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Self-consistent Monte Carlo model for ECRIS plasma simulation

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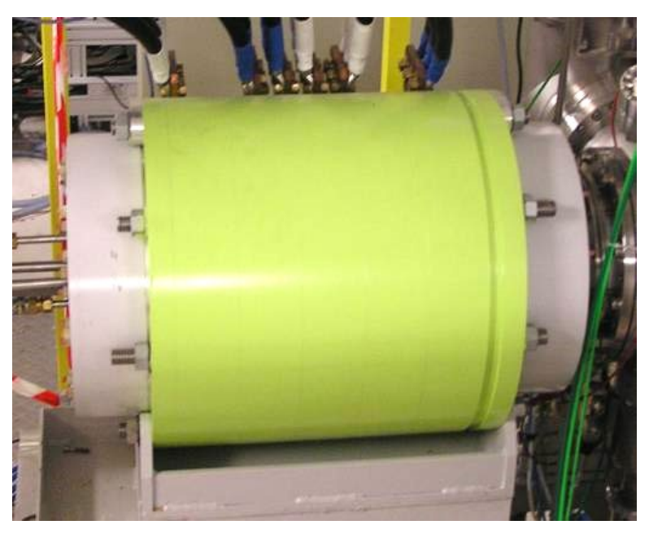
Abstract

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 characterize 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.

