NEW SPINDLE CUSP ZERO-B FIELD FOR ECR ION AND PLASMA SOURCES

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Abstract

A traditional ECR ion source (ECRIS) or plasma source use magnetic min-B field for plasma containment and energizing electrons based on the principle of the ECR process. A cusp field produces modified min-B or zero-B field. A new cusp magnetic field (NCMF) configuration with symmetric field at the cusp positions, corresponding to a given RF frequency confirming the standard model of ECR Ion Source, is simulated to contain large volume high density plasma for producing beam for low or high charged ion. The magnetic field increases along and across the magnetic lines of force starting from zero at the centre and maximum value at the periphery. The cusp field with convex lines of force towards the plasma is ideal for confining it as drift of the particles take place either in the azimuth or towards the low field region at the centre. Non-adiabatic behaviour of electrons at the centre can be either tackled by gas-dynamic confinement at high density or exploited to generate more secondary electrons. Confinement feature of the field is assessed by electron simulation. A new technically viable cusp ECRIS has a bright prospect ahead as it is simple, stable, compact and cost-effective compared to the traditional ECRIS.

INTRODUCTION

Geller's group pioneered constructing ECRIS like MAFIOS and its variants [1-3] at Grenoble in 1970's and later. The ECR plasma and its property have been described well by him [4] in terms of confinement of plasma, ECR heating and techniques to improve working of an ECRIS. A minimum-B field was produced employing axial field and radial magnetic field for confining plasma quiescently. The cold electrons with some initial kinetic energy gyrate about a magnetic line of force, that is magnetic line of force (MLF) with f_G (gyro-frequency) $\propto$ B (magnetic field). At resonance condition, $f_G \approx f_{RF}$, electrons get energy from the RF wave.

The main motivating factors of the present study are i) to study the possibility of more confinement of electrons and ii) to construct a simple, compact and cost-effective ECRIS to alleviate some of the problems of traditional ECRIS like complicated magnet system, small plasma volume, limited injection and extraction regions etc.

Earlier the classical CMF was used to design an ECR ion source (ECRIS) [5] because of its inherent plasma confining nature. But it had a little success because of huge loss of plasma at the cusp (mainly ring cusp, RC) positions owing to insufficient and asymmetric magnetic field. The CMF has been reconfigured here adopting a simple, novel and cost-effective technique to shrink the loss area [6]. It helps to achieve high value of $n_e \tau_i$ for generating intense HCI beam. The variation of plasma pressure, $P_{par} = n_e k_B T_e$, along the MLF depends on the magnetic pressure, $P_B = B^2/(2\mu_0)$. The gravitation-like inward force because of the curvature of MLF's produces a MHD-stable configuration.

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DESIGN SCHEME TO PRODUCE NCMF

A classical CMF can be produced using either a pair of coaxial coils carrying opposite current or a single ring of radially magnetized permament magnet. The field does not rise along the radius at the mid-plane as rapidly as along the central axis. But rise in field in both the direction in new improved CMF (NCMF), on the average, is equal. The field is zero at the centre and is weak in a small region around it. The deduced vector potential in eq. (1) represents the NCMF and can be used to visualize the field line distribution and calculate the field components in the cylindrical co-ordinates.

$$A_\theta(r,z) = g\ rz + b\ rz^3 + c\ r^3 z + C \quad (1)$$

$$B_r(r,z) = -g\ r - 3b\ rz^2 - c\ r^3 \quad (2)$$

$$B_z(r,z) = 2g\ z + 2b\ z^3 + 4c\ r^2 z \quad (3)$$

Where constants $g = (11B_0)/(14L)$, $b = (-2B_0)/(7L3)$, $c = -(3/4)b$ and $C=0$ (say). A NCMF of any dimension, L and maximum field, B_0 can be evaluated. The absolute NCMF for B_0=40 kG and L=16cm is plotted in Fig. 1 using eqs. (2) and (3).

The magnet geometry consists of yoke, end-plugs and centre disk of highly permeable material in addition to coil pair or PM ring to generate NCMF. There is no limitation to magnet size and field strength in case of using coils to produce NCMF. Application of PM discards the power supplies, major cooling system etc. It can be used to produce NCMF for high-B mode cusp ECRIS of as high as 18 GHz RF frequency [7]. The calculated field can be realized feeding proper geometry similar to Fig. 2 in a field computing code [8, 9].

