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Numerical simulation for optimization of multipole permanent magnets of multicusp ion source

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ABSTRACT

A new ion source will be designed and manufactured for the CYCLONE30 commercial cyclotron with a much advanced performance compared with the previous one. The newly designed ion source has more plasma density, which is designed to deliver an H^- beam at 30 keV. In this paper numerical simulation of the magnetic flux density from permanent magnet used for a multicusp ion source, plasma confinement and trapping of fast electrons by the magnetic field has been performed to optimize the number of magnets confining the plasma. A code has been developed to fly electrons in the magnetic field to evaluate the mean life of electrons in plasma in different magnetic conditions to have a better evaluation and comparison of density in different cases. The purpose of this design is to recapture more energetic electrons with permanent magnets. Performance simulations of the optimized ion source show considerable improvement over reported one by IBA.

1. Introduction

Plasma (ion) sources are widely employed in a number of technologically important applications including particle sources [1,2], etching [3], implantation [4], deposition [5], fusion devices [6], production of precursors [7], etc. Multicusp ion source has been used widely in fusion reactors and particle accelerators mainly for radioisotope production.

The CYCLONE30 commercial accelerator utilizes an ion source technology similar to a LBL style ion source dating from the early 1980s [8]. The 30 keV H^- beam current produced by this ion source is typically about 2.5 mA with an emittance of 400 mm mrad [9]. In order to reduce the emittance and increase the beam current from the CYCLONE30 multicusp-type $H-$ ion source, improvements to the magnetic confinement system are required. To facilitate this, the present geometry requires optimization.

It has been shown that permanent magnets can be used to improve the density and uniformity of DC discharge plasma [10]. Confinement of plasma by different cusp geometries has been investigated. Nowadays it is clear that full-line cusp geometry gives the highest plasma density regardless of pressure. Increase in density is primarily due to confinement of primary electrons [11].

An appropriate source design is based on permanent magnet arrays to create multicusp magnetic fields to effectively increase the ionization efficiency in the source. Arc discharge occurs between the filament that function as the cathode and the arc chamber wall that functions as the anode. The neutral gas filled into the arc chamber will be ionized and become weakly ionized plasma. The plasma is expected to exist uniformly throughout the arc chamber, because the cusp field formed by surrounding magnets reflects the charged particles.

The plasma source for a particular application must provide useful ion species with the needed current density, electron temperature, and plasma uniformity. There is a distinct trade off in terms of the volume of multicusp plasma and the number of cusps.

In this article, we make an analysis of a multicusp negative ion source by CST Particle Studio™ [12] for plasma confinement and trapping of fast electrons by the magnetic field. Also the effects of magnetic field and number of magnetic poles on the plasma density are examined.

To this end, a simulation code is developed to optimize the number of magnets confining the plasma in the H^- multicusp ion source. This code improves the existing drawbacks in the particle studio CST program and predicts the lifetime of primary electrons and the effects of different configurations on plasma density.

Our simulation illustrates that there is an optimum point in choosing the number of permanent magnets confining the plasma. The results of investigations have demonstrated that the electron confinement effect becomes stronger with increasing N (the number of rows of permanent magnets), on the other hand, the escape of electrons from the loss cone becomes more frequent as N increases. The optimum value of N is the case when the two competitive effects balance.

2. Review of cyclone30 magnetic confinement assembly

A schematic 3D view of the Cyclone30 ion source and permanent magnets arrangement for plasma confinement is illustrated in Fig. 1.

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The magnets assembly is composed of ten pieces of permanent magnets made of Nd–Fe–B with different magnetization directions to generate cusp shaped magnetic field for electron confinement. This magnets array produces magnetic field of 6.2 kG at poles and a roughly zero magnetic field in the center of chamber which is measured by the Gauss meter.

The body of the source is a 154 mm high copper cylinder 98 mm in diameter around which four decapoles of permanent magnets are mounted. The magnets are arranged with alternate poles facing the chamber, thus producing cusp-shaped magnetic fields.

3. Magnetic mirror confinement

Magnetic bottle is efficient in containing plasma with minimal losses. The losses are happening mainly through a small area at the ends of the bottle, through which the ion extraction is also done.