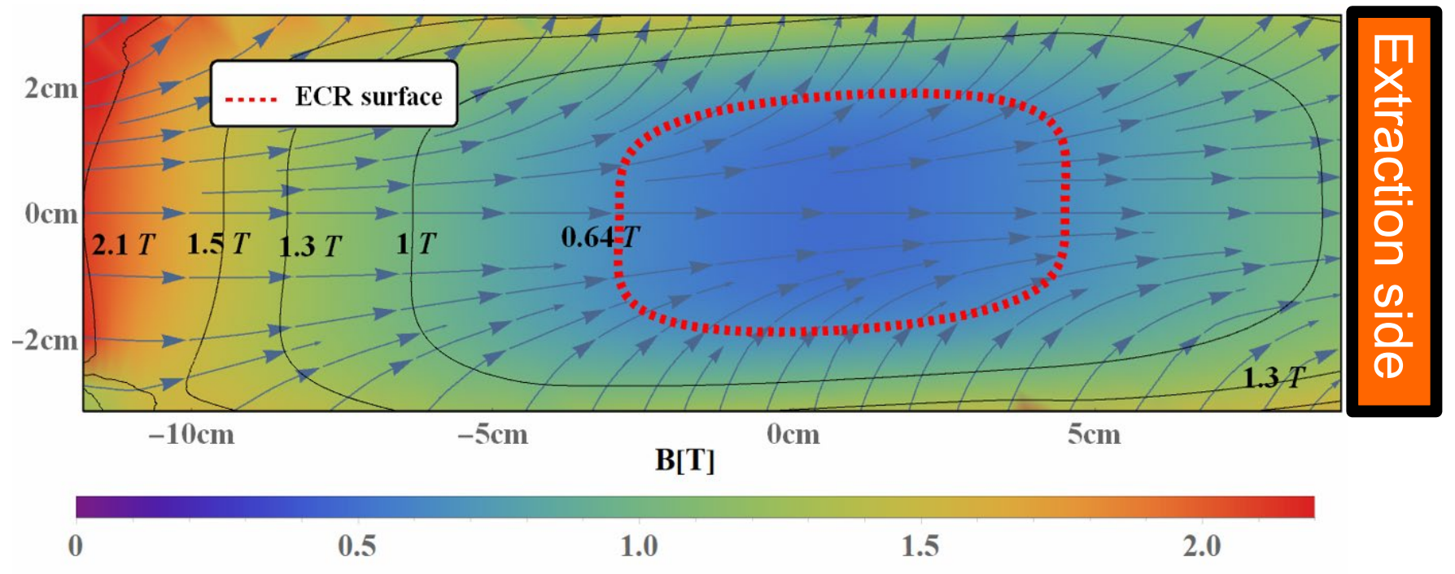
The PHOENIX V2 ECR Ion Source

Picture of the PHOENIX V2 ECRIS

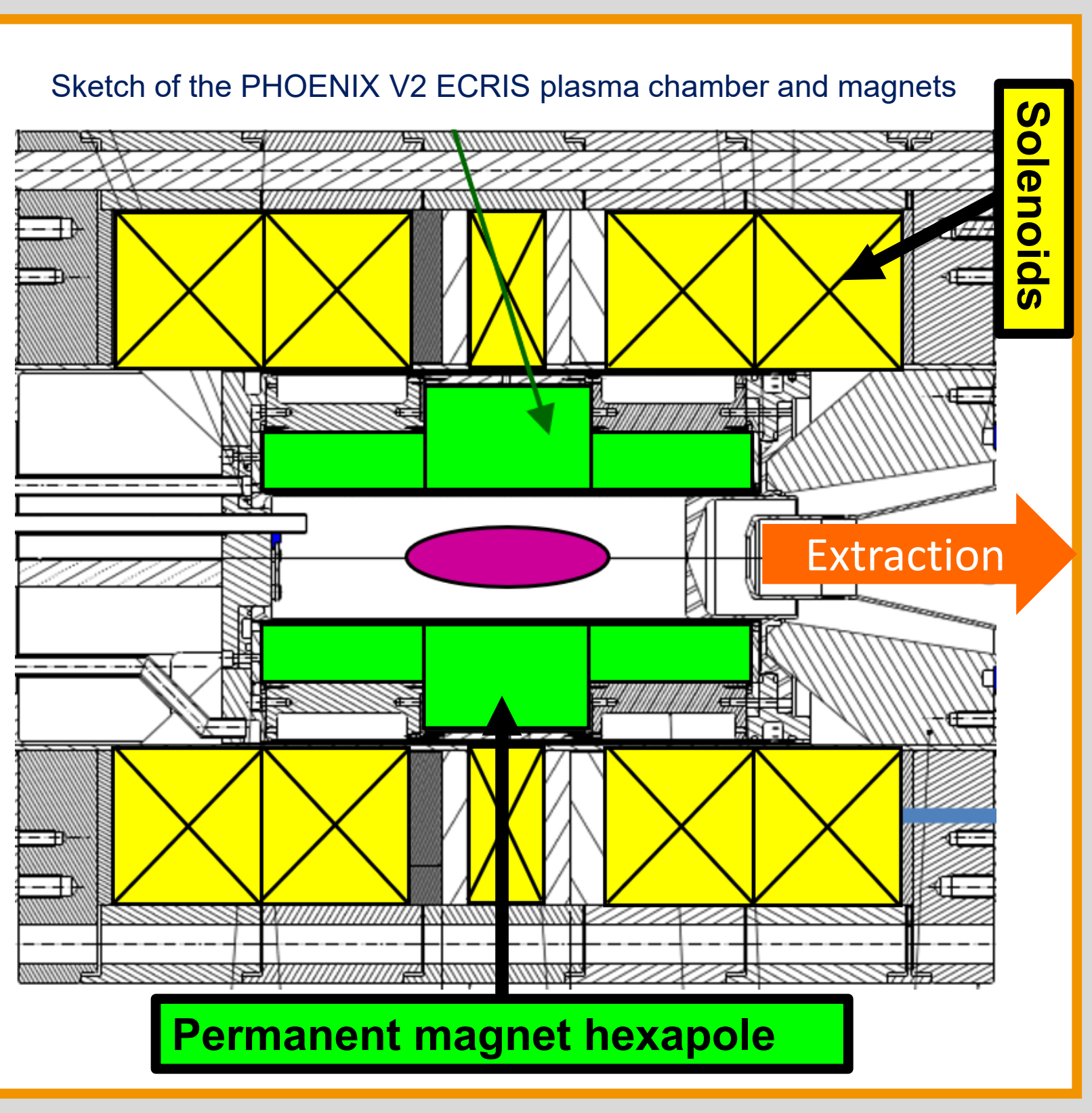


- Compact ECRIS at LPSC, used to commissioned the SPIRAL2 accelerator
- 0.6L plasma chamber volume (L204mm , Ø63mm)
- Operation frequency of 18GHz
- Magnetic , static electric field and RF field map considered

