SYMMETRIC AND SUFFICIENT CUSP FIELD FOR 18 GHZ ECR ION SOURCE

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Abstract

A successful attempt has been made in this short report to reconfigure the cusp magnetic field using a pair of coaxial coils either room temperature (RT) or super conducting (SC). Shortcomings of magnetic field at the cusp positions were mitigated using a highly permeable mid-iron disk (MID) in the case of field due to coil system. The technique increases the density of plasma charged particles and consequently the extracted beam current of highly charged heavy ions (HCHI). A simple design for constructing a novel cusp ECRIS of 18 GHz is described herein.

INTRODUCTION

Many workers in the area of improving the performance of conventional electron cyclotron resonance ion source (ECRIS) have achieved some success for extracting sufficient beam of the HCHIs but at the cost of simplicity and economy. Some workers tried to achieve and experiment with the cusp magnetic field for producing multi-charge heavy ions but they could not succeed because of insufficient and asymmetric field at the ring cusp (RC) and point cusp (PC) positions.

It is very important to achieve minimum-B field configuration to contain plasma. In conventional ECRIS, it is done superimposing bumpy axial mirror field and radial sextupole field. In cusp field configuration it is achieved just by energising two co-axial coils oppositely. In this case, the field at the centre is zero and the field configuration is termed as *modified minimum-B* field. Its feature can be understood by considering *curl* $\vec{B}$ =0 equation through Fig. 1. The line integral of $\vec{B}$ around an infinitesimal contour as C in the figure should vanish. The contour C has two sides perpendicular to field lines and two sides along field lines. Since the arc length of the latter two sides is proportional to the distance from the local centre of curvature, the intensity $\vec{B}$ must be inversely proportional to the radial distance [1].

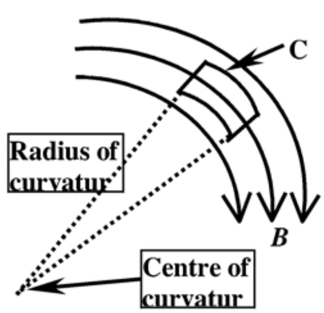

Figure 1: Loop C for field integration in a curved field.

It has superb plasma confining feature, but the earlier devices using it hesitated to provide HCHI on extraction because of insufficient and asymmetric field at the RC position with respect to the PC on the central axis [2]. There was a lot of plasma loss mainly at the RC at the mid-plane. Here, the development of the technique is described to attain the required magnetic field for 18 GHz microwave frequency ECRIS to be operated at high-B mode (HBM) as earlier reported for 14.4 GHz ECR ion source [3]. The sufficient symmetric magnetic field work as magnetic mirrors for escaping electrons and ions and increases the plasma density and stability.

It is now possible to make more powerful and bigger ion device using optimised cusp field created by a pair of coaxial coils. It may be referred to a theory of equilibrium, which takes into account mirror reflection of particles and therefore permits the existence of finite contained plasma. It is seen that the containment time is proportional to mirror ratio and average plasma density and inversely proportional to the average speed of particles. It increases with dimension of the chamber also.

CUSP FIELD CONFIGURATION

Particles constituting plasma is assumed to be at the centre of the cusped geometry. Centres of curvature of the field lines are situated outside the plasma. From the following discussion we get the result that the cusp geometry, indeed, has more confining property and can be used to design ECRIS to obtain HCHI beam for various applications. The feature of the cusp field (Fig. 2) and the behaviour of the plasma in such field have been described briefly elsewhere [3].

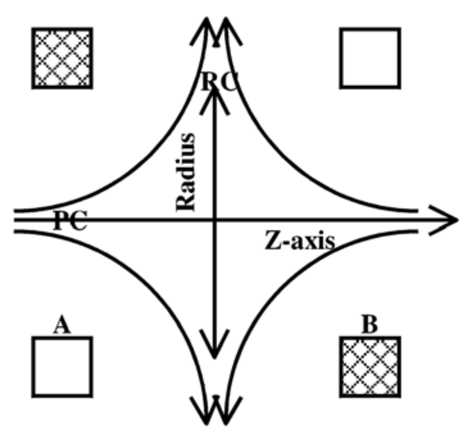

Figure 2: Scheme of simple cusp field created by oppositely energised two co-axial coils A and B.