This area has a maximum magnetic field, which decreases the beam quality. Plasma is confined in the minimum field region in the middle. The so-called mirror equation gives the conditions for the trapping of the plasma particles

$$B_0/B_m = \sin^2\theta$$

where B_0 and B_m are the minimum and maximum magnetic field values. θ is the minimum angle between the particle velocity and magnetic field vectors for the particle to be trapped in the bottle. Magnetic field strength is increased at the ends. Charged particles that approach the end slow down, and many are reflected from this "magnetic mirror."

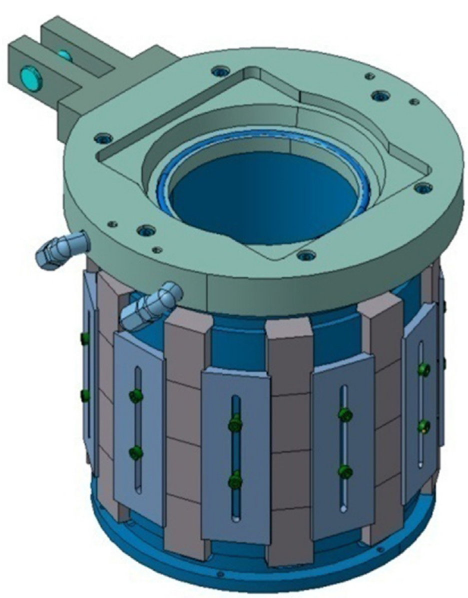

Fig. 1. Schematic view of Cyclone30 ion source magnetic confinement assembly.

The main idea is that the magnetic field is weak at the center and strong at either end. If the electric field is zero, then the kinetic energy of the plasma particles is conserved since the magnetic field does not work. Using the fact that the magnetic moment μ_m of a charged particle in a local magnetic flux density B is given by

$$\mu = IS = mv^2{}_\perp/2B = E_\perp/B = const \quad i.e.\ d\mu/dt = 0$$

where $E_\perp$ is the kinetic energy related to the velocity component perpendicular to the magnetic field $v_\perp$. As it is obvious, the magnetic moment μ_m is the same as the usual definition for the magnetic moment of a current loop with area *S* and current *I*.

It can be also derived that the magnetic moment is time independent (if the particle energy remains constant). Assuming that the particle starts its motion from magnetic field B_1 and moves towards the higher magnetic field B_2 ($>B_1$), equation gives

$$E_{\perp,1}/B_1 = E_{\perp,2}/B_2$$

As the magnetic moment is constant, the rotational energy $E_\perp$ has to increase with the magnetic field. Due to the conservation of energy ($E_{tot}=E_\perp+E_\parallel$) the "parallel" kinetic energy has to simultaneously decrease, i.e. $E_{\parallel,2} < E_{\parallel,1}$. Consequently, the velocity parallel to the magnetic field decreases and finally the particle is reflected back to direction of lower magnetic field. The increasing magnetic field acts as a mirror for charged particles. Two magnetic mirrors can be used to form a magnetic bottle.

However, the magnetic mirror cannot reflect every charged particle. Only particles with a large enough $\mathbf{v}_\perp/\mathbf{v}_\parallel$ ratio will be reflected. This ratio is often referred to as the pitch-angle (α) defined in Fig. 2. Particles having a smaller pitch angle than the critical pitch-angle (α_0) can go through the magnetic mirror.

In order to derive the critical pitch-angle α_0, it is assumed that the magnetic field of the starting point is B_0, the maximum magnetic field is B_m and $v_\perp$ is set to be $v \sin\alpha$. The critical pitch-angle is then given by equation

$$\sin^2\alpha_0/B_0 = \sin^2\alpha_m/B_m \Rightarrow \alpha_0 = \arcsin(B_0/B_m)^{1/2}$$

At the mirror point, $v_\parallel$ is zero and the pitch-angle $\alpha_m=90^\circ$ The equation shows that the critical pitch-angle is smaller when the magnetic field maximum (B_m) increases. Consequently, the magnetic field maxima should be as high as possible to achieve better confinement of the particles in the magnetic bottle. In three dimensions (3D) the critical pitch-angle defines the loss cone as shown in gray in Fig. 2.