Minimum-B confining magnetic field of the PHOENIX V2 ECRIS

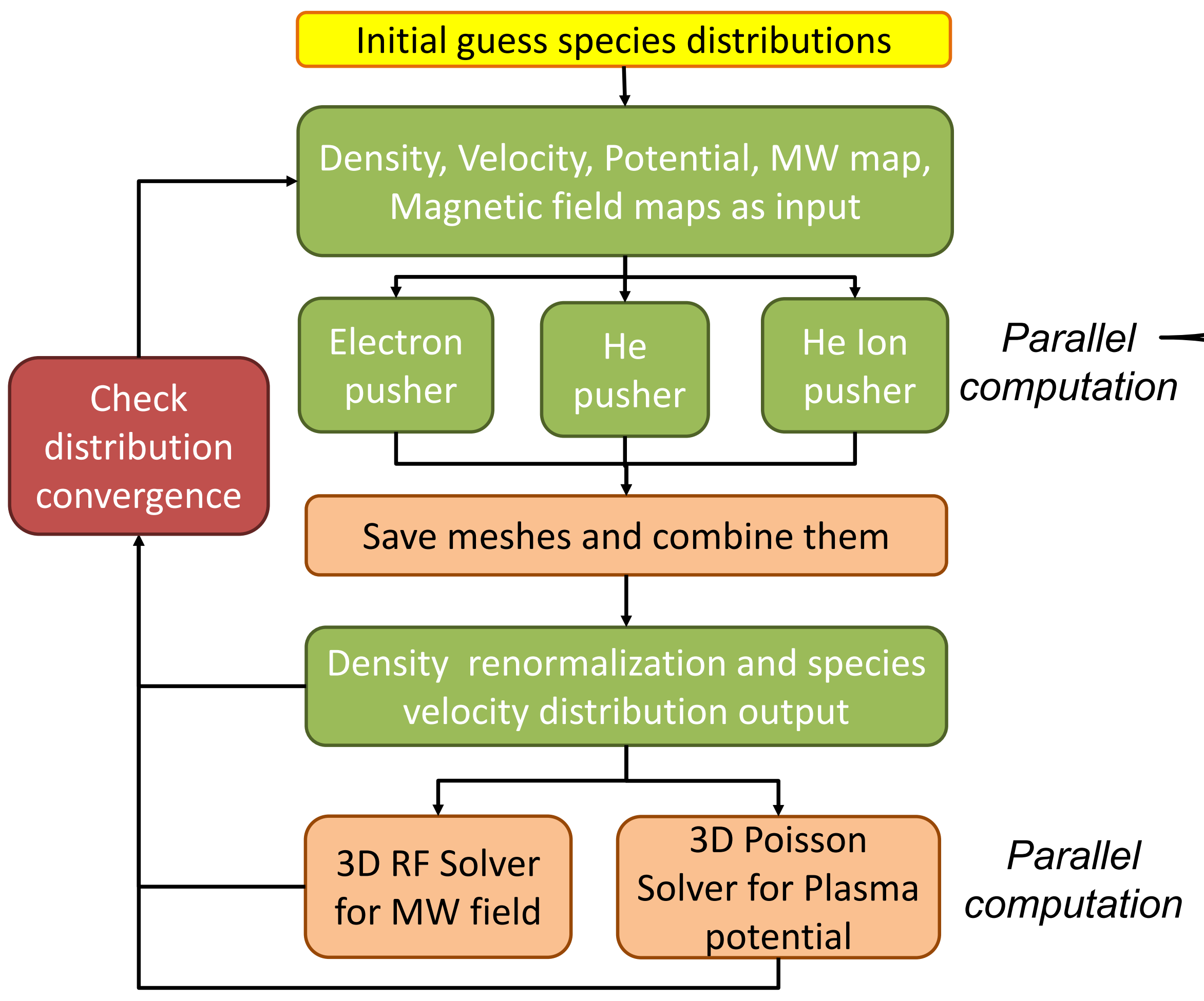


Sketch of the PHOENIX V2 ECRIS plasma chamber and magnets

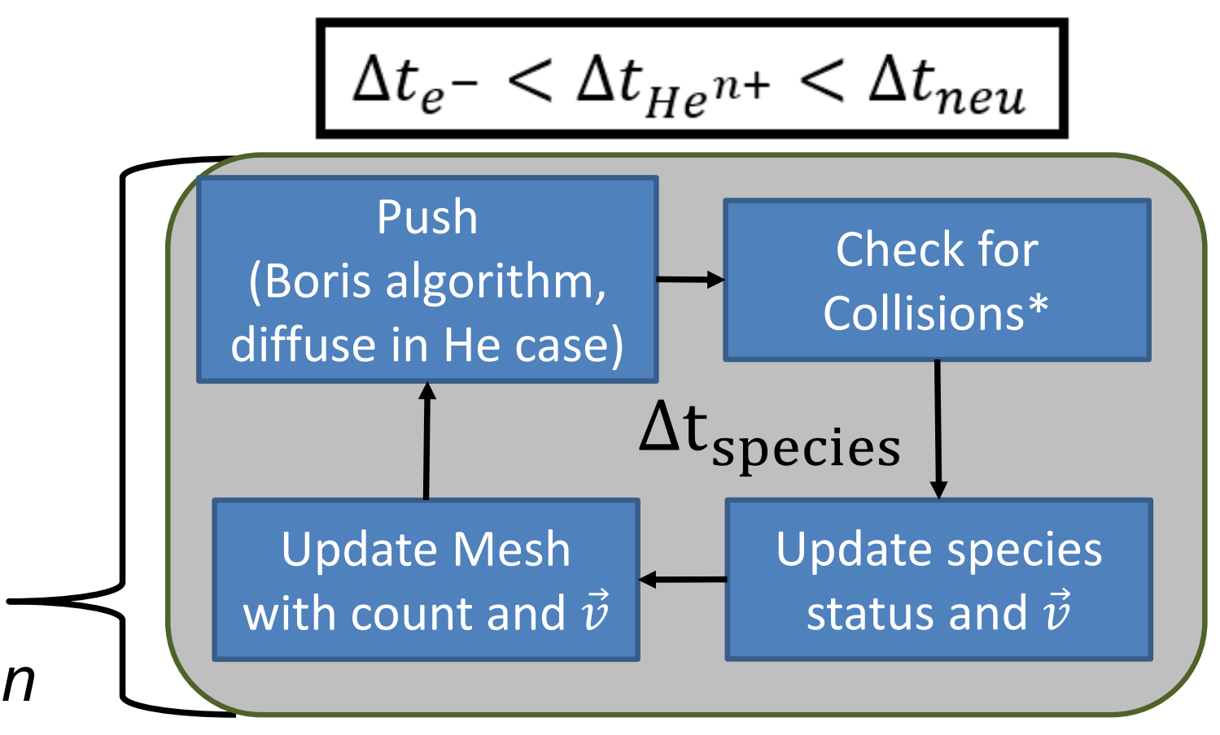


Simulation Overview

ECR He Plasma Monte-Carlo Flowchart



$$\Delta t_{e^-} < \Delta t_{He^{n+}} < \Delta t_{neu}$$

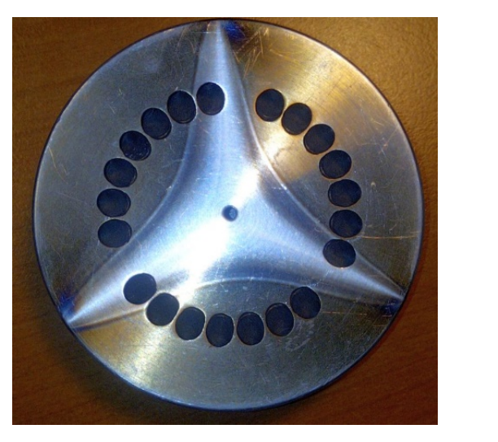


Collision processes considered*	Energy range [eV]	~ν_{max} [Hz]	Relevance for the species prop.: e^-	He^+	He^{2+}	He
e^- impact ionization of He	24.5874<E	112	yes	no	no	no
e^- impact ionization of He^{+1}	54.4178<E	801	yes	yes	no	no
e^- impact excitation of He 1s2	19.8196<E	37	yes	no	no	no
e^- impact excitation of He^+ 1s	40.8<E	1400	yes	no	no	no
e^- radiative recombination with He^{+1}	0<E	2.4	yes	yes	no	no
e^- radiative recombination with He^{+2}	0<E	27	yes	no	yes	no
Single charge exchange He^{+1}+He	0<E	114	no	yes	no	yes
Single charge exchange He^{+2}+He	0<E	800	no	no	yes	yes
Double charge exchange He^{+2}+He	0<E	80	no	no	yes	yes

Coulomb scattering handled independently

Plasma Chamber Symmetry and Meshing

- The cylindrical plasma volume has a $2\pi/3$ rotational symmetry. The plasma chamber mesh can be then defined in that region to save on memory requirements ($N_{cell} \rightarrow N_{cell}/3$).
- While simulated species particles propagate through the whole plasma chamber, their coordinates are assigned to a position on the $2\pi/3$ mesh through rotation.
- The circular cross section of the cylinder mesh is skewed and one can define the cell size by $R = \mathrm{N_R}\Delta R$.

