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Loss cone profile on the imaginary surface just enclosing the resonance surface in 14.4 GHz ECR ion source

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Abstract A 14.4 GHz ECR ion source was designed [1] recently for the superconducting cyclotron The concept of local mirror ratio at a point has been defined A relationship between mirror ratio and the loss cone is deduced The mirror ratio giving the loss cone profile on the surface of an imaginary box just enclosing the resonance surface (assumed plasma volume) are evaluated. Electron reflection and loss is discussed in the plasma chamber

Keywords : Magnetic mirror, loss cone, plasma confinement

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1. Introduction

The plasma confinement takes place in a smooth inhomogeneous magnetic field on the principle of adiabatic invariance of the magnetic moment of electrons. For this reason, there are two circular coils (400 Amps) on the two sides left and right to create tandem static axial magnetic mirrors and produce an axial and a radial magnetic field at the position of the sextupole magnet. A long sextupole magnet around the horizontal cylindrical sides is placed between the two axial magnetic mirrors for creating the tandem static radial magnetic mirror along the whole length. The iron plugs in the injection and extraction ends plays an important role in positioning and enhancing the field maxima. The optimised minimum axial magnetic field at the centre (of the plasma) of the source (~3.0 kG) was obtained. Radius of the inner cylindrical surface of the plasma chamber is 3.48 cm and end-surfaces are about 30.0 cm long (Figure 1).

Many authors discussed about loss cone [2] and significance of it on the loss of electrons falling in it but they did not evaluate it quantitatively which gives qualitative idea of the loss of electrons all around the plasma chamber. It gives qualitative idea of the loss of electrons because its motion is vigorously affected by many other physical phenomena like collision, diffusion, magnetic drift *etc.* So for the first time, an attempt has been made to calculate it on a surface just enclosing the resonance zone and evaluate the reflection coefficient of electrons at a point of its creation on the surface.

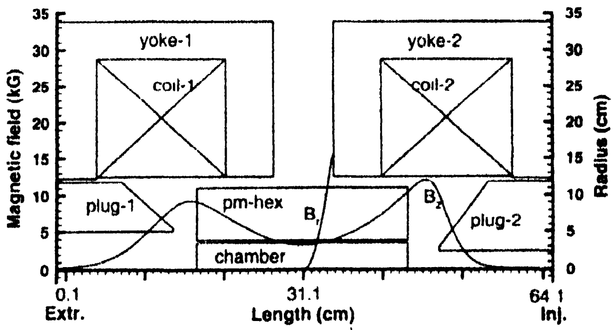

Figure 1. Geometry of the magnet system of the ECR with magnetic fields

2. Theory and calculations

2.1. *Loss cone :*

It is very important to know about the loss cone because the electrons which fall inside the loss cone get lost until they collide with other particles and move to other position and fall outside the realm of the new loss cone either by change in momentum components, mirror ratio or the both.

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2.2. Loss cone formulation :

A plasma is considered in three dimension. We assume a line of force PSOF in the plasma chamber which encounters the cylindrical wall or end of the chamber in both the forward and backward direction of the line (Figure 2a). Let an

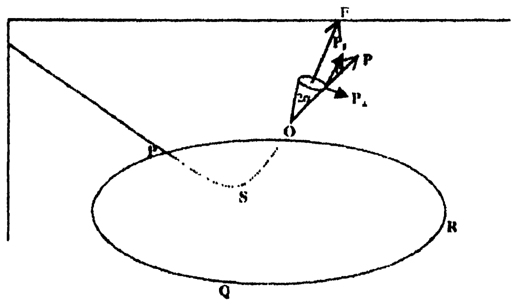

Figure 2a. An electron created at O on the line of force subsequently moves in OA direction at an angle α with the line of force.

electron gyrates around the line of force at O with total momentum $P = |\boldsymbol{P}|$ having components parallel and perpendicular to the line of force $P_{\|}$ and $P_{\perp}$ respectively. A remarkable point is that the electrons may have $P_{\|}$, parallel or antiparallel *i.e.* it may move forward (positive direction) or backward (negative direction) with reference to the line of force. The magnetic field at the two points where the lines of force meet the wall may be different and represented by B_{s+} and B_{s} in parallel and antiparallel direction respectively. The local magnetic field at O is B_o and B_{min} is the minimum field at certain point on the line of force. The eqs. (1a) and (1b) give the local mirror ratios in forward and backward directions respectively at the point O whereas eq. (1c) gives the mirror ratio in common use so far defined by other authors. The function $\max(B_{s+}, B_{s-})$ in eq. (1c) selects maximum of the two values.

$$R_+ = B_{s+}/B_o, \tag{1a}$$

$$R_- = B_{s-}/B_o, \tag{1b}$$

$$R_m = \max(B_{s+}, B_{s-})/B_{min}. \tag{1c}$$

The mirror ratio R_m gives a qualitative feeling of the tightness of the plasma confinement and the efficiency of the multiply stripped ion production in the plasma. But as far as the production of electron at certain position and subsequent motion of the electron is concerned, the concept of local mirror ratio (R_+ and R_-) is very important for evaluation and estimation of electron reflection or loss. The actual angle and apex angle of the cone of the spiralling electron around the line of force is given by eqs. (2a) and (2b) respectively. The loss cone is coaxial to the line of force.

