Implementation of physical processes on confined plasma simulations

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Outline

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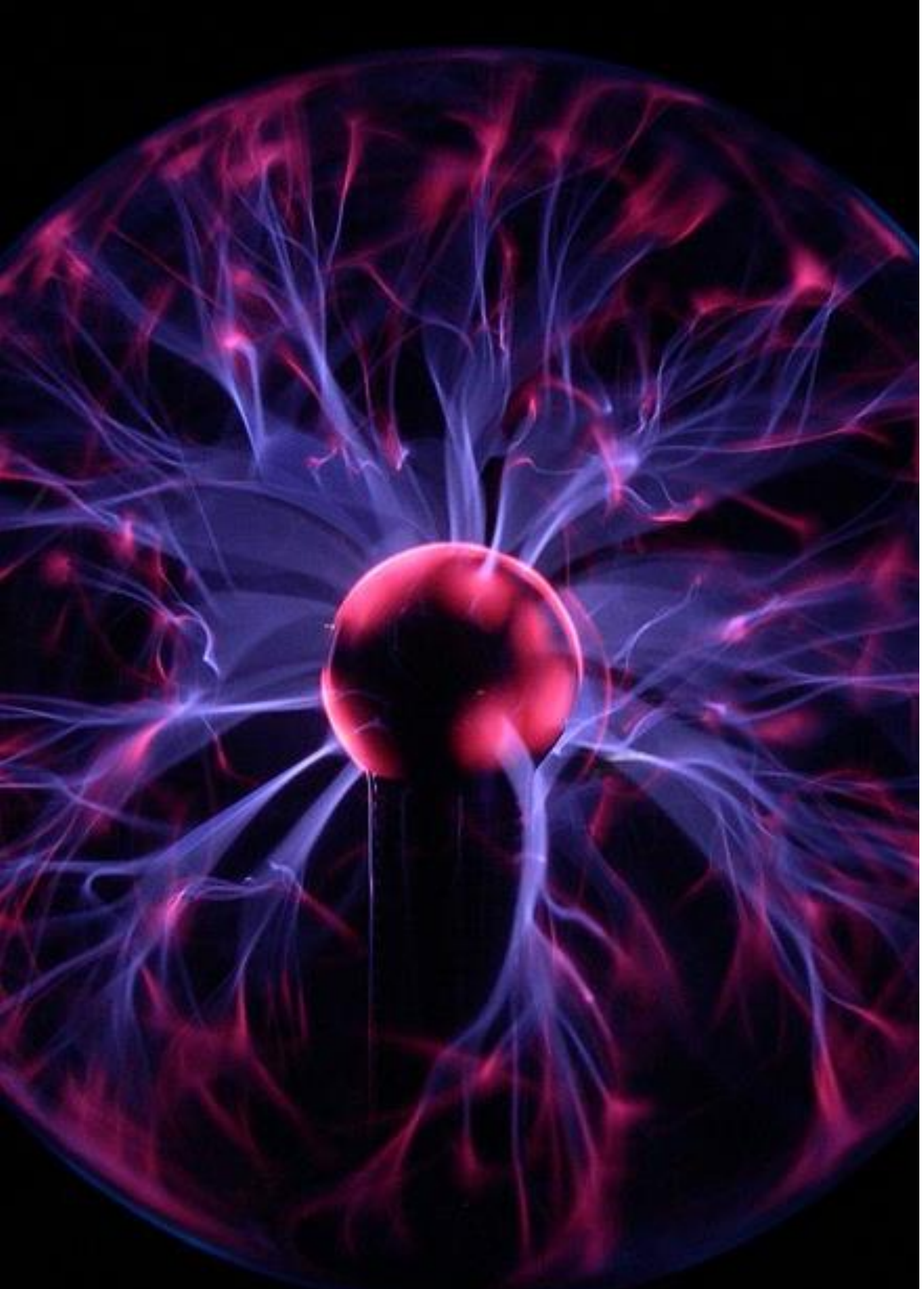


Introduction

Plasma is the fourth state of matter which consist of ions and free electrons. This is obtained by heating a neutral gas so that electrons have high temperature and thus are removed from atomic nuclei.

Because of the high temperature the behavior is hard to predict.

Also, because of the high particle density, a direct calculation of the force between particles is complicated.