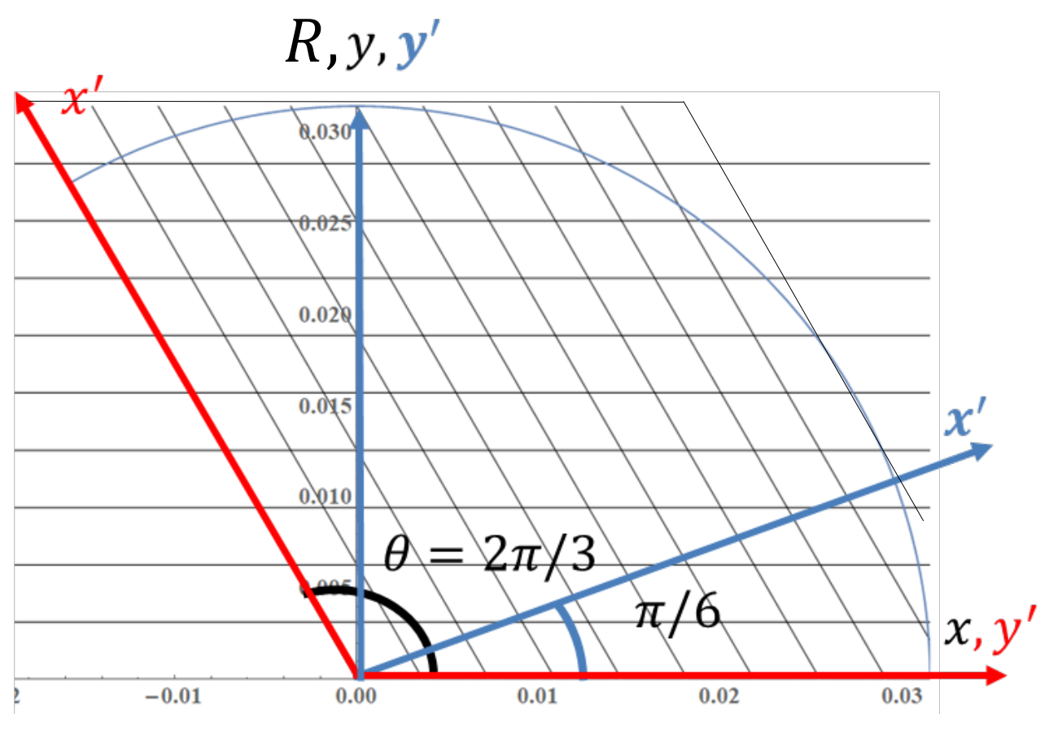


Erosion on the plasma electrode shows plasma symmetry

A skew mesh allows for easier boundary handling

With a meshed region of $\theta = 2\pi/3$

- Transformation:
  - $y' = y$
  - $x' = cos\left(\theta - \frac{\pi}{2}\right)x + sin\left(\theta - \frac{\pi}{2}\right)y = sin(\theta)\,x - cos(\theta)\,y$
- Inverse:
  - $y = y'$
  - $x = sec(\theta)\,x' - cot(\theta)\,y'$

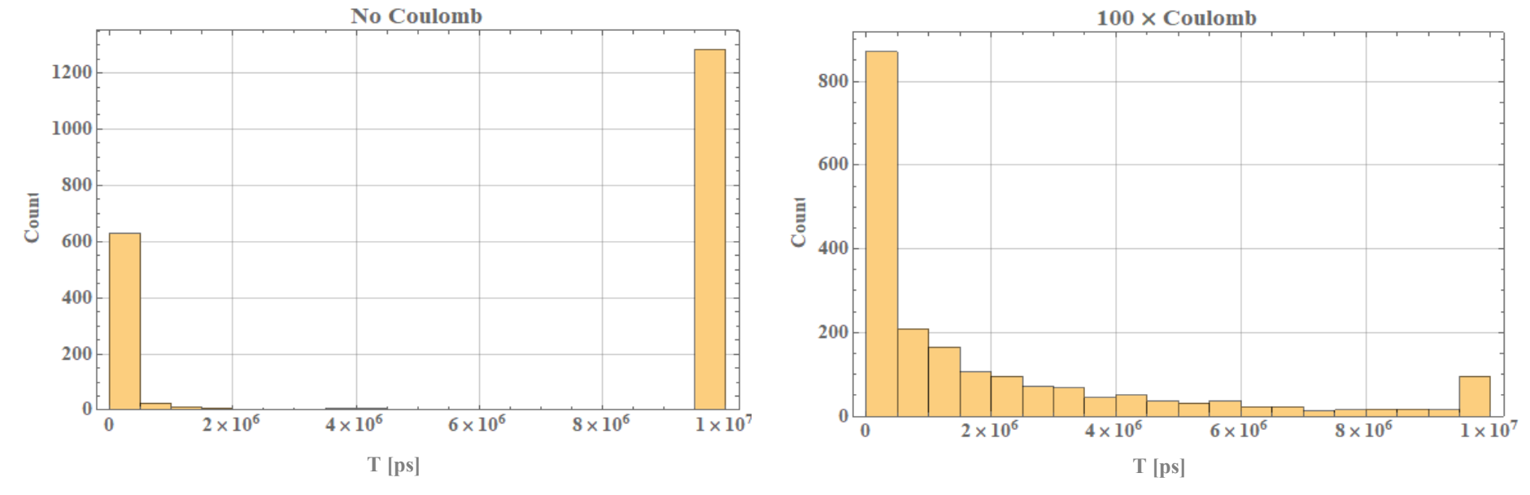


Collision Handling and Validation

Coulomb scattering and inelastic collisions are handled independently

1) Coulomb scattering is handled by an adapted Takizuka-Abe method

- Binary collision model which requires a pair of particles at each collision step (usually by grouping particles in pairs)
- As each individual species is propagated independently, a collision partner needs to be randomly generated from the prior plasma distributions (species and velocity), requires an initial collisionless propagation to populate the first mesh



