CUSPED MIRROR MAGNETIC FIELD FOR ELECTRON CYCLOTRON RESONANCE HEAVY ION SOURCE

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Abstract

Sufficient beams of Highly Charged Heavy Ions (HCHI) have been obtained in conventional electron cyclotron resonance ion sources (ECRIS) but at the cost of simplicity and economy. A cusped magnetic field (CMF) has more plasma-confining feature but a little current of HCHI's was extracted from ECRIS using it. The CMF has been reconfigured adopting a simple, novel and cost-effective technique. It uses a pair of coaxial coils either normal conducting or super-conducting, a mid-iron disk (MID) and properly shaped plugs. It can be designed now for higher microwave frequencies for high-B mode operation of the cusp ECRIS. The CMF, so created at the cusp positions is referred to a theory of equilibrium, which takes into account mirror reflection of charged particles. An ion source using the field configuration can be used to obtain stable or radioactive ion beam of high charge state. A simple design of 14.4 (18.0) GHz cusped mirror ECRIS and electron simulation in the field is presented herein for developing the compact, cost-effective and robust source of future.

INTRODUCTION

There has been a constant quest for better field configuration and magnetic well for confining plasma particles superbly in addition to improving techniques and discovering new methods to make conventional ECR source more powerful and compact in terms of production and extraction of high quality multi-charged heavy ion beams for various applications. In the same vain, the CMF configuration is put forth in the paper is one step forward in achieving more plasma confining field configuration consisting of convex lines of force towards the plasma contained at the center of the conceived source. Earlier, ECRIS using the configuration were constructed but they were little successful to be dismantled. The failure was attributed to the huge constant loss of plasma on the cusp positions because of insufficient magnetic field for providing mirror reflections of charged particles [1,2]. Plasma was lost at the point cusp (PC) holes and along the length of the ring cusp (RC) gapes.

A conventional ECRIS uses the principle of adiabatic invariance for mirror reflection and high-B mode (HBM) operation to successfully generate and confine plasma. This principle can be utilized in a properly configured cusp field also. The main objective is to achieve closed ECR magnetic field surface far off the plasma chamber inner surface. When microwave (μ-wave) power at the resonance frequency is injected into the box, plasma electrons crossing this closed surface will, in general, be heated to hundreds of electron volt due to transfer of energy from the EM wave to electrons at ECR resonance ($\omega_\mu = \omega_{c(e)}$). The heated electrons strike the atoms and ions and ionize them to high charge states by stripping them of electrons in stepwise manner and generate plasma. It is possible to make more powerful and bigger ion device using either normal-conducting or super-conducting coils and millimeter wave high frequency gyrotrons if sufficient field at the cusp regions is generated for magnetic and electrostatic mirror reflection of the charged particles.

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CUSPED FIELD CONFIGURATION

The CMF configuration is described by the vector potential $A=Grz$ in cylindrically symmetric r-z plane, where $G=(1/2z_0)B_0$ is a constant and B_0 is the magnetic field at z_0 on the central axis. It is generated energizing two coaxial solenoids C+ and C- in opposite direction (Fig.1). When the distance between the two solenoids is half the diameter of the solenoids, the same field gradient G is achieved in the radial direction in the mid-plane also. Moreover, the magnitude of the magnetic fields at the mid-plane ring of certain radius is never sufficient and equal to the field at same distance from centre on the central axis (z-axis). The magnetic field at the extreme radius in the mid-plane between the coils never reaches the absolute maximum magnetic field on the central axis. For achieving the feature of symmetry we have to raise the field at the extreme radius and reduce the maximum field on the central axis by invoking some new technique. It is done manipulating the coil geometry and highly permeable ferromagnetic material geometry around the coils.

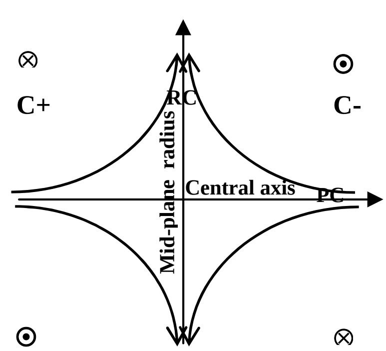

Figure 1: The scheme lines of force in CMF.