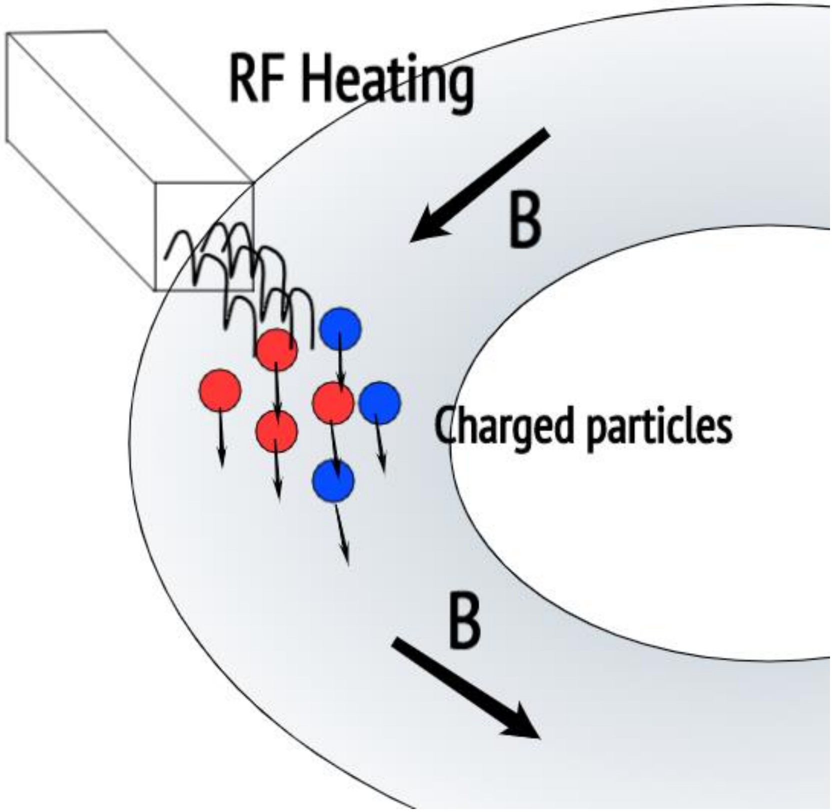
As such, a numerical approach is preferred and thus computer simulations are viable in solving this kind of problems.

Methodology

Simulations of a system of charged particles confined to a volume.

Use of two different methods:

- Monte Carlo with Dynamics (MCD) method.
- Particle-In-Cell (PIC) method.



Implementation of several physical processes such as Radio-Frequency (RF) electric field and drift from curvature of magnetic field lines.

PIC method

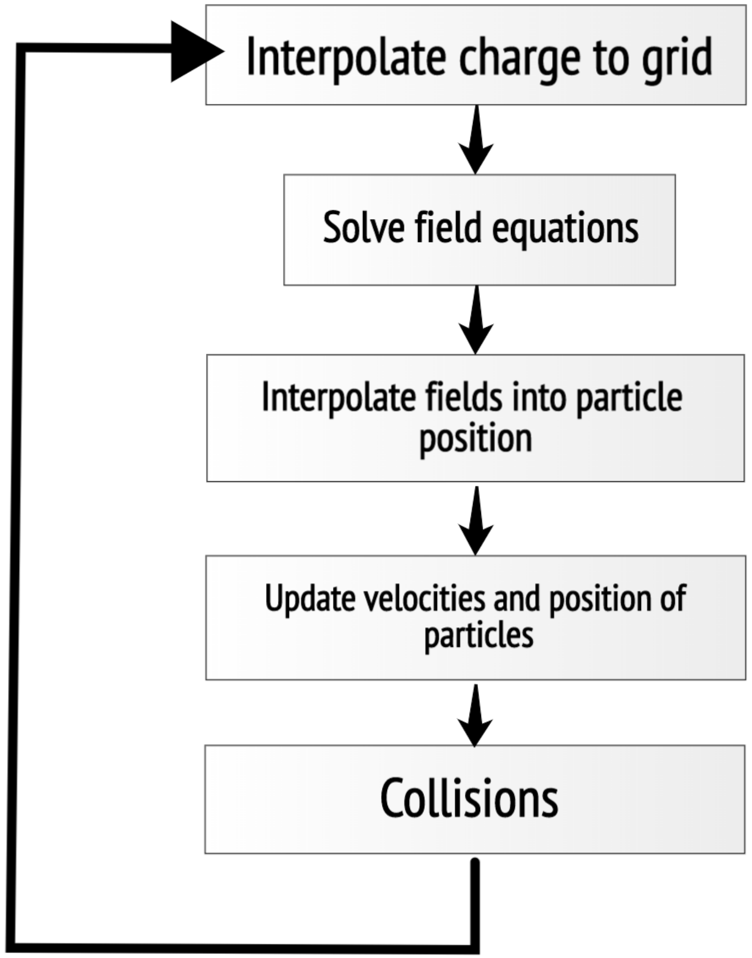
Macro particles on a grid.

Solving of the electric field equation.

Numerical integration of equations of motion.