The conservation of energy and magnetic moment in the magnetic mirror field gives the following equations:

$$\varepsilon = m(v_{\parallel 0}^2 + v_{\perp 0}^2)/2 = mv_0^2/2 = m(v_{\parallel 1}^2 + v_{\perp 1}^2)/2$$

$$\mu = m\, v^2{}_{\perp 0}/2B_0 = m\, v_{\perp 1}^2/2B_1$$

The axial confinement is accomplished if $v_{\parallel 1}^2=0$. Thus, the loss cone angle θ_0 is determined with the mirror ratio by the following

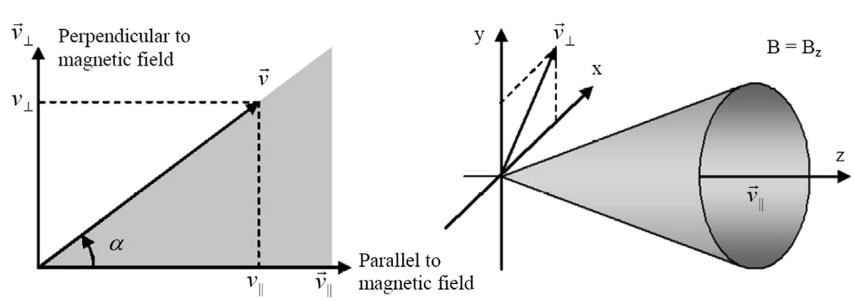

Fig. 2. Definitions of the pitch-angle and loss cone in 2D and 3D.

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equation. Thus, the loss cone angle θ_0 is determined with the mirror ratio by the following equation:

$$1/R = B_0/B_1 = v^2_{\perp 0}/v^2_{\perp 1} = v^2_{\perp 0}/v_0^2 \equiv \sin^2\theta_0$$

It is clear that if plasma is placed inside a magnetic mirror machine then all of the particles whose velocities lie in the loss cone promptly escape, but the remaining particles are confined [13].

4. Magnetic field

The complete topology of the magnetic field configuration of the ion source is calculated by the 3D numerical solution based on the magnetic charge model. The magnetic field calculated using this model is shown in Fig. 3. The line cusp field can be seen along the chamber wall.

5. Magnetic line configuration

We can assume an exponential dependence of the magnetic field strength defined by

$$B = B_{max}\exp(-\gamma(\pi/d)^{*}y)$$

Where B_{max} is measured at the edge of the magnets and γ is a geometrical factor [14]. Equation above, which fits the experimental data, shows the variation of the magnet field strength, B, along the chamber radius.

Fig. 4 shows the flux density profile on the line in the y direction from the wall to the center. The strength of flux density ranges from a few Gauss at the center of the chamber to about 3 kG at the chamber wall in front of a magnet.

6. Theoretical simulations

6.1. Field free region calculation

Figs. 5 and 6. show the simulation of the magnetic field for different number of cusps from 6 to 14. This shows that as N increases the field free region (the space in the center of chamber where magnetic field is roughly zero) increases which results in better plasma confinement.

The region of a higher magnetic field of multipolar magnet is farther to a chamber wall. Negative ions created on the sidewall hardly can reach the center of the source due to trapping by the multicusp magnetic field. As a result, H^- beam created on the side wall do not have a significant effect on the H^- current [15].

6.2. Electron trajectories in the magnetic field

The motion of an electron is calculated by solving the equation of motion as following:

$$m d\mathbf{v}/dt = q(\mathbf{v} \times \mathbf{B})$$

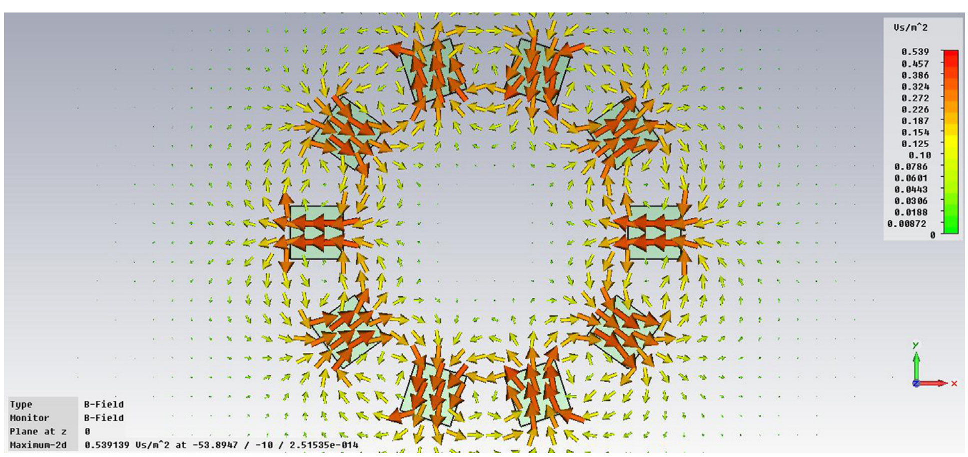

Fig. 3. Magnetic field line of Cyclone30 ion source.