- Artificially increasing the strength of coulomb collisions by a factor of 100, results in an electron confinement time $\sim 10\ \mu s$, which in turn suggests a real e^- confinement time in the ms *range.* Consistent with expectation.

2) Inelastic collisions

- Handled by a null-collision method

$$\nu' = \max_{\mathbf{x},\varepsilon}(v\sigma_T n_t) = \max_{\mathbf{x}}(n_t)\max_{\varepsilon}(v\sigma_T) \quad \textit{where} \quad \nu_i(\varepsilon_i) = \mathrm{v}_i\sigma_i(\varepsilon_i)n_t(\mathbf{x}_i)$$

$$P_{null} = 1 - \exp(-\nu'\Delta \mathrm{t}) \rightarrow \tau_{TOF} = -\ln(1 - P_{null})/\nu'$$

After a time of τ_{TOF}

For a random number R [0,1]
$R \le \nu_1(\varepsilon_i)/\nu'$
$\nu_1(\varepsilon_i)/\nu' < R \le (\nu_1(\varepsilon_i) + \nu_2(\varepsilon_i))/\nu'$
…
$\Sigma_{j=1}^{N}\nu_j(\varepsilon_i)/\nu' < R$ -> null-collision

Rates for inelastic collisions for e- near the centre of the plasma chamber

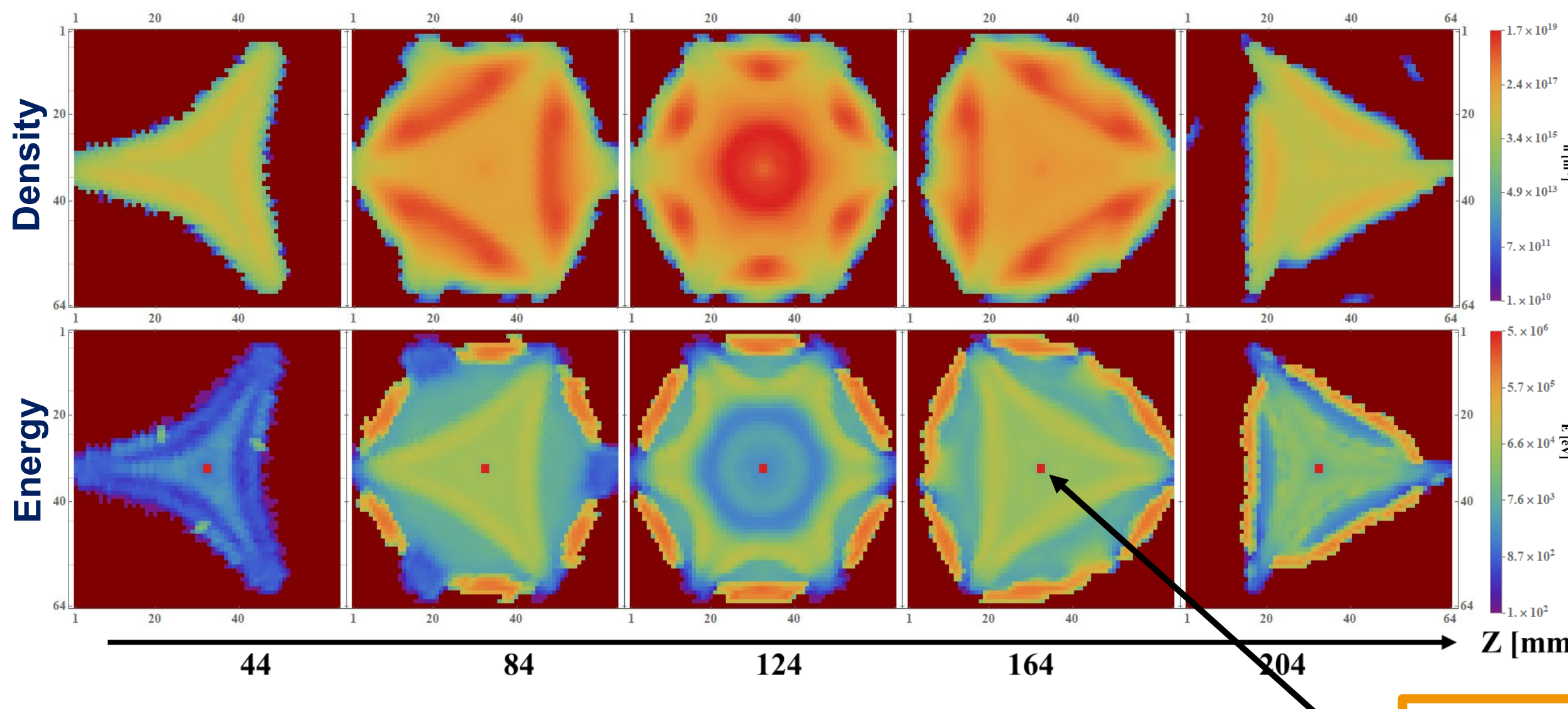
E_{coll} = 1eV	He (n = 5E15 m^{-3})		He^{1+} (n = 1.318E18 m^{-3})			He^{2+} (n = 1.008E17 m^{-3})
Interaction	ION	EXC	ION	RREC	EXC	RREC
Predicted rate (Hz)	0	0	0	4.3E-02	0	9.9E-03
Exp rate (Hz)	0	0	0	4.3E-02	0	1.0E-02
Error	0%	0%	0%	0.76%	0%	4.9%