Only DC voltages on this code.

Collisional processes between particle species [1].



MCD method

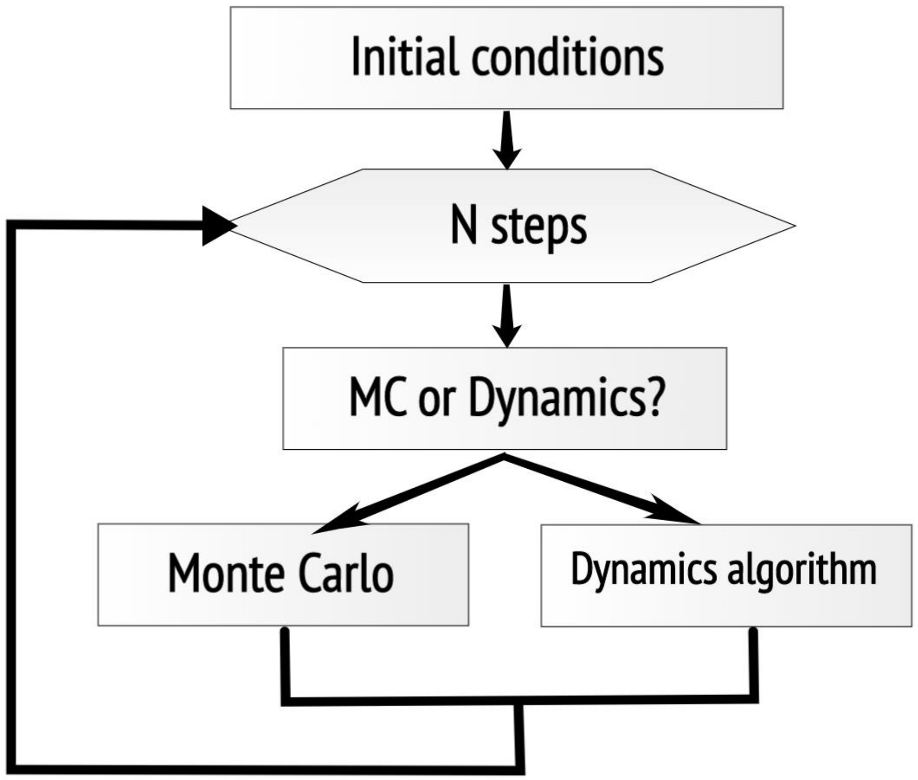
Metropolis-Hastings Algorithm [2].

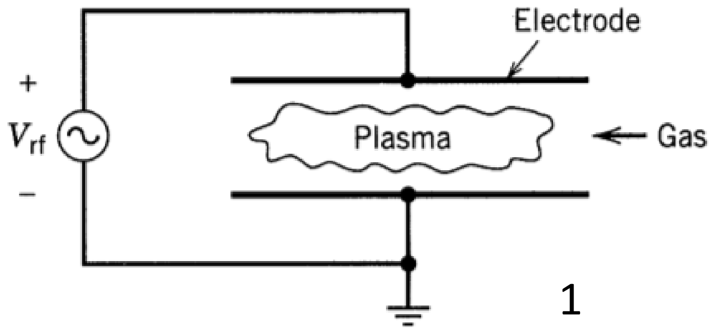
- Random trial move with a proposed probability distribution.

Canonical ensemble (NVT).

- Boltzmann Distribution.

Dynamics to second order in time.





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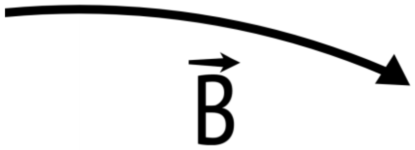
Implementation tests

MCD METHOD

- Implementation of the algorithm for the dynamics.
- Drift from curved magnetic fields.



PIC METHOD

- Implementation of an RF electric field.
- Drift from curved magnetic fields.

[1]Source: http://people.physics.anu.edu.au/~jnh112/AIIM/c17/Plasma_discharge_fundamentals.pdf