The solid angle of the loss cone is deduced from Figure (2b). Let an electron is at O. Taking the magnitude of the momentum of electron as radius we imagine a sphere around O. The circular shaded portion ACD enclosed by the gyrating electron is a part of the sphere. The area (S) of the shaded dish and the solid angle of the electron is given by

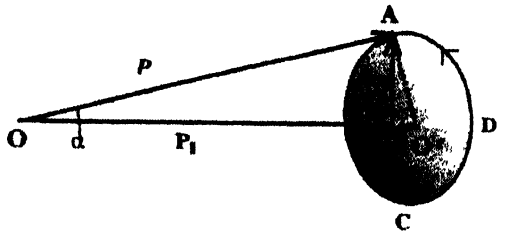

Figure 2b. The shaded circular portion is a part of the spherical surface with radius P (the magnitude of electron momentum). The line of force passes along the line O and O' (the centre of the shaded dish). The parallel and the perpendicular component of the momentum is shown.

eqs. (3) and (4a) respectively. Using the apex angle obtained by the adiabatic invariance of the magnetic moment of electron we obtain the solid angle of the loss cone which is given by eq. (4b).

$$\alpha = \sin^{-1}(P_{\perp}/P), \tag{2a}$$

$$\alpha_{apex,i} = \sin^{-1}\left(1/\sqrt{R_i}\right), \tag{2b}$$

$$S = 2\pi P(P - P_{\|}) = 2\pi P^2(1 - \cos\alpha), \tag{3}$$

$$\Omega = 2\pi(1 - \cos\alpha), \tag{4a}$$

$$\Omega_i = 2\pi\left(1 - \cos(\alpha_{apex,i})\right), \tag{4b}$$

where $R_i \in \{R_+, R_-, R_m\}$ *i.e.* the subscript $i = +, -$ or m If $\alpha < \alpha_{apex,i}$ then the electron falls inside the loss cone and there is sound probability of it being lost unless it switches over to another position by some physical means and starts moving from a point out of the loss cone there afresh. Normally the mirror ratio is below 10 in most of the ECR plasma chamber. The solid angle of the loss cone has been plotted against mirror ratio (Figure 3) using the above formula just to show their mutual relationship.

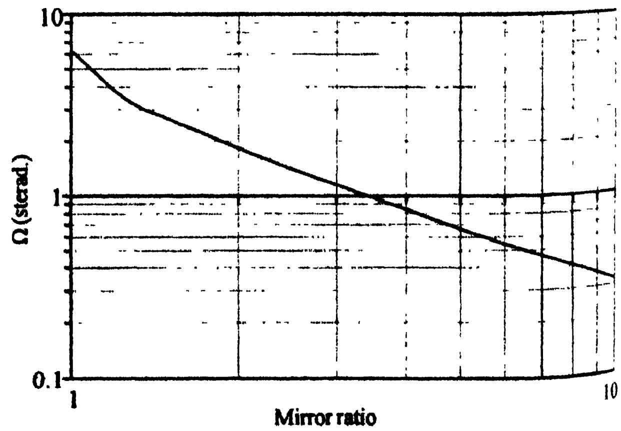

Figure 3. The plot showing the relationship of solid angle and mirror ratio in log-log scale.

2.3. *Loss cone evaluation :*

The value of mirror ratios R_+, R_- and R_m at any point in the chamber are given by TrapCAD [3,4] on the line of force passing through the point after properly feeding the coil and multipole magnetic field data. If the local field at the point, we assume the field (B_o) at point O, is known then all the fields B_{s+}, B_{s-} and B_{min} can be calculated readily using the obtained values from above formulae of mirror ratios. The apex angle $\alpha_{apex,i}$ and solid angle Ω_i of the loss cones were evaluated on the surface of the imaginary box (Figure 4a) just enclosing the resonance magnetic field surface (Figure 4b) in the chamber corresponding to the rf

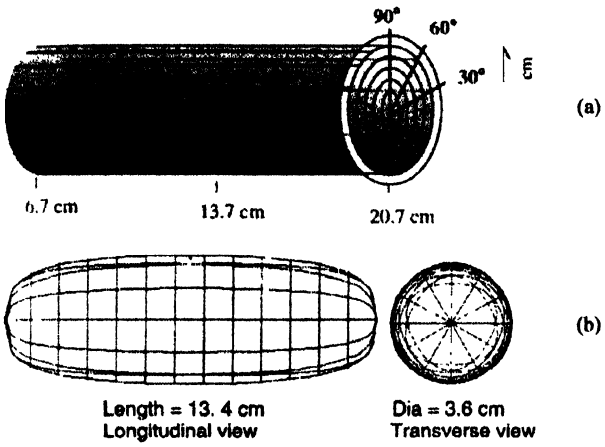

Figure 4. (a) Loss cone evaluated on the surface of the imaginary box just enclosing the plasma. (b) The iso-Gauss surface at the resonance field 5.143 kG corresponding to the rf frequency 14.4 GHz.