Magnetic Mirror Bouncing

The magnetic mirror ratio R_m is defined as $R_m=B_{max}/B_{min}$ on the magnetic lines of forces (MLF). An electron have parallel ($P_{//}$) and perpendicular ($P_{\perp}$) component of its total momentum (***P***) with respect to vector magnetic field (***B***), which makes it move along and gyrate around the MLF respectively at an angle given by $\alpha = sin^{-1}(P_{\perp}/P)$. The apex angle of the electron is defined as $\alpha_{apex}=sin^{-1}(1/\sqrt{R_m})$. Magnetic field at the RC is insufficient and less than the field at the PC (Fig. 1). The loss cone is large due to small R_m at the RC and the charged particles (electrons) fall easily into the loss cone defined in the momentum space. In absence of collisions, i. e. in classical regime, particles for which $\alpha<\alpha_{apex}$ leak through the magnetic mirrors otherwise they will be bounced back towards the centre.

The radial loss rate of charged particles is much larger than the axial loss rate in unmodified CMF so, no enhancement of high charge state components results in the extracted beam. It is further enhanced by the inappropriate radial plasma potential generated. The plasma around the centre is extremely starved of electrons and the production of ions particularly highly charged heavy ion becomes very difficult and whatever ions produced prefer to migrate radially towards the ring cusp positions. The radial loss is further enhanced by the negative radial density gradient of plasma; however, it is restricted by stronger electric and magnetic mirror reflection.

When the fields at RC and PC are symmetric and obtained sufficiently high, it may be referred to a theory of equilibrium, which takes into account mirror bouncing back of particles and, therefore, permits the existence of finite contained plasma without flow and is apt for generation of HCHI's. So the confinement of the plasma contained in such improved field will increase with the improvement of electrostatic and magnetic mirror action at the cusp positions.

Plasma Containment

The plasma contained in such CMF is stable if inequality (1) is satisfied. The variation of integral is along the perpendicular direction to the plasma surface between two infinitesimally close field lines. It means physically that the necessary and sufficient condition of plasma stability is the increase of the average field along the field lines outwards from the plasma boundary. This is called the *modified minimum-B* (MMB) concept [3]. In this situation the field lines are convex towards the contained plasma at the centre. This feature is achieved in this configuration and so it represents a stable field configuration.

$$\delta\int (dl / B) < 0 \qquad (1)$$

DESIGN OF PROPER CUSP FIELD

The size of the double walled cylindrical plasma chamber (CH) has 12 cm inner diameter and axial extent, which is large enough compared to wave-length 60 mm corresponding to 10 GHz μ-wave. This is to realise a so-called '*multi-mode cavity*'. Proper cooling arrangement of chamber can be provided, if needed. It has oblate spheroid of the ECR resonance surface around its centre. A design of the improved CMF was reported in reference [4] using the normal temperature coils for 14.4 GHz frequency. The designed parameters of an ion source of frequency 18.0 GHz using super-conducting coils were reported in APAC'04, Gongue, Korea (2004). The magnetic field at the ring cusp was made stronger by placing a specially shaped MID in the mid-plan. The yokes and plugs made of highly permeable material like magnetic steel are also properly placed. In the geometry for field computation the coils can be made of either normal or low/ high temperature super conductor using about 150 (200) kA-turn magneto-motive force to generate 12.0 (13.2) kG minimum magnetic field at the chamber surface on the central axis and the mid-plane radius corresponding to 14.4 (18.0) GHz μ-wave frequency. The general structure of the magnet geometry is shown in Fig. 2. The generated field is shown in Fig. 3 (4). The coils C+ and C- are oppositely energized. When the MID was not present the field was not proper. The generated improved field corresponds to the HBM operation for 14.4 (18.0) GHz μ-wave frequency.

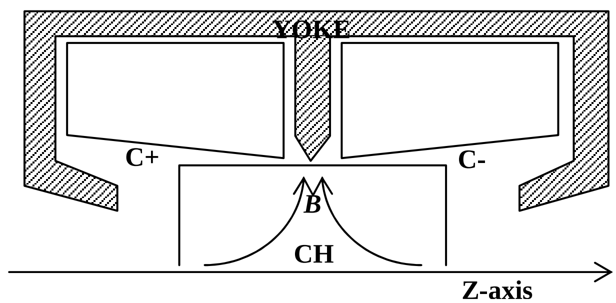

Figure 2: The schematic geometry of the magnet. The hatched area consists of iron plugs, yoke and MID.

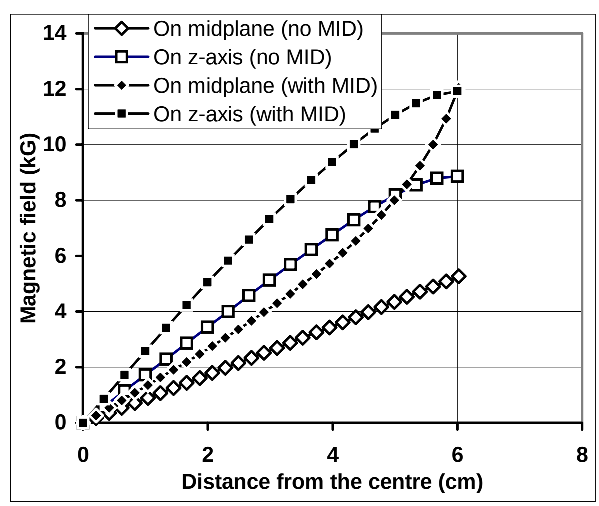

Figure 3: Field plot for 14.4 GHz frequency.