Results

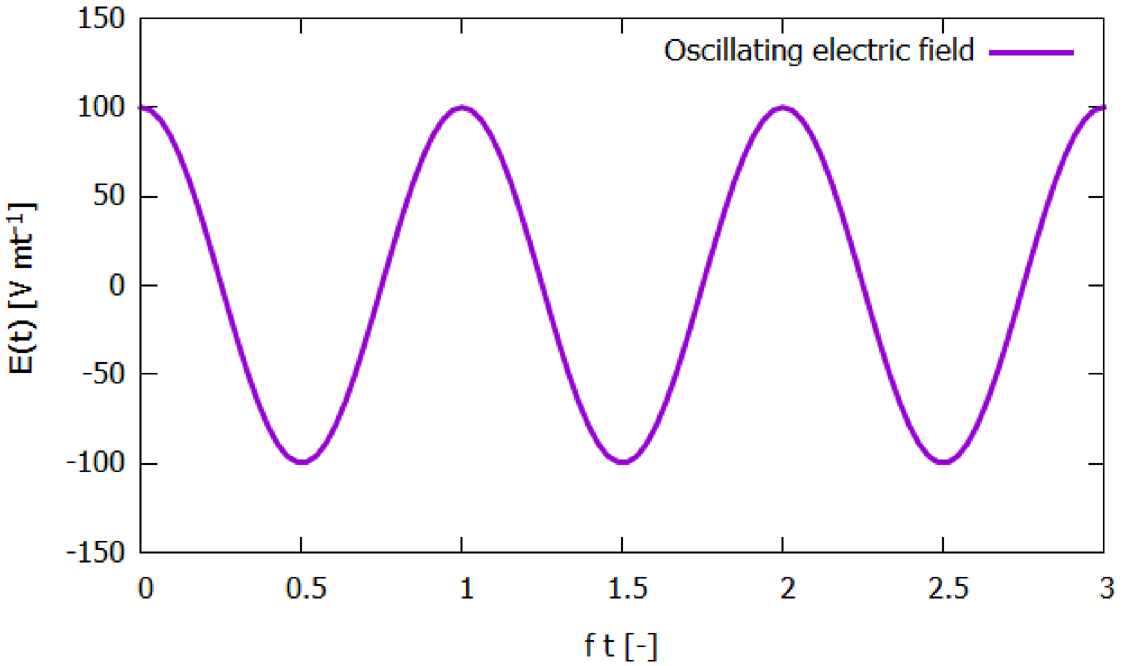
Implementation of an RF electric field (PIC)

Oscillating electric field in 1D:

$$E = E_0 \cos(2\pi f t + \phi)$$

General solution for this electric field:

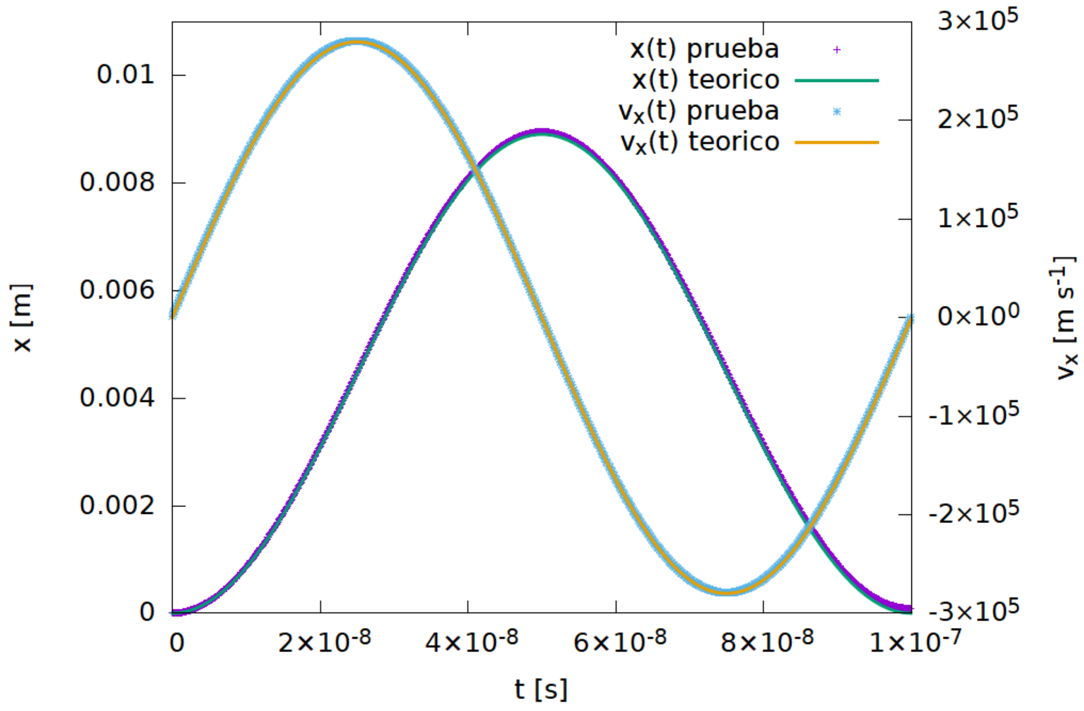
$$x(t) = A + Bt - \frac{q}{m}\frac{E_0}{(2\pi f)^2} cos(2\pi f t + \phi)$$