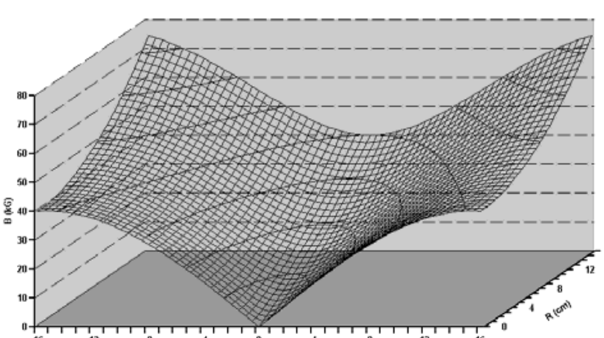

Figure 1: Plot of absolute field due to NCMF

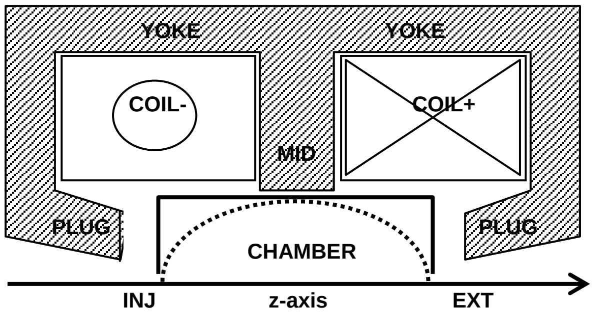

Figure 2: Scheme of magnet system to produce a NCMF

CHARACTERISTICS OF NCMF

Some initial results of NCMF computation were reported in the InPAC [10] showing that a traditional ECRIS of 14.4 GHz [11] can, on paper, be split into two NCMF ECRIS'es; one using the same coils and the other using the same PM after rearrangement to generate the required improved CMF.

Bent mirror ratio in the calculated NCMF

It is seen that the magnitude of the field at the cusp positions is sufficiently high to achieve the high-B mode condition as well as $\pi/2$ angle rotated point cusp-ring cusp (PC-RC) mirror [12]. The TrapCAD code [13] is capable of calculating the magnetic mirror ratio, M_R on a MLF. The M_R on a MLF passing through (r, z) points on r = z line starting from r=0.1cm to 10.0 cm is shown in Fig. 3 in the calculated field. The M_R, with respect to the B_{min} on $|z|\approx|r|$ conical plane, increases as one goes towards the centre of the field, so the loss cone angle ($\alpha_{apex}=\arcsin(1/\sqrt{M_R})$) narrows down too.

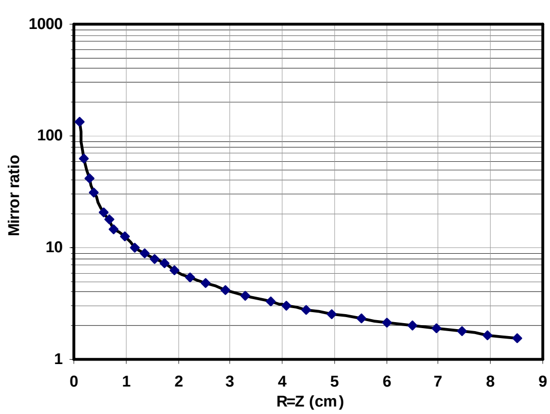

Figure 3: Mirror ratio with distance r=z from the centre

Electron simulation in the calculated NCMF

The calculated field was fed into the TrapCAD code to visualize the electron motion when launched at various positions around the magnetic centre in the plasma chamber with different energy and energy partition along the direction of the magnetic field ($W_{\|}$) and perpendicular ($W_{\perp}$) to it. It is seen that there are three types of motion, electrons undergo.

A little far away from the low field region the electrons always execute a stable adiabatic motion The guiding centre of the electrons oscillates between mirror points placed at PC and RC positions on the chamber surface. There are MLF's towards which electron moves on the average, so they gradually but constantly shift on the adjacent flux tube. This fact signifies that the flux enclosed by the tube, on which the electron moves, is not conserved as the enclosed flux slowly varies with its longitudinal position of the electron between the bouncing points [14]. So, electrons perform stable adiabatic motion drifting slightly towards the higher field direction at higher radius after successive bounce from PC and RC. The region beyond a small so called black region of approximate diameter ~2.14 cm is stable for electron energy upto ~35.0 keV with the energy partition confirming $\alpha_{loss}\geq\alpha_{apex}$, where α represents the loss-cone angle. As a matter of fact, the value of α_{apex} decreases as one moves inward on the r=|z| cone surface.