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Charged Particle Motion

The motion of a charged particle in a static cusp magnetic field of axial symmetry ($B_\theta=0$ and $\partial/\partial\theta=0$) is described by the following Hamiltonian, Eq. (1), in absence of any electric potential:

$$H = \frac{1}{2m}\left\{ p_r^2 + p_z^2 + \left(\frac{p_\theta - rqA_\theta}{r} \right)^2 \right\} \qquad (1)$$

Where p_r and p_z are kinetic momenta and P_θ is the canonical momentum and it can be shown that P_θ=constant and it does not depend upon azimuth θ. For a cusp configuration of magnetic field, $\vec{\boldsymbol{B}}=curl\ \boldsymbol{A}$ can be satisfied by the proper choice of $A_\theta(r,z)$ with $A_r=A_z=0$.

From *curl**A*** it follows that the flux enclosed by a circle of radius r is $\phi=2\pi rA_\theta$. The magnetic lines of force (MLF) in a cusp configuration lie in the r-z planes. A charged particle moving along a MLF will drift slowly to other MLFs due to curvature of the MLFs and the field gradient. This turns out to be purely azimuthal one. Hence, the guiding centre remains on the same *flux surface*, defined by rotating a field line around the axis of symmetry.

A particle with sufficient energy, when injected (off axially) along a magnetic line of force (MLF), follows the flux surface until it passes the median plane at z=0, where B_z, B_r and A_θ all change sign. On the other side of this plane the particle is forced to encircle the central axis.

When charged particles (electrons) in motion gyrate around an off axis MLF in the improved cusp field, they undergo the bouncing action due to the sufficient mirror field seen by the particles at the positions of PC (on the central axis) and RC (on the midplane ring). An elaborate simulation of the electron motion of the few keV energy in the earlier designed improved cusp field for 14.4 GHz ECRIS was performed. The result, to be reported, shows that electron gyrates around MLFs, bounces back by mirror action at cusp positions at or far off the chamber surface and drifts continuously along the azimuth around the central axis.

Particles injected into a cusped field of intensity B_0 at the throat of radius ρ at PC have a chance to pass through the other throat only if their velocity exceeds critical velocity $v_{crit}=\omega_c\rho$ which depends on the injection radius. It also follows that under otherwise similar condition the critical velocity is much higher for electrons than it is for ions.

Confinement Time

The confinement time is now expressed by Eq. (2).

$$\tau \approx \frac{3DR_m}{2\bar{v}_i}\frac{\bar{n}}{n_r + n_p}\left(\ln\frac{D}{\delta_r k} + 1 \right) \qquad (2)$$

Where n, D, R_m, v_i, δ_r and k are the particle density, diameter (length) of the chamber, mirror ratio, particle speed, RC hole width and a constant respectively. Thus it is seen that the confinement time is proportional to mirror ratio and average plasma density and inversely proportional to the average speed of particles. It increases with dimension of the chamber also.

The loss formulae and the containment time of particles are modified in the presence of electric fields [4]. A decelerating field reduces the loss rate by the factor in expression (3):

$$\exp\left[-\left| e\phi \right| / k_B T_\theta \right] \qquad (3)$$

Where T_θ is the temperature in the central region. But there must be a disparity between the electron and ion loss rates because of the differences of their physical properties like charge, mass, etc. So, a negatively biased electrode helps in confining plasma by electrostatic reflection. This effects the plasma potential. The applied negative potential shrinks the loss cones at the cusps and reduces or plugs the electron loss through cusp holes.

PROPER CUSP FIELD

The first attempt here is to achieve sufficiently strong magnetic field ($B_p=B_r$ for symmetry) at the positions of PC and RC on the chamber surface for HBM operation i.e. it should follow the inequality (4). The optimised cusp field design for 18 GHz was done for the plasma chamber dimensions shown in Table 1.

The magnetic field at the ring cusp is made stronger by placing a specially shaped disk at the *z=0* plane (mid-plane). Yokes and plugs made of highly permeable material like magnetic steel (MS) are also properly placed. These techniques will increase the density of plasma particles consequently extracted HCHI beam. Normal conductor or super-conductor can be used to wind the coils and achieve the required field. Here, super-conductor was used for designing 18.0 GHz ECRIS.

$$B_p = B_r \geq 2B_{ECR} \qquad (4)$$

Table 1: Cylindrical Plasma Chamber Dimension

ID (mm)	OD (mm)	Length (mm)
160	168	160

Superconductor and Cryostat

The coils of the magnet system can be wound from NbTi super conducting composites consisting of 500 filaments of 40 µm diameter softly soldered into a copper matrix substrate/stabilizer. Specifications of the conductors used in calculation for wounding coils are short-listed in Table 2.