Implementation of an RF electric field (PIC)

Simulation parameters:

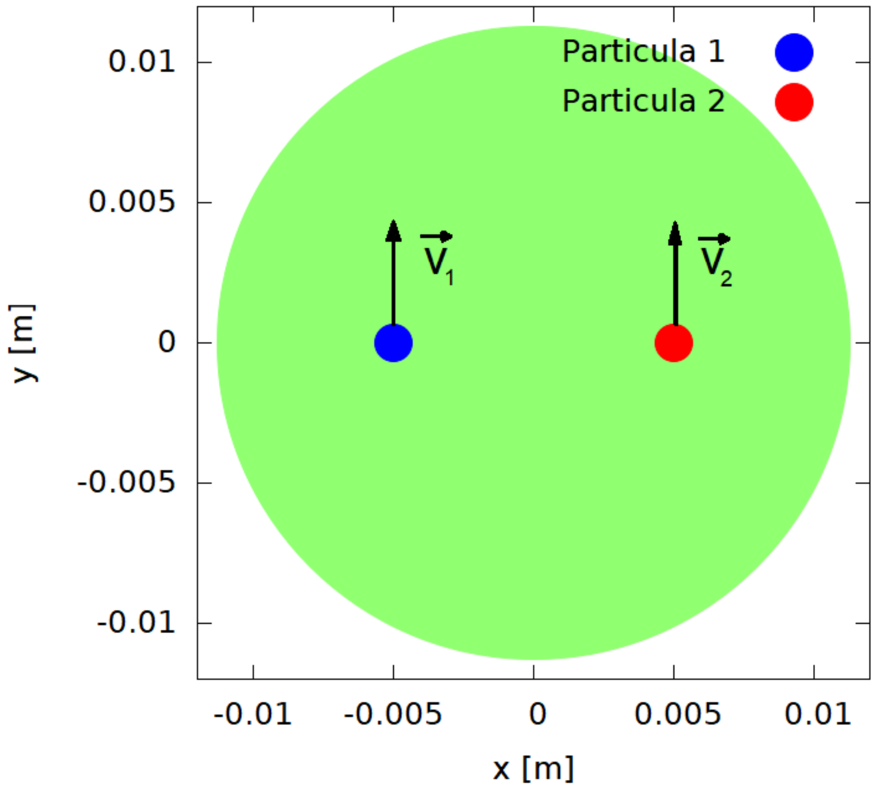
$$m = m_e$$
$$q = e$$
$$E_0 = 100\ V\ m^{-1}$$
$$f = 10\ MHz$$
$$x(0) = 0, \mathrm{v}(0) = 0$$



Implementation of the algorithm for the dynamics (MCD)

- 2D solution to second order in time for a constant magnetic field in z-direction.
- Simulation parameters:

$$m_1 = m_2 = m_e$$
$$q_1 = -q_2 = e$$
$$\boldsymbol{x}_1(0) = (-5mm, 0\ )$$
$$\boldsymbol{x}_2(0) = (5mm, 0)$$
$$\boldsymbol{v}_1(0) = (0{,}4.23 \times 10^6 ms^{-1})$$
$$\boldsymbol{v}_2(0) = (0{,}4.23 \times 10^6 ms^{-1})$$
$$\boldsymbol{B} = (0{,}0{,}0.01T)$$



Implementation of the algorithm for the dynamics (MCD)

Larmor radius:

$$r_L = \frac{mv}{|q|B}$$

For previous parameters:

