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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.

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### 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.  $\theta$  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

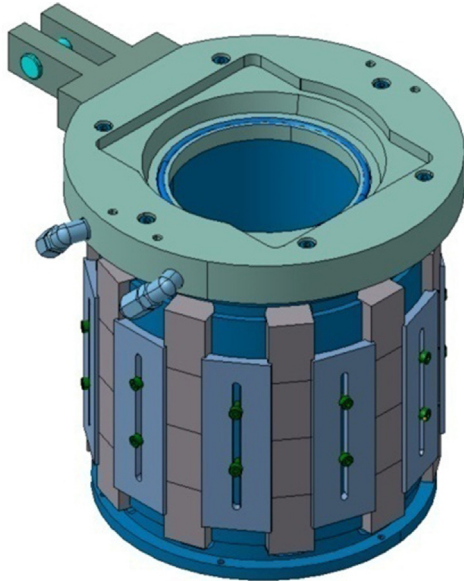


Fig. 1. Schematic view of Cyclone30 ion source magnetic confinement assembly.

that approach the end slow down, and many are reflected from this “magnetic mirror.”

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  $\mu_m$  of a charged particle in a local magnetic flux density  $B$  is given by

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

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  $\mu_m$  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 ( $E_{\text{tot}} = E_{\perp} + E_{\parallel}$ ) 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  $v_{\perp}/v_{\parallel}$  ratio will be reflected. This ratio is often referred to as the pitch-angle ( $\alpha$ ) defined in Fig. 2. Particles having a smaller pitch angle than the critical pitch-angle ( $\alpha_0$ ) can go through the magnetic mirror.

In order to derive the critical pitch-angle  $\alpha_0$ , 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:

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

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

The axial confinement is accomplished if  $v_{\parallel 1}^2 = 0$ . Thus, the loss cone angle  $\theta_0$  is determined with the mirror ratio by the following

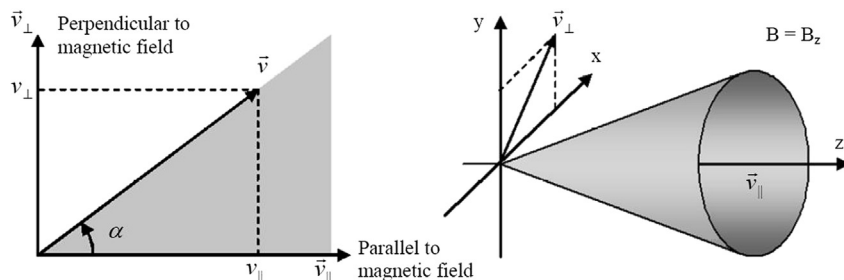


Fig. 2. Definitions of the pitch-angle and loss cone in 2D and 3D.

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