionic species of helium and electrons using the Boris algorithm, the standard for magnetised plasma simulations [5, 6]. Given that simulated instances of the plasma species are propagated independently, this code lends itself very well to parallel computation. This can be done by simply running multiple instances of the executable

Table 2: Relevance of considered collision processes for the propagation of each plasma species

Collision processes considered*	**Energy range [eV]**	**e^-**	**He^+**	**He^{2+}**	**He**
e^- impact ionization of He	24.5874<E	yes	no	no	no
e^- impact ionization of He^+	54.4178<E	yes	yes	no	no
e^- impact excitation of He 1s2	19.8196<E	yes	no	no	no
e^- impact excitation of He^+ 1s	40.8<E	yes	no	no	no
e^- radiative recombination with He^+	0<E	yes	yes	no	no
e^- radiative recombination with He^{2+}	0<E	yes	no	yes	no
Single charge exchange He^++He	0<E	no	yes	no	yes
Single charge exchange He^{2+}+He	0<E	no	no	yes	yes
Double charge exchange He^{2+}+He	0<E	no	no	yes	yes

which run sequentially on one thread each and then combining their results.

It takes maps of the source's magnetic fields as well of the injected microwaves as input. The latter is produced by an independent simulation using the commercial physics simulation software Comsol Multiphysics, which is a work in progress that in its current state is yet to achieve convergence when coupled to the electron distributions due to unmet hardware requirements. The microwave mode in vacuum is currently being provided instead. The source's magnets are modelled using the Radia software package developed at ESRF, Grenoble, which includes a Boundary Integral method solver for their magnetic fields [7].

The Plasma chamber is meshed using an array of cells delimited in a skew manner in the cylinder's circular cross section. This reduces memory requirements, as it allows for the meshing of a $2\pi/3$ section given the expected plasma symmetry with exact internal boundaries. This results from the hexapolar symmetry of the magnetic field and the validity of this approximation is confirmed by experimental observation of the source, specifically marks on the plasma chamber walls, the extraction electrode and the bias disk. The cells of the mesh store the density and a velocity distribution for each of the plasma species. The mesh from the previous iteration is saved in memory and given as input to the next. At the propagation phase at each time-step a species count is updated in the cell corresponding to the current position, this serves as a proxy for the local density and is re-normalised at the conclusion of each higher order loop. The species velocity is also binned in the corresponding cell in order to update its distribution.

2.1. Collision handling

Coulomb scattering and inelastic collisions are handled independently. Coulomb collisions are handled by an adapted Takizuka-Abe method[8, 9]. Inelastic collisions in turn are handled by the null-collision method [10, 11]. The original version of this algorithms, groups the simulated particle instances in pairs. This being impossible in this model, a collision partner is generated by randomly sampling the density and velocity distributions from the previous mesh, which remains static during each propagation loop. This creates the need to run a first propagation loop in non-collisional mode to populate the first mesh or define an initial distribution to sample from, the former option is currently being used.

3. Preliminary Results and Discussion

3.1. Collision Validation

Non-collisional propagation of electron in the plasma chamber lets one identify two distinct populations, confined and non-confined. Predictions based of the reflection rate of the magnetic mirror predict around 70% of electrons initialised in a random direction will be confined. This

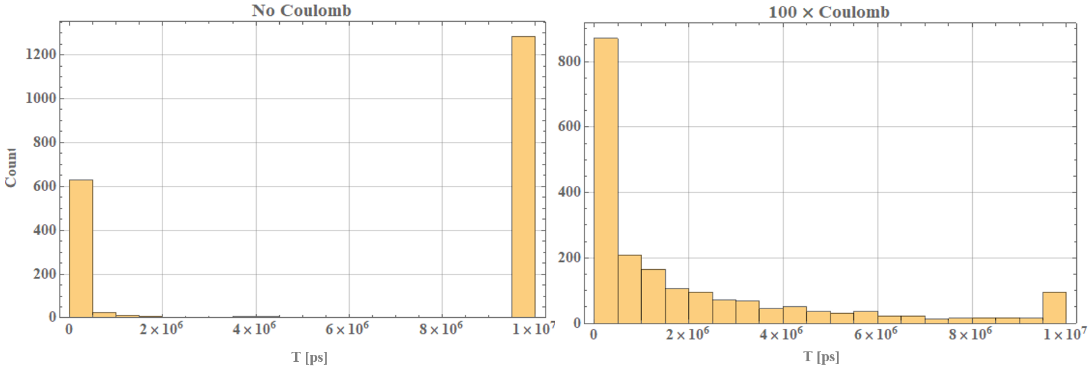

Figure 3: Comparisson of electron confinement times with and without considering coulomb collisions for $10^7\,ps$ of maximum propagation time. The strength of Coulomb collisions is synthetically increased by a factor of 100 in order to more easily observe their effects