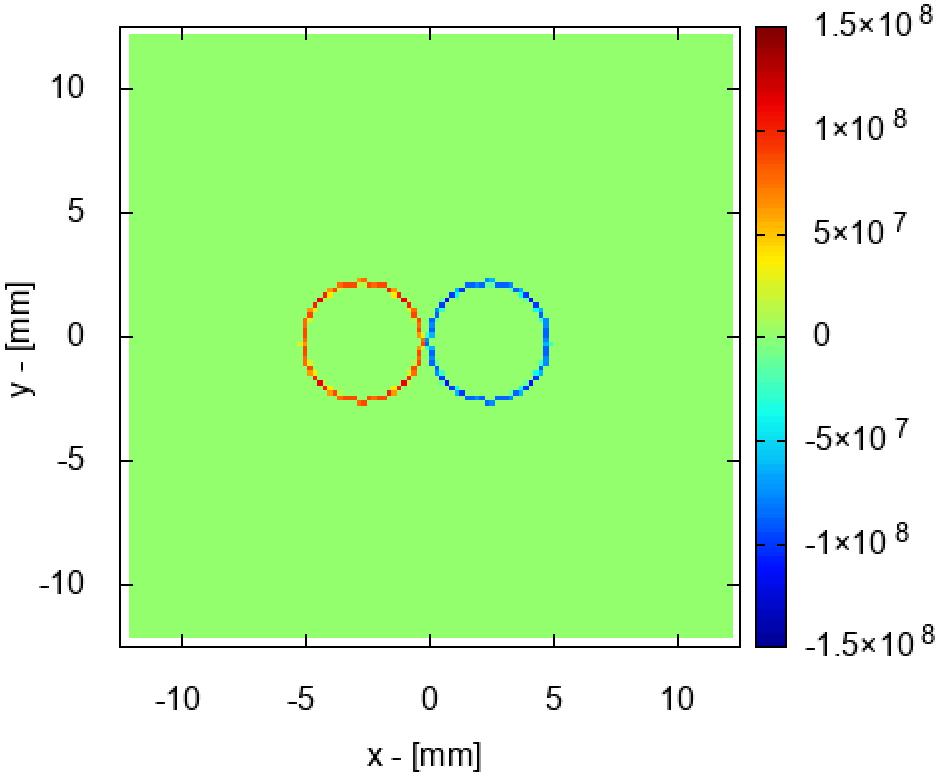
$$r_{L,teo} \approx 2.406519\, mm$$

Simulation radius value:

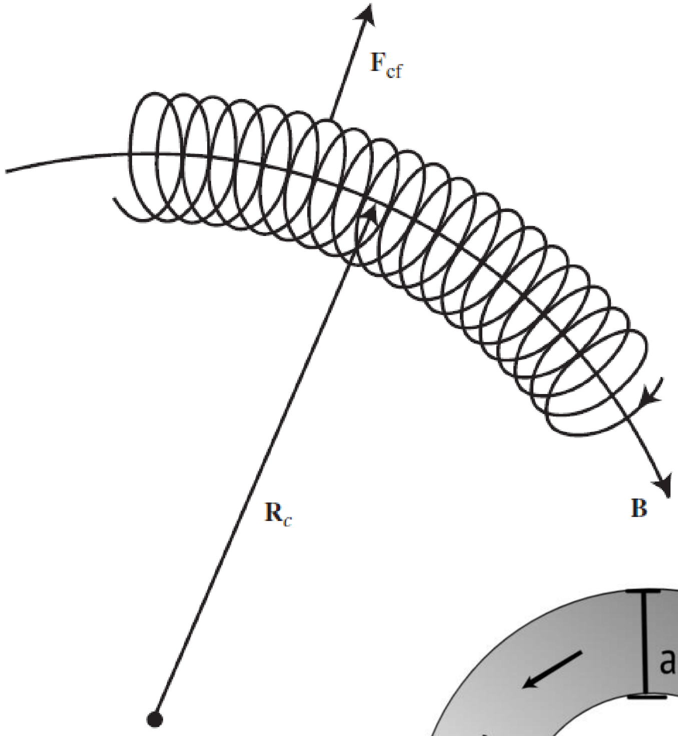
$$r_{L,simu} \approx 2.406858\, mm$$

Relative error:

$$\varepsilon = 0.014094\%$$



Implementation of drift from curvature of magnetic field

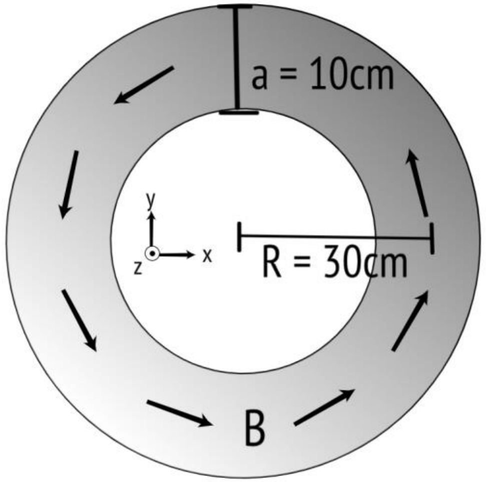


Ref. [3]

Drift velocity for a force $\boldsymbol{F}$ in a magnetic field $\boldsymbol{B}$ [3]:

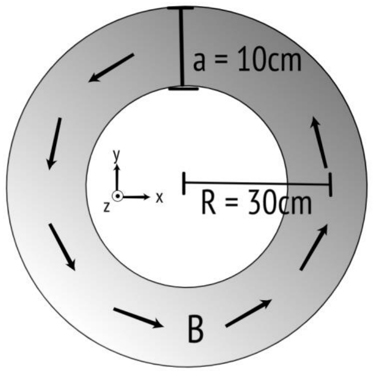
$$\boldsymbol{v}_F = \frac{1}{q}\frac{\boldsymbol{F}\times\boldsymbol{B}}{B^2}$$

