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PIC numerical study of ECR plasmas confinement in a minimum-B and zero-B magnetic traps with GPU

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Abstract. This work analyzes through computational methods the phenomenon of confinement and heating of plasmas, in open magnetic traps, Minimum-B, and zero-B under conditions of resonance electron cyclotron (ECR). This simulation is made using electrostatic particle in cell method. First, it simulates the minimum-B trap, which has been studied both numerically and experimentally, by which is accomplished the confrontation of 6 different types of results that help us to validate our code. In the same way the zero-B trap is analysed. Proposed by Dr. Dugar-Zhabon, the main characteristic of the trap is the nullity of the magnetic field in the centre of the trap. The results show the detailed behaviour of the electronic component in the initial stage of the formation of plasma. Given the computational cost of the used model that allowed us to simulate fine details of the dynamics of plasma. Results were only reached in the time of half-life of the electrons. During this period the minimum-B trap proved to be better for the production of ions than the zero-B trap. Due to the huge amount of equations needed to solve the motion equations and the charge density, they are calculated in a Parallel way by GPU clustering.

1. Introduction

ECR plasmas are using in several scientific, industrial and technologist research areas [1,2]. In almost all practical applications are required of high density plasmas that need that the ions and electrons have to be confined to a limited space where plasma can stay and increase their energy.

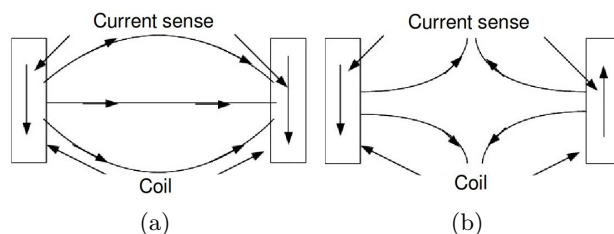


Figure 1. View of fields from coils for (a) minimum-B and (b) zero-B.

The magnetic trap system called minimum-B is used in ECR ion sources. This system is used to produce intense, high charge state ion beams. In order to produce higher multi-charged ions it is necessary to increase the density and time confinement of the plasma. In the minimum-B trap the magnetic field is minimum in the geometrical centre, that makes the plasma be pressured



toward this region. So, a way to increase this effect could be achieved making the whole magnetic field in the centre as zero. This can be possible if the sense of the currents that feed the coils placed at ends of chamber (Figure 1) have an opposite sense. This idea was proposed by Dr. Valeriy Dougar-Zhabon [3]. In this work, we present a comparative study between zero-B and minimum-B configurations through computational simulation using PIC method. Which runs during 30000 microwave cycles. Due to the huge amount of equations to solve by cycle, the code has been performed in parallel by using the Cuda C library.

2. Physical and computational modeling

The plasma is modelled by electrostatic PIC method on a uniform mesh, which step length is 0.2cm. The charge weighting is performed in three-linear way. The plasma is confined inside cylinder discharge chamber, it has 4cm in radius and 26cm in length, the z-axis coincide with the symmetry axis of the chamber and the XY plane coincide with the transverse centre plane. The plasma is considered as a hydrogen one, it is heated by 14 GHz microwaves for a TE_{114} mode. The temporal mesh step is taken as the microwave period divided by 160. We have taken 5×10^6 superparticle for electrons and the same amount for ions, each superparticle represents to 1×10^6 real particles. The static magnetic field of the trap is formed by two coils to produce the longitudinal magnetic field, a hexapole system to generate a transversal magnetic field. The ECR zone has the shape like an ellipsoid. The evolution of the plasma is made as individual interacting particles in electromagnetic fields by solving the Newton-Lorentz equation as is present in our before work [4]. The discretized Newton-Lorentz equation for electrons 1 was calculated in one GPU using CUDA C library. While the corresponding Newton-Lorentz equation for ions was make using the CPU cores with OpenMP library. The discretized Poisson equation was solved in the CPU through iterative method. In case of a particle go out from chamber it is returned inside of chamber in aleatory way.

$$\frac{\vec{u}^{n+1/2} - \vec{u}^{n-1/2}}{\Delta\tau} = \vec{g}^n + \frac{\vec{u}^{n+1/2} + \vec{u}^{n-1/2}}{2\gamma_B^n} \times \vec{b}^{n-1/2} \quad (1)$$

where $\vec{u} = \frac{\vec{v}}{c\gamma}$ relativistic moment in units of m_0c , $\vec{g} = \frac{\vec{E}_T}{B_0}$ total electric field, $\vec{b} = \frac{\vec{B}_T}{B_0}$ total magnetic field; both of them are divided by the magnitude of the magnetic resonance field $B_0 = \frac{m_q\omega c}{q}$; $\gamma_B = \sqrt{1 + u^2}$ relativistic factor and $\tau = \omega t$.