Table 2: Specification of the Super-conductor

SC wire diameter	1.27 mm
Overall conductor x- sec.	2.794 mm x 4.978 mm
Current density	5800 A/sq.cm
Design current	800 A

The super-conducting coils can be cooled by immersing in a liquid helium bath chamber (SC chamber) of the source. The electrical connections to room temperature environment can be made using high T_c super-conducting current leads. The use of cryo-coolers may permit to operate the cryostat without external supply of liquid helium. Robust and reliable cryo-coolers for the liquid helium temperature range are commercially available nowadays. Owing to their limited cooling capacity, however, more than one machine may be necessary for the present application. In addition, one should be attentive to the breakthrough of new cryo-cooler technologies, such as pulse tube cryo-cooler [5].

Designed Cusp Field

The size of the coils as well as the magneto motive force (MMF) i.e. the total ampere-turn (NI) now becomes ~200000 Aturn. Considering the chamber wall thickness, end flanges, plugs *etc*. properly, the field is calculated using POISSON code for geometry shown in Fig. 3. Calculated sufficient field in magnitude and symmetry is shown in Table 3 and Fig. 4.

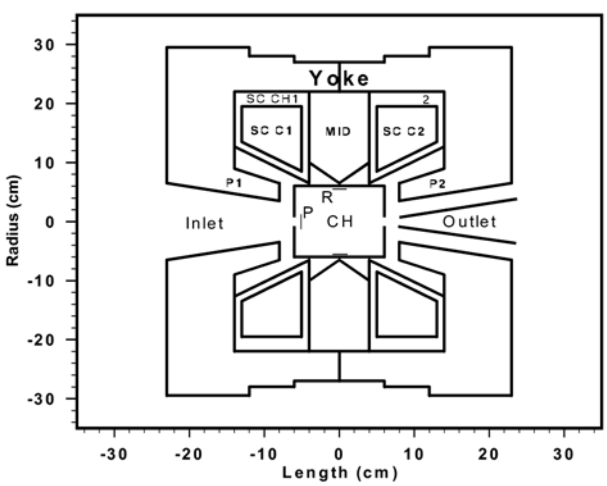

Figure 3: The geometry of the chamber CH, coils (SC C), coil chamber (SC CH), yoke, plugs (P1, P2) taken into the field calculation.

Table 3: Cusp Field for 18 GHz ECR Ion Source

Parameters	Each coil (200000 A)
Inner cryo-dia. (mm)	170
Outer cryo-dia. (mm)	440
Length (mm)	100 (with cryo-width)
Gap (mm)	80 (width of MID)
Field (kG)	~12.9 (at injection) <12.9 (at extraction) 0.0 (at the centre) ~13.0 (at extreme radius)
Electrical power	Few kWs at 800 A

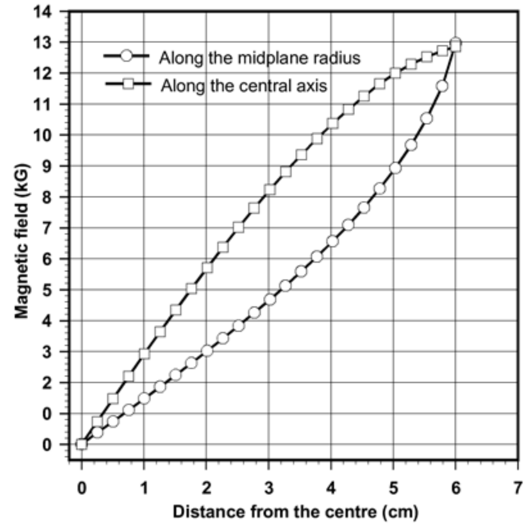

Figure 4: The computed field along the central z-axis and mid length radius i.e. the radius passing through the RCs.

CONCLUSION

It is apparent from Table 3 and Fig. 4 that the magnetic field achieved at PC and RC of the cusp field configuration in the given geometry is ~13 kG. Thus the field becomes symmetric at the two positions. The magnitude of the field achieved at the RC is spectacular as it was impossible earlier and not achieved anywhere by any one. It was because of the technique of using / not using iron disk with special pole shape in between the coils. In the achieved field the charged particles will magnetically get reflected due to mirror action. So, the lifetime of the particles in the plasma in the chamber will increase. Now the HCHIs will be created as well as extracted superbly. This optimised field can contain plasma created by either ECR discharge or inductive/ other discharge.

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