For a toroid with **B** field $\mathbf{B} = B\hat{\boldsymbol{\varphi}}$



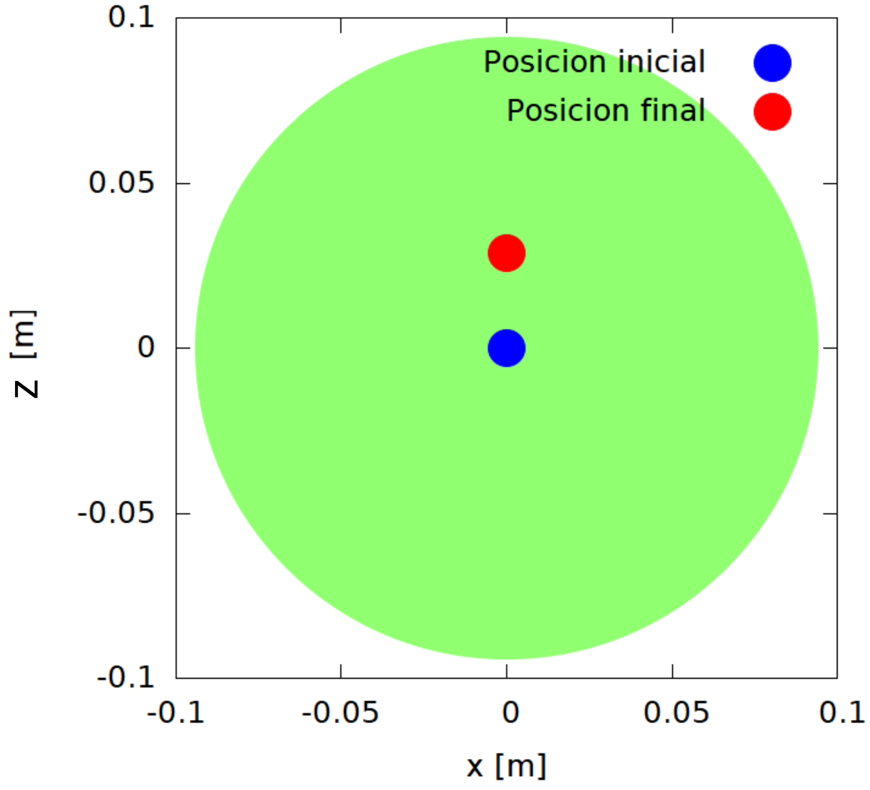
$$\boldsymbol{v}_F = \frac{mv_p^2}{qR_cB^2}\hat{\boldsymbol{z}} \qquad (1)$$

Implementation of drift from curvature of magnetic field (MCD)

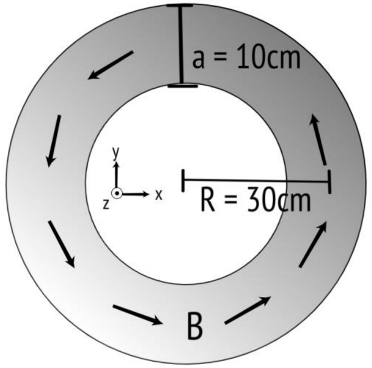


Simulation parameters:

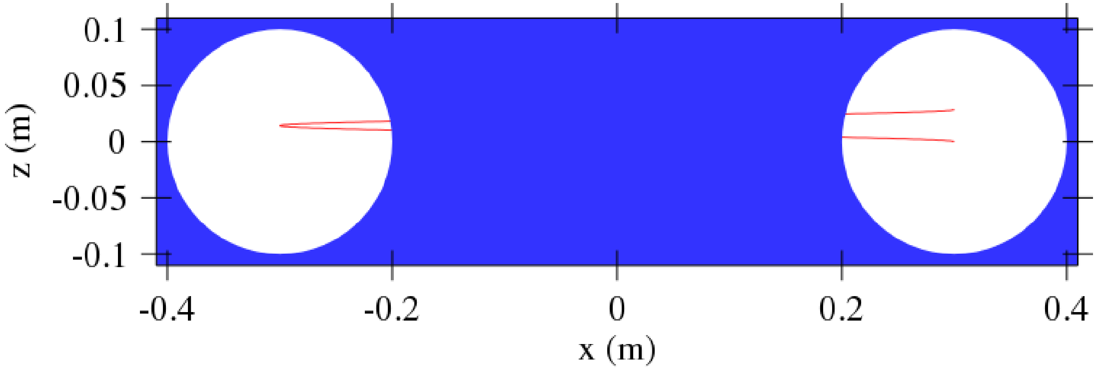
$$m = m_p, q = e$$
$$\boldsymbol{x}(0) = (0,0,0)$$
$$\boldsymbol{v}(0) = (0,0,4.392 \times 10^5 ms^{-1})$$
$$B = 1T$$
$$R = 0.3m$$
$$a = 0.1m$$
$$\Delta t = 4.29 \times 10^{-8} s$$