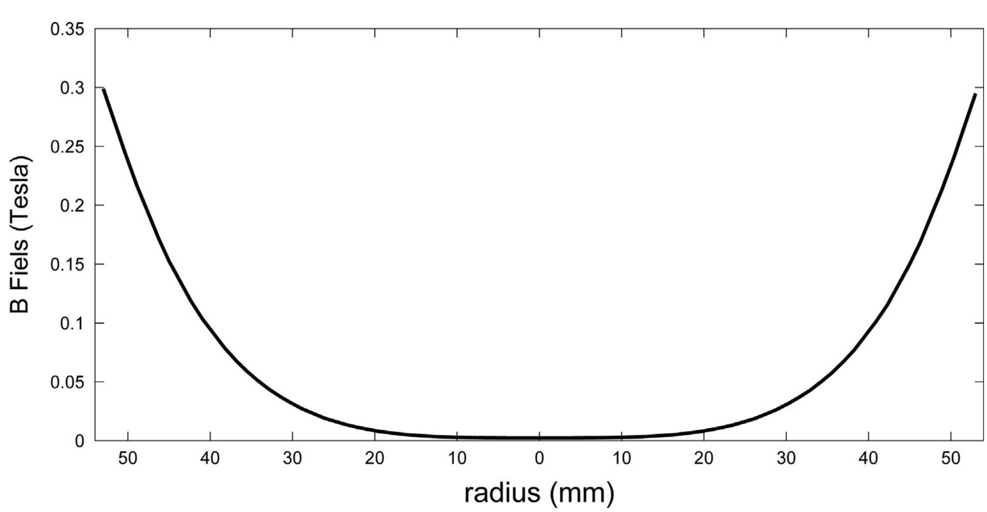

Fig. 4. Magnetic flux density profile along the radius through the pole tips for $N = 10$.

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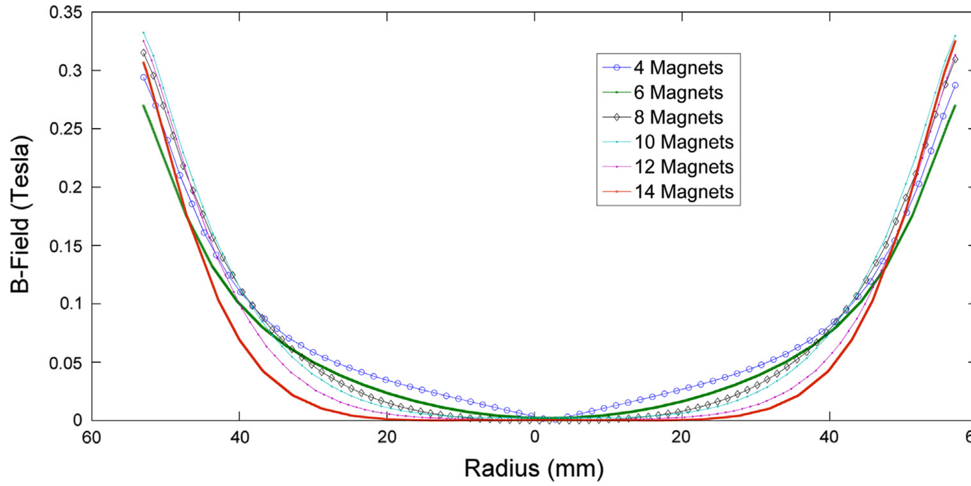

Fig. 5. Magnetic flux density profile along the radius through the pole tips for N=4–14.