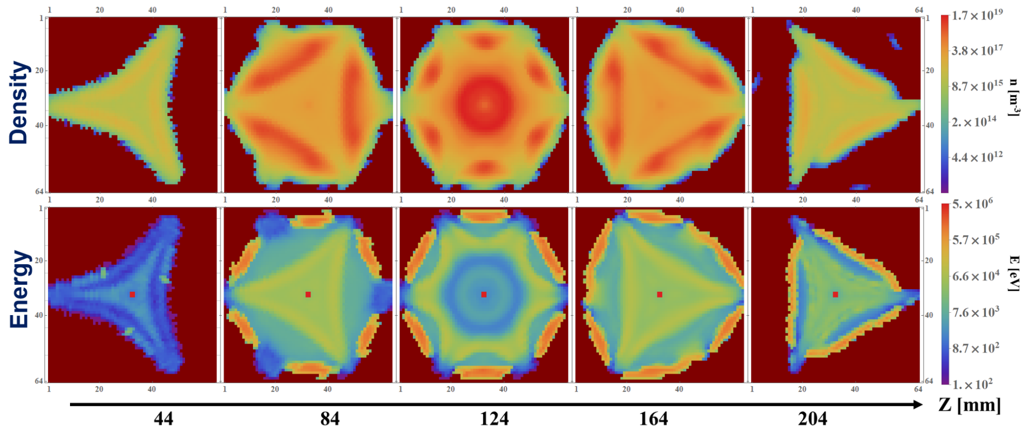

Figure 4: Transversal cuts of the preliminary electron density distribution (up) and energy distribution (down) for the collisional propagation of 12000 electrons with microwave heating for a $0.1ms$ maximum confinement time, Z is the position along the plasma chamber's axis.

is corroborated by simulation results, see figure 3 (left).

After the introduction of coulomb scattering, synthetically increased in strength to observe its effect in a shorter propagation, we see both population blend together towards a tail-like distribution with less electrons remaining confined for the $\sim 10\mu s$. Adjusting for the increased Coulomb strength, this suggests a $\sim 1ms$ maximum confinement time, consistent with expectation, see figure 3 (right).

The rates of inelastic collisions given by the implemented null-collision algorithm were computed at set positions in the plasma chamber and compared with expectation ($\nu = n_t \sigma u$). Good agreement was seen after a propagation time of the order of milliseconds, with a relative error below 1% in most cases. The exception being very infrequent processes, like in the case of radiative recombination at an energy of 1keV, where a considerable statistical error is seen ($\sim 50\%$), consistent with Poisson's distribution statistical uncertainties associated to rare events.

3.2. Electron Distributions

Qualitative examination of the electron density and energy distributions points to behaviour consistent with expectation. Electrons initialised at a temperature of 1keV are seen to heat up to up to 1MeV in some regions, while stay at around the tens of keV in others, remaining largely confined. A halo of high electron energy can be observed to surround the ECR surface.

High electron density is contained by the ECR region, which can point to a localised dip in the plasma potential and is consistent with some prediction. This dip is thought to play an important role in ionic species confinement. This is due to theoretical predictions taking only magnetic confinement into account fail to explain the long ionic confinement required for the high charged states produced [12].

A hotspot of well confined electrons with diverging energy along the plasma chamber's axis is seen, see figure 4. This phenomenon is being investigated as it seems to be a simulation artifact. One possibility being looked at is of it being a product of the microwave modelling and could go away with further iteration of this module.

4. Conclusions and Prospects

This Monte-Carlo model is so far promising for providing a relatively light-weight framework for this type of plasma simulation. After evaluation of the collision and microwave heating implementation, it is seen to have good qualitative agreement with expectation.

Charge exchange between neutral and ionic species is thought to play an important role on the charge distribution of the extracted beam. The implementation of this process is the next step in development. Then the higher order loop calling the propagation phase, as well as the microwave plasma coupling and Poisson equation solver for the plasma potential will be automated. This is a step towards consolidation of this frame-work and would be a good ease of use feature to have for future tests. After all the parts are completed a move towards obtaining higher statistics is required. A refining of the mesh towards the order of the Debye length ($\lambda_d \sim 10\mu m$) is the next step, alongside the parallel propagation of a larger number of simulated particle instances. Validation of this simulation results can then be performed by comparing with experimental data. Beam emittance and current measurements for a helium beam produced by the PHOENIX V2 ECRIS are expected to be done before the end of 2021.

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