3. Minimum-B system

The ECR surface has a shape like an ellipsoid which volume is 131.63cm^{-3} .

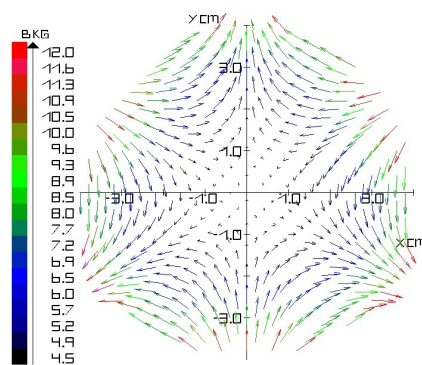


Figure 2. The magnetic field profile on z-axis.

The magnetic field on XY plane is shown in Figure 2, this configuration can form the local plasma tramps since the magnetic field has azimuthal and longitudinal gradients, the azimuthal

ones is due to two factors. The first is that the radial component from the coils reinforcement the field from south poles and reduce field from north poles in the half first part of the chamber ($z < 0$). The opposite phenomenon is then on in the second part of the chamber ($z > 0$). This magnetic configuration make that electronic component of the plasma form a six-bar shape in the central region, its transversal section view can be shown in the Figure 3. These bars can unite by couples near the planes $z = 3.5$ cm and $z = -3.5$ as is shown in the Figure 3.

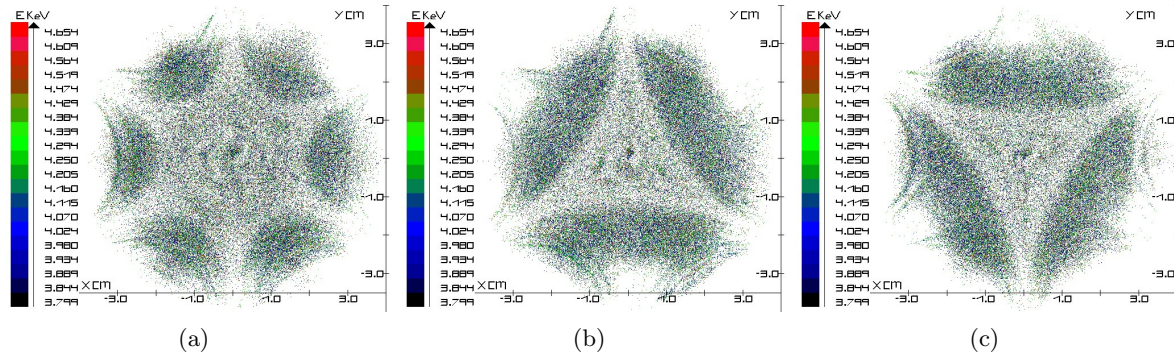


Figure 3. Spatial distribution of electrons confinement in the local trap for minimum-B system. (a) XY view of the electrons located in the local magnetic trap (around plane $z=0$ with 2cm in width, (b) XY view of the electrons located in the local magnetic trap (around plane $z=3.5$ cm with 2cm in width and (c) XY view of the electrons located in the local magnetic trap (around plane $z=-3.5$ cm with 2cm in width.

The asymmetry in the connections can be explain as a consequence of asymmetry in the magnetic field before mentioned, since in the regions where the magnetic field was weakened, the electrons can leakage from plasma and to impact the cylinder chamber walls. This phenomenon can be shown in the plasma marks on the wall, which ones are shown in the Figure 4(a). This result is agree with the experimental data [5].

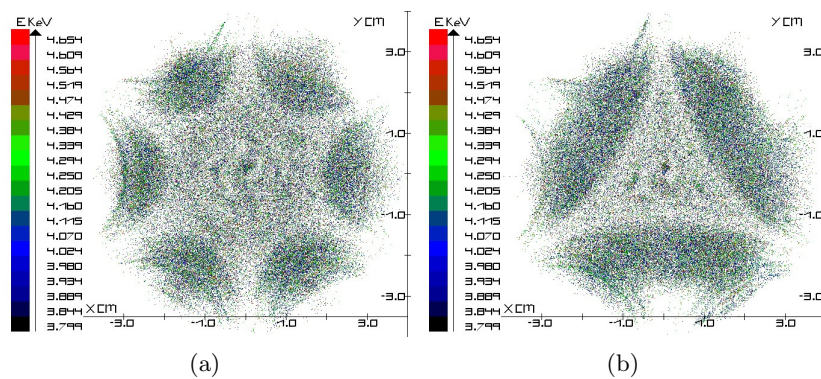


Figure 4. Results for minimum-B system. (a) Plasma marks leaved for the electronic component on the cylinder wall of the chamber and (b) Electronic distribution function.