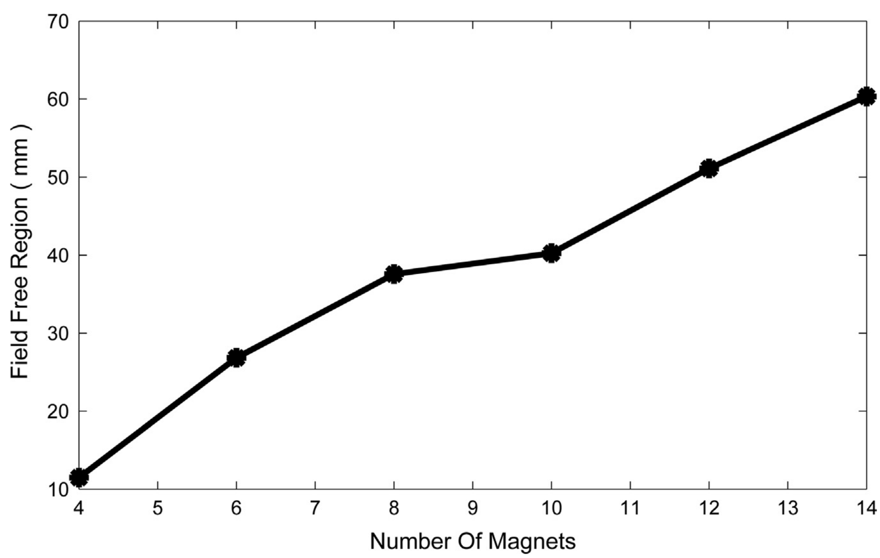

Fig. 6. Field free region calculation of different rows of permanent magnets.

where m is mass of the electron, q is charge, **v** is the velocity vector and **B** is the vector of magnetic flux density.

Electrons are emitted from the filament and move in the magnetic field created by the surrounding magnets and the filament currents. The initial energy of emitted electrons is assumed to be 200 eV in the present simulations, because the discharge voltage is 200 V. Electrons fly in the chamber until they collide with the chamber wall that results in electron destruction.

Figs. 7–9 show the radial distributions of the electron density in a multicusp magnetic field with N=6, 12 and N=14 cusps.

As shown in Fig. 7 there is relatively small area of constant magnetic field for 6 cusps and the relatively low number of electrons which have stationary orbits.

In Fig. 8 the area of constant magnetic field increases by adding the number of cusps and also the number of electrons which have stationary orbit increases.

By again increasing the number of cusps in Fig. 9 although still the field free region increases but the escape of electrons from the loss cone becomes more frequent as N increases and electron density decreases. So there is an optimum point for choosing the number of magnetic poles for plasma confinement in multicusp ion sources.

Hence from above simulations it is clear that to decrease the total cusp loss, smaller N is desirable but that would decrease the field free region. So an optimum value of N is to be chosen so as to have sufficient field free region and at the same time low total cusp loss width.

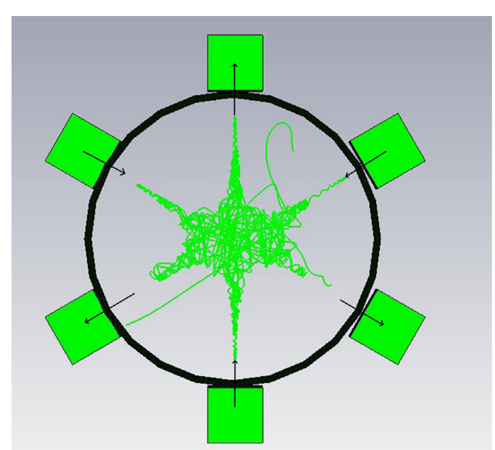

Fig. 7. Electron orbits in the Cyclone30 ion source with 6 columns. The field free region is small and relatively low number of electrons has stationary orbits.

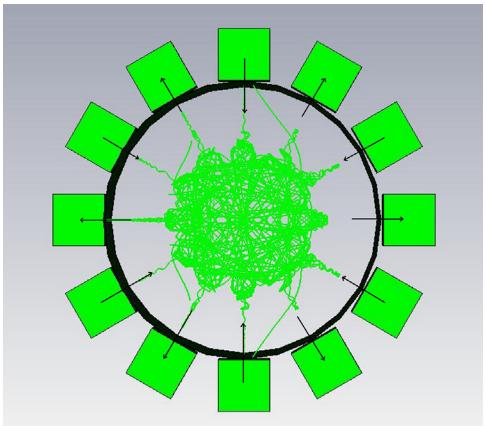

Fig. 8. Electron orbits in the Cyclone30 ion source with 12 columns. The field free region is good enough and relatively high number of electrons has stationary orbits.