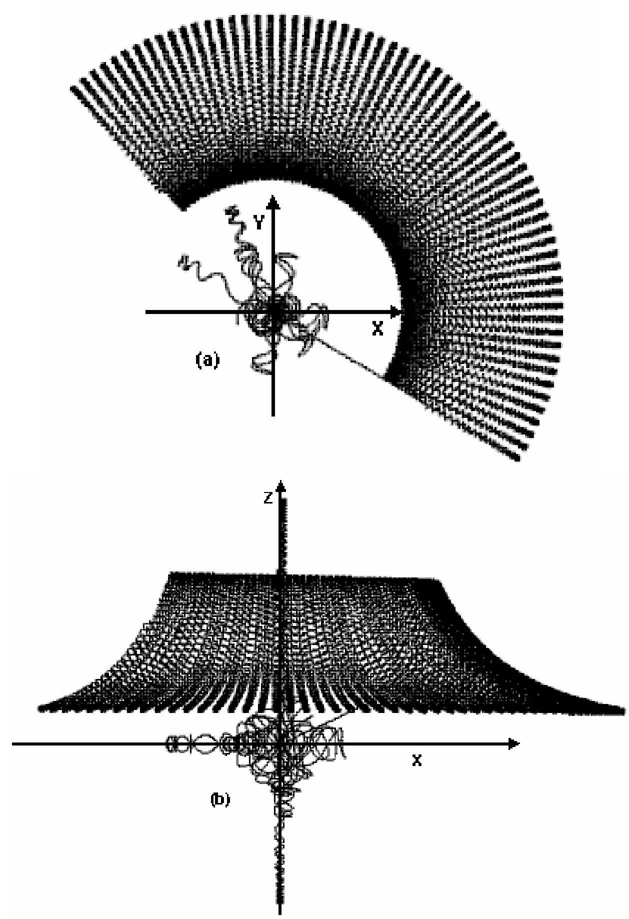

Figure 4: Electron motion when launched near the centre.

When the total launching energy of an electron is increased, it mostly executes unstable or non-adiabatic motion while passing through r=|z| points because of either approaching the apex angle of the loss cone due to high $W_{\|}$ or enclosing a thick flux tube having large gyration radius due to very high $W_{\perp}$. An electron having lower energy and low $W_{\perp}$ tends to be unstable as the launching point approaches the magnetic centre where the $(r/B)\nabla B$ approaches 1.0 for the MLF, which signifies that the local curvature of the MLF becomes comparable with the curvature of electron trajectory. The electron may ultimately be lost at the PC or RC positions (at 16 cm away from the centre) in a short time because of instability. Or it may execute stable motion for long time. This region may be termed as the transition region from adiabatic to non-adiabatic motion of electrons for the caculated magnetic field and chamber geometry.

If electrons are launched further near the magnetic centre, they execute random motion due to Coulomb like scattering as little flux is defined by $\mu \cdot \mathbf{B}$. In this case the invariance principle of electron magnetic moment is not applicable. The average length of the electron excursion in this region does not depend on the history of an orbit. Yet, the electrons are bounced several times towards the low field region performing spiral or banana motion before being lost in little time, which is, dependent on the launching energy W as well as on $W_{\parallel}$ and $W_{\perp}$.

It is worth mentioning the observation during the simulation that a non-adiabatic motion of electron near the centre may turn into an adiabatic motion while travelling far away from the centre (Figs. 4) or vice versa due to scattering of electrons towards the centre as a result of binary collision among the particles. The simulation also establishes that the electrons get lost innately at the RC or PC positions on the chamber surface.

Mitigating effect of non-adiabatic motion

The magnetic field at the central region of the CMF is weak and the invariance principle of adiabatic magnetic moment of electron is not perfectly valid. The plasma density at 18 GHz or higher frequencies exceeds 1×10^{12} /cm^3, so the plasma enters into a collisional regime. Then, quasi-gas-dynamic confinement of plasma takes place [15] because of the collisions of the electrons with slow ions on their course of being lost. The quasi-gas-dynamic regime is characterized by very small mean free path of electrons under electron-ion collisions compared to the extent of the excursion of the electrons between the magnetic mirror plugs. The rate of filling the loss cone by electrons due to high collision frequency is more than the rate of electron-loss within. The average electron velocity distribution function remains isotropic in the filled loss cone. Then the non-adiabatic motion of electrons at the magnetic centre is insignificant [16, 17] for generation of multi-charged ions of heavy elements.

CONCLUSION

A CMF has inherent property of MHD stability, so quiescent plasma is contained in such field. The designed NCMF can be used to construct very cost-effective and simple cusp ECRIS. Since it does not need any sextupole for radial confinement of plasma, the volume of the plasma chamber increases, which helps in extraction of an intense beam of HCI's. The EM energy can be injected to boost the source operation at several lower RF frequencies simultaneously.

The plasma loss is reduced because of high mirror field, shorter cusp line ($2\pi L$, where 2L is the chamber diameter), convexity of lines of forces, further electrostatic mirror action, secondary electron emission and gas-dynamic confinement effect due to collision dominated plasma. A cusp ECRIS with further high microwave frequency will need more upgraded NCMF, which is possible to be generated using superconductors [18]. The cusp ECRIS is capable of accepting radioactive fragments or particles also from targets to produce and deliver intense radioactive ion beam. It can work in continuous or pulsed modes. The loss of electron at the cusp positions can be utilized to produce secondary electrons to further boost the plasma density.

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