E_{coll} = 1keV	He (n = 5E15 m^{-3})		He^{1+} (n = 1.318E18 m^{-3})			He^{2+} (n = 1.008E17 m^{-3})
Interaction	ION	EXC	ION	RREC	EXC	RREC
Predicted rate (Hz)	1.2E+02	4.3E+01	5.5E+03	3.6E-04	2.7E+04	2.5E-04
Exp rate (Hz)	1.2E+02	4.3E+01	5.5E+03	4.4E-04	2.7E+04	1.2E-04
Error	-0.031%	0.050%	0.008%	22%	0.0008%	-52%

Charge exchange between ion and neutral species is under implementation

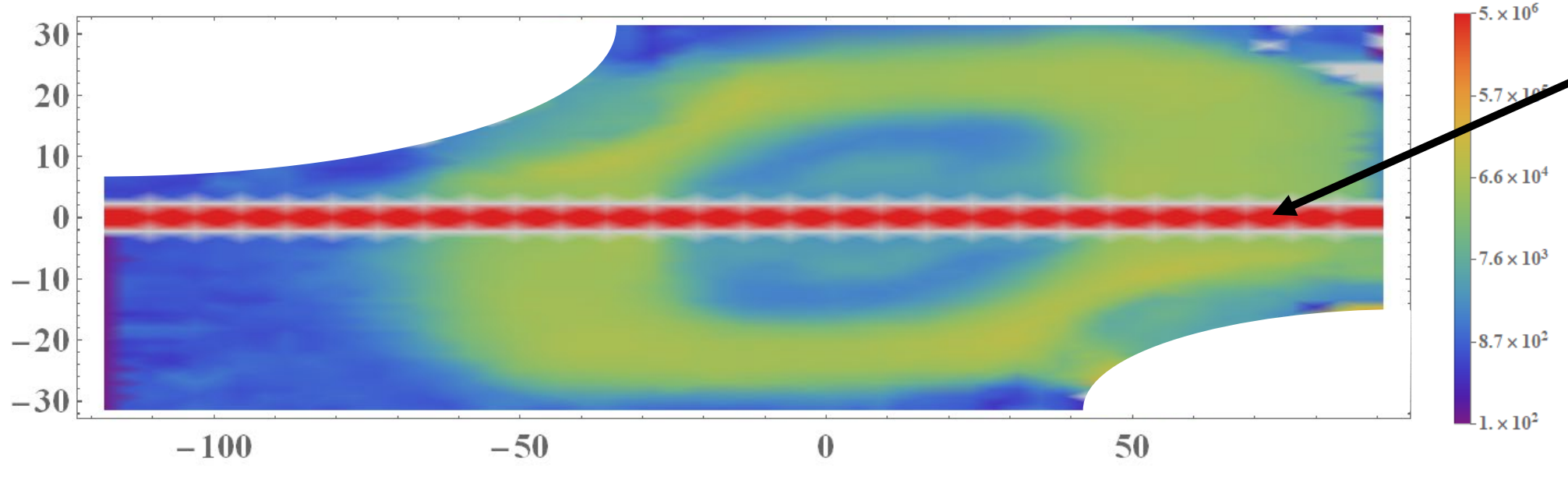
Preliminary Plasma Distributions for e^-

Preliminary electron density and energy distribution for a collisional propagation including the MW heating field



- Distribution obtained by the collisional propagation of 12000 electrons for a maximum confinement time of 0.1 ms. The code is running well so far.
- High electron density observed near the centre of the plasma chamber (conforming with expectation of a plasma potential dip aiding in ion confinement).
- Hot electron temperature (~1 MeV) observed around the edges.