The particles in this region has a energy range of 3.8-4.61keV. This local trap represents an accumulation zone, it can be shown in its energy spectrum (Figure 4(b)), which has a peak around 4.5keV. The average electronic density inside of ECR zone is $8.88 \times 10^9 \text{ cm}^{-3}$.

3.1. Software validation

For validate our software we using some experimental results and we also compare with other computational results. First, we make a plasma photo in the light visible spectrum,

corresponding to cold electron emissions [6, 7]. To do it, we calculate the energy density in the same instant, and draw it in a plane without consider the deep. The image of this is shown in Figure 5.

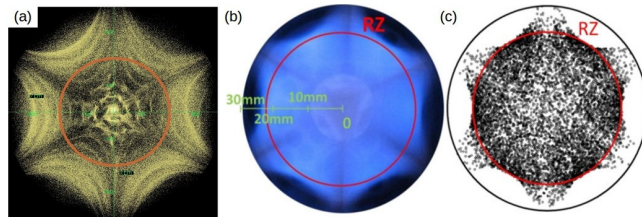


Figure 5. XY distribution of the cold electrons: (a) our results, (b) light visible photo of a real plasma [6] and (c) TrapCAD code [6].

Although this result is not exactly (Figure 5), however can be consider as good since the results do not corresponding at the same magnetic configuration; but its general behaviour can be showed, Like this one, we make another 3 results, for warm electrons 3.5-10keV (Figure 6) which are in the X-ray spectrum [6, 8–10], our results look like the real ones, for hot electrons we take the range of 5-10keV see [11, 12].

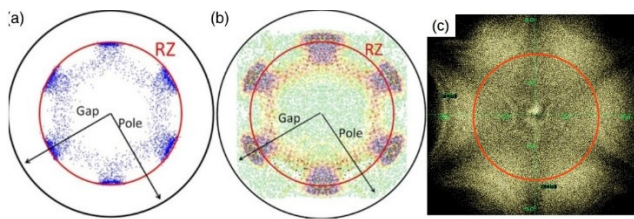


Figure 6. XY distribution of the cold electrons: (a) TrapCAD code [6], (b) X-ray photo of a real plasma [6] and (c) our results.

We also present the spatial distribution of warm electrons which energy range were taken as 10-50keV in Figure 7 where it was shown with other similar results. We can appreciate that our result is agree with the real ones, in the gradients of intensity.

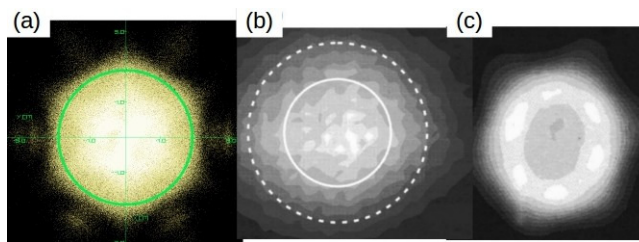


Figure 7. XY distribution of hot electrons: (a) our result and (b) experimental result [11] and (c) another simulation [11].

To measure the cold electron lifetime, we allow the particles leakage from chamber. We suppose an exponential decay then making an semi-logarithmic graph, we get two lifetimes the first 1.184855×10^{-5} s. This value is agree with [13]. The second was 1.184855×10^{-5} s, this can be possible according to [7]. The period of free decay was on during 1000 microwave cycles. In this time the electron component of the plasma was reduced by 8.48%, the 38.4% leave the plasma by cylinder walls, while the 61.16% do it for the end walls.

4. Zero-B system

For zero-B trap we only change the sense of the coil currents, the ECR zone has a volume of 400.88cm^{-3} . In this trap we also can find local traps the spatial distribution is shown in Figure 8. These particles have an energy range of 3.8-4.61keV. This zone also is a accumulation region as is shown in Figure 9(b). However during the period of free decay the electron component

of the plasma was reduced by 20.56%, the 91.6% leave the plasma by cylinder walls, while the 8.4% do it for the end walls. The fact that the most particles go out from cylinder walls can be partly explain by the longitudinal magnetic cusp guide the electrons to cylinder walls and their radial component always reduce north poles which are converted in leakage zone greater than zones next to south poles (Figure 9(a)). The average electronic density inside of ECR zone is $7.52 \times 10^9 \text{cm}^{-3}$.

We also find two lifetimes for the cold electrons the first was $1.02 \times 10^{-6} \text{s}$ and the second was $3.78 \times 10^{-6} \text{s}$.