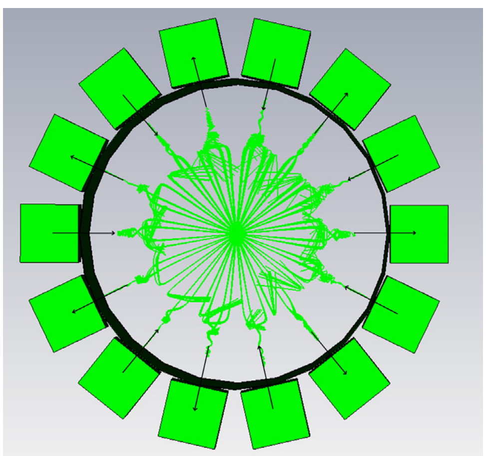

Fig. 9. Electron orbits in the Cyclone30 ion source with 14 columns. The field free region is largest but escape of electrons through the cusps is more probable.

To this end a computer code was developed to investigate the optimized configuration precisely.

6.3. Cusps optimization by developed code

To the best of our knowledge, no specific simulation method has been reported yet to explore the optimized number of cusps of the magnetic field; furthermore, there is a lack of proper theoretical method to economize the time and cost of the design and fabrication. To evaluate the performance of different cusp spacing, the total distance that electrons travel is calculated by simulation.

CST is able to track the particles in electric and magnetic fields but also it does not provide any data concerning the trajectory of a particle, position and velocity in the desired time and the total path that each particle has traveled. So in order to optimize the CYCLONE30 ion source, a computer program is developed.

The process of optimization is as follow: the number of permanent magnets used to create magnetic field lines is the optimization parameter, and the chamber radius, height and filament position are constant. The number of magnets is varied from 4 to 14 ones with geometrical specifications shown in Fig. 1. The magnetic field is calculated by CST software and exported to our code.

Having magnetic flux density at every point of the chamber, 5000 electrons are emitted from the filament and are allowed to leave the filament cathode in different positions and since they

Table 1
The results of simulations with developed program.

Mean life of electrons(s)	Sum of electron trajectory (m)	Number of magnets
7.06e−7	29,453	4
1.47e−6	61,641	6
5.51e−6	231,440	8
7.8e−6	328,062	10
8.79e−6	368,032	12
7.01e−6	294,260	14

have random velocity direction they move in the magnetic field created by the surrounding magnets.

The initial energy of emitted electrons is assumed to be 200 eV in the present simulations, because the discharge voltage is 200 V. Electrons fly under the effect of magnetic field and the trajectory that they travel and their mean life time are monitored. When the electrons collide with the chamber wall and get out of the chamber it is assumed that destruction occurs.

In this simulation, the total length that electrons have traveled and the mean life of electrons inside of chamber in the different magnetic conditions are calculated.

7. Results and discussion

Table 1 shows the value of total electron path and the mean life of electrons for different number of magnets. As can be seen, these values are the highest for 12 numbers which shows a super performance in comparison to the other configurations for this specific dimension.

When 12 columns are employed, electron trajectories and mean life is highest. This result shows that 12 is optimum case because electrons take more trajectory which results in more collision, ionization and finally more plasma density which is the goal of this research.

Electrons are stopped either due to termination of their energy in the process of tracking or colliding with the chamber of ion source.

As it is evident in Table 1, when the number of magnets is 12, more electrons fly in the chamber which entails more negative ion current production.

8. Conclusion

Numerical simulations were used in optimization of Cyclone30 multicusp ion source with a multipolar magnetic field. The effects of magnetic field and number of poles on the plasma structure were confirmed.

The electron confinement effect becomes stronger with increasing N. On the contrary, the escape of electrons from the loss cone becomes more frequent as N increases.

To evaluate this optimization more precisely, we developed an electron orbit simulation code, which included the electron trajectory and its mean life to optimize the cusp spacing for our ion source. In this simulation different numbers of magnets were studied. The simulation showed a considerable improvement in the performance when 12 magnets were used. The developed approach allowed a proper theoretical method to gain efficient configuration in multicusp which could lower the cost and decrease the design and fabrication time.

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