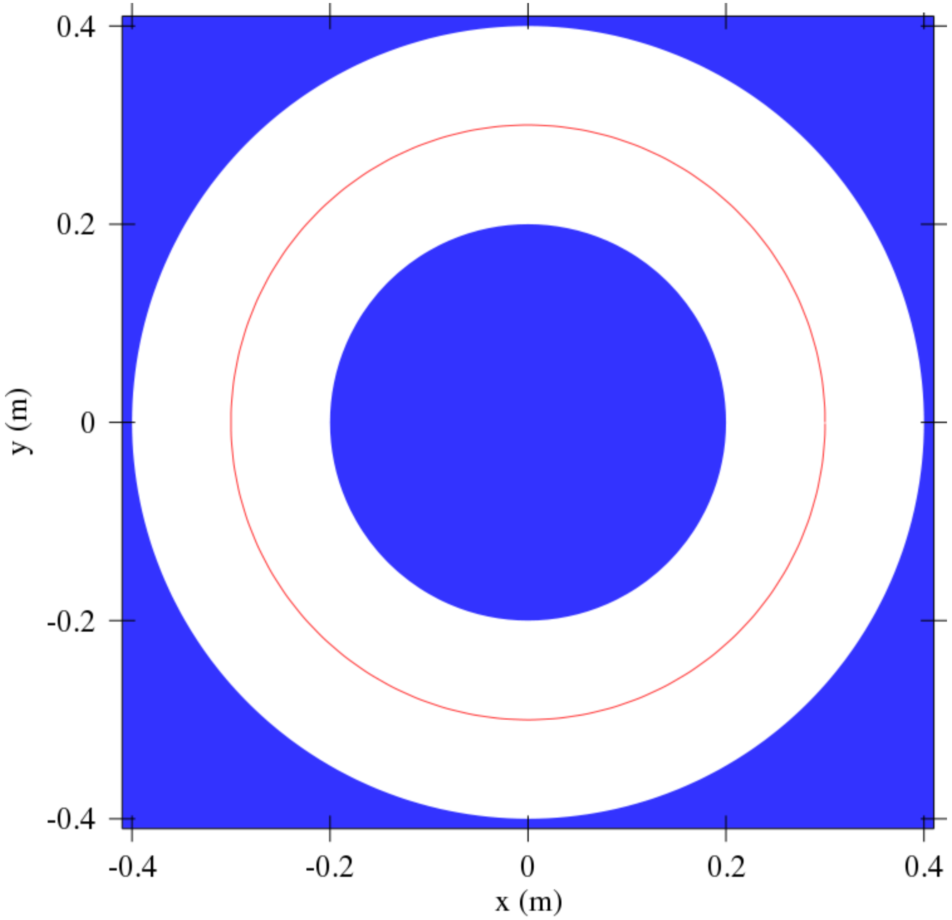


Implementation of drift from curvature of magnetic field (PIC)



Same parameters as MCD implementation.





Implementation of drift from curvature of magnetic field (Theory)

Using the same parameters we get the theoretical drift distance from equation (1) as follows:

$$\Delta s_d = v_d \Delta t \approx 0.028605m$$

Summary of results		
Source	Drift distance	Relative Error
Theory	$0.028605m$	-
PIC	$0.028618m$	0.05%
MCD	$0.028649m$	0.16%

Conclusions

We developed a code in C++ for simulation of a plasma inside a toroidal vessel.

We successfully implemented an algorithm for the dynamics of charged particles moving through a magnetic field into a Monte Carlo simulation.

Finally we implemented several processes of interest into the simulations, such as an RF electric field for the PIC method and the drift from curvature of magnetic field lines for both methods and compared them to the theoretical results with success.

References

[1] V. Vahedi and M. Surendra, “A Monte Carlo collision model for the particle-in-cell method: applications to argon and oxygen discharges”, Computer Physics Communications , vol. 87, no. 1, pp. 179 – 198, 1995.

[2] N. Metropolis, A. W. Rosenbluth, M. N. Rosenbluth, A. H. Teller, and E. Teller, “Equation of state calculations by fast computing machines”, The Journal of Chemical Physics, vol. 21, no. 6, pp. 1087–1092, 1953.

[3] U. Inan and M. Gołkowski, Principles of Plasma Physics for Engineers and Scientists. Cambridge University Press, 2010.

THANKS!