Longitudinal cut of the electron energy distribution in the plasma chamber (to scale)



- A hotspot of very well confined electrons with diverging energy observed on axis. This phenomenon is being investigated.

- Halo of high electron temperature observed around the ECR surface.
- “Forbidden” regions near two corners of the plasma chamber, where the hexapolar field is perpendicular to the wall and provides less confinement.

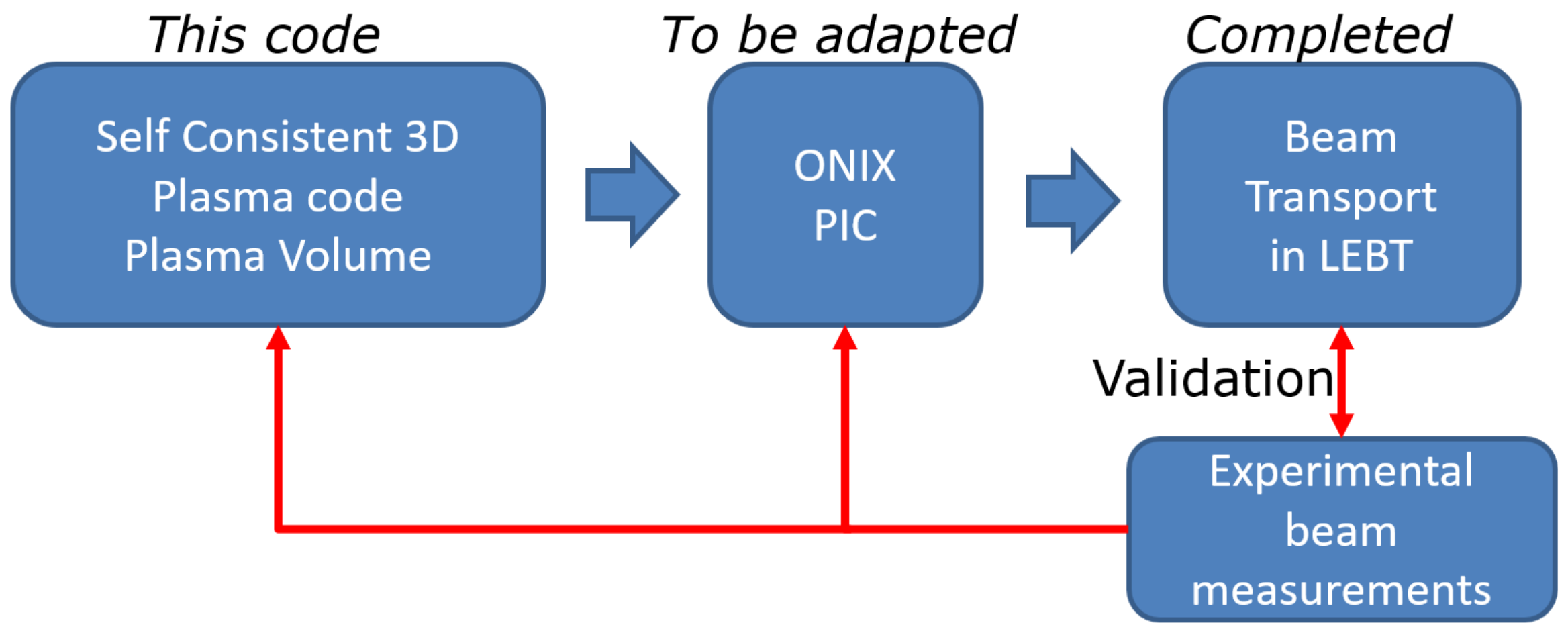
Conclusions and Prospects

Conclusion

- The implementation of collision dynamics and MW heating to this model is observed to conform qualitatively with physical expectations.
- This Monte Carlo approach for the simulation of ECR Plasma is so far promising in terms of providing a relatively light-weight framework for this type of plasma simulation.

Prospects

- Implement charge exchange between ions and neutral species.
- Automatize the high order loop calling species propagations and solving for the plasma potential and MW.
- Increase statistics in term of number of species propagated in parallel and refine mesh ($\sim\lambda_d$).
- Integrate with other simulations in order to predict extracted beam emittance and compare with experiment.



Refer to article in the ICIS’21 proceedings for referenced work