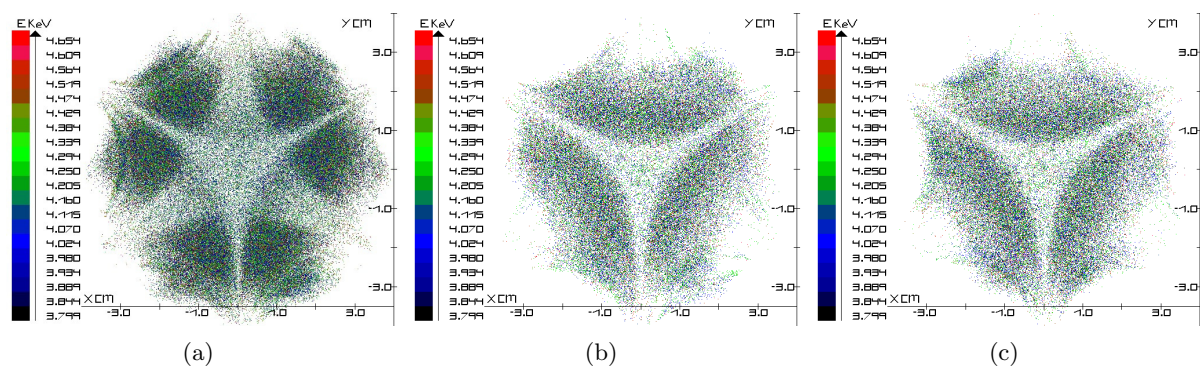


Figure 8. Spatial distribution of electron trapped in the local traps for zero-B system. (a) XY view of the electrons belong to local magnetic trap (around plane $z=0$ with 2cm in width), (b) XY view of the electrons belong to local magnetic trap (around plane $z=5\text{cm}$ with 2cm in width) and (c) XY view of the electrons belong to local magnetic trap (around plane $z=-5\text{cm}$ with 2cm in width).

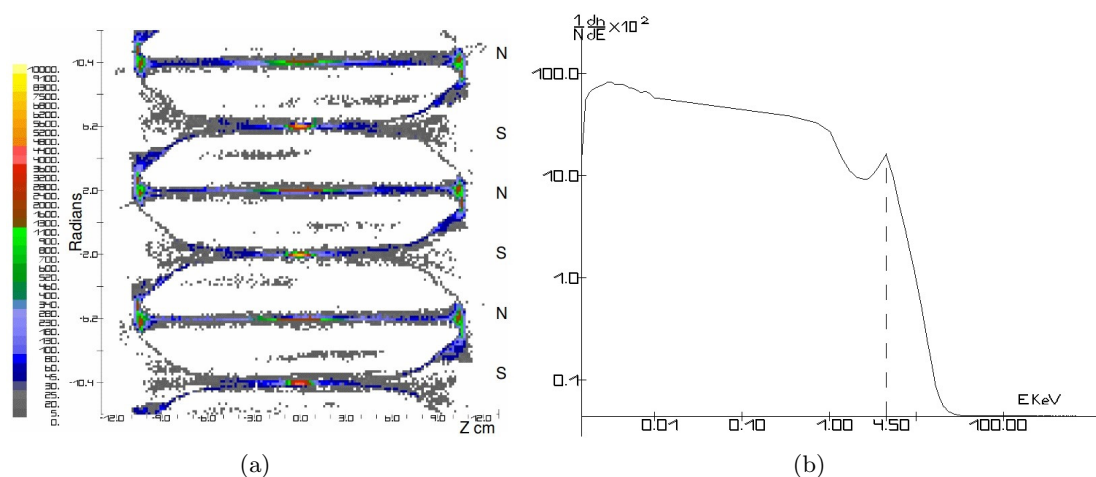


Figure 9. Results for zero-B system. (a) Plasma marks leaved for the electronic component on the cylinder wall of the chamber and (b) Electronic distribution function.

5. Conclusions

At this stage, the minimum-B has better parameters, the first lifetime for cold electrons is 1.84 times higher than zero-B; the second lifetime for cold electrons is 3.12 times higher than zero-B. The amount of leakage particles in the zero-B trap was 2.42 times higher than minimum-B trap.

The density in the minimum-B was a little greater, it was 1.18 times higher than zero-B trap. Therefore the minimum-B trap showed advantages front zero-B trap, it can be possible for the absence of longitudinal magnetic field in the zero-B trap, specially in centre region where the plasma is pushed longitudinally but radially can be addressed on the cylinder walls. Although is necessary to reached the lifetime of ions to have a definitive results, since only at that moment the Lawson parameter of plasma can be measurement. Then our work simply show one small deficiency in the design of the zero-B trap. However, the bigger volume of the ECR zone represent a significative advantage since can be increase the probability of ionization process.

Acknowledgment

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