Comparison with Conventional ECRIS

A conventional ECRIS was designed for 14.4 GHz μ-wave frequency [5] for injecting HCHI's in the super-conducting cyclotron under construction at our centre. The magnetic field was changed into a CMF using the same magneto-motive force of 150 kA-turn passing through the same designed normal conducting coils. The geometry of various iron structures including the mid iron disk was changed to optimise the field on the chamber inner surfaces at the cusp positions. The parameters are depicted in Table 1 in cgs unit. A comparison [6] of some of the parameters of the conventional magnetic field and the mirror CMF has been done in it. There is a lot of gain in the resonance surface area and the hot plasma volume in the new CMF configuration mostly because of new ECR zone and absence of sextupole magnet.

Table 1(a): The source (col. 2-3) & the chamber (col. 4-6)

ECRIS	**length**	**dia.**	**length**	**dia**	**cooling**
Conv.	65.0	68.0	26.6	6.9	yes
Cusp	53.0	68.0	24.4	24.4	no

Table 1(b): Resonance zone (spheroid)

ECRIS	**c(z-axis)**	**b, a**	**shape**	**area**	**volume**
Conv.	6.5	1.8	prolate	111	88
Cusp	5.0	8.2	oblate	625	1408

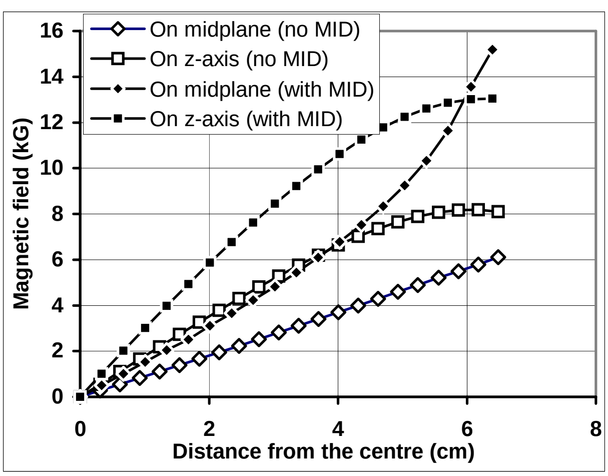

Figure 4: Field plot for 18.0 GHz frequency.

Electron Motion Simulation

The motion of an electron was simulated in the typical field of the complete design of improved spindle CMF ECRIS as in the reference [7]. When electrons move off axially, they are bounced back time and again from the cusp positions because of sufficient and symmetric magnitude of field. The electrons moving along the axis also have high probability of bouncing back towards the centre. It will be boosted further by electro-static reflection caused by the negatively biased electrodes, if placed at the cusp positions.

DISCUSSION AND CONCLUSION

The geometry of the coils and the iron structure consisting of the plugs, yokes and the MID have been optimised for achieving the maximum symmetric mirror CMF for both the frequencies. It is heartening to find that the required minimum field is generated easily on the interior chamber-surface. The techniques are meant to improve the cusp field configuration to increase the confinement time and density of plasma [8] charged particles, consequently extraction of HCHI's. The MMB field configuration is stable even for scattering dominated gas-dynamic regime at high field/ frequency case and expected to produce HCHI's. The high particle current is expected on extraction from the charge and current scaling laws [9] for both stable and radioactive species. The proper cusped mirror CMF, so achieved, is meant to contain plasma superbly not only discharged by ECR process but also by other means. The loss of plasma reduces on the RC in present design due to shorter cusp-line than in the conventional ECRIS due to presence of multicusp field. The comparison of ECRIS using conventional and cusp field configuration and the simulation of electron dynamics in the improved CMF for 14.4 GHz have revealed that the plasma confinement time and magnetic mirror action is sufficiently strong.

The field configuration can be adopted for low as well as high frequency of ECRIS or containing plasma generated by other means. The field can be further optimised for ECRIS or tailored for ion-implanting device. A radially magnetized ring pole made of permanent magnet having high remanence and ceorcivity also can be used to generate such improved cusp field. The confinement time and plasma density are expected to be high for HCHI's generation because of application of strong mirror field and biased electrode at the cusp positions inside the plasma chamber.

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