frequency of 14.4 GHz. The resonance surface is positioned from 24.4 cm to 38.4 cm (Figure 1) and from 6.7 cm to 20.7 cm with reference to the extraction end of the plasma chamber along the length. The inner to outer circles are at r = 0.2, 0.6, ..., 2.2 cm and from 30°–90° at the interval of 4° and 1 cm along the length form the meshes for evaluation. It is seen that the apex angles of the loss cone increase as we go towards the chamber wall. The values of Ω_i were evaluated in the parallel and anti-parallel directions of the lines of force along the whole plasma length and from 30° to 90° azimuth and plotted in Figures 5–7 respectively. The sum of the two gives the total solid angle ($\Omega_i = \Omega_+ + \Omega_-$) at a point. The solid angle Ω_m evaluated in one direction of the line of force by taking the conventional mirror ratio R_m is plotted in Figures 5a–7a respectively at the extraction side (6.7 cm), injection side (20.7 cm) and cylindrical surface (r = 1.8 cm) of the box (Figure 4a). Similarly Ω_+ and Ω_- are plotted in Figures (5b–7b) and (5c–7c) respectively.

3. Discussion

The loss cone value at the extraction side of the box at 90° azimuth and similarly at the extraction side at 30° azimuth increases with radius becomes uncomfortably high. The field configuration is 3-fold symmetric along the azimuth because of sextupolar radial field. The loss holes are formed

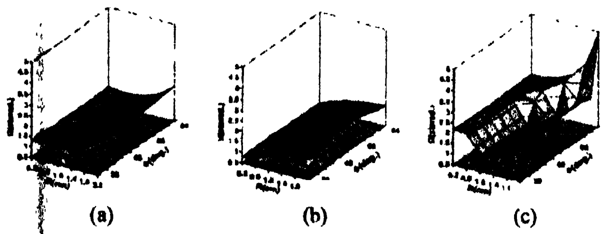

Figure 5(a–c). The plot of loss cone solid angle at the surface on extraction side taking R_m, R_+ and R_- as the mirror ratio respectively.

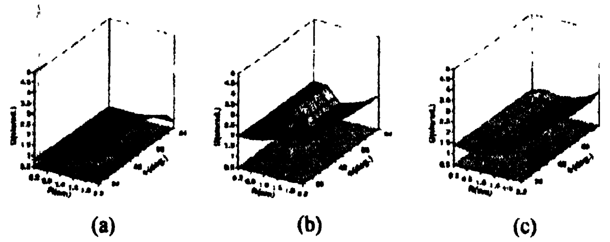

Figure 6(a–c). The plot of loss cone solid angle at the surface on injection side taking R_m, R_+ and R_- as the mirror ratio respectively.

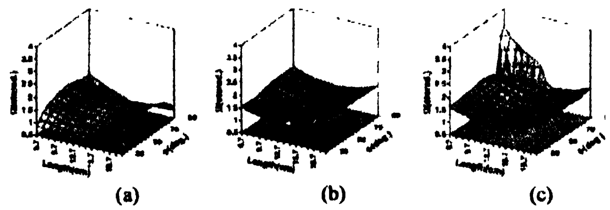

Figure 7(a–c). The plot of loss cone solid angle at the surface on cylindrical part taking R_m, R_+ and R_- as the mirror ratio respectively.

at 90°, 210° and 330° azimuth at the extraction side for electrons moving towards the negative direction of the field *i.e.* towards the extraction (Figures 5c, 7c). The azimuthal position of the loss hole is rotated by 60° at the injection side for the electrons moving towards the positive direction of the field *i.e.* towards the injection due to the presence of reverse radial field component of the axial field with reference to the extraction side due to the coils (Figures 6b, 7b). But these loss hole positions are far away from the resonance field surface at the ends and we are not alarmed with it.

The loss of the electrons takes place inherently since $\Omega_i \neq 0$ at any point. But how much loss at the point happens? First, we consider the point of creation of electrons (O) on the line of force in the plane, $2D$ surface, containing the line of force. The electrons move isotropically about the point then the reflection coefficient ($R_{coeff,i}$) is given by [5].

$$R_{coeff,i} = \cos^2(\alpha_{apex,i}) = 1 - R_i \quad (5a)$$

But this is not the reality, one has to take into account the three dimensional situation at the point because a particle may move in any direction after creation there. A quantitative measure is given by $\Omega_l/2\pi$ at a point in the direction of the drift of the gyrating electron in a special case in which we assume for an instance that there is no effect on motion of electrons due to plasma, they are absolutely guided by the electromagnetic field present in the chamber, production of electrons takes place isotropically at a point inside the chamber and at certain point the probability of scattering of electron in a direction is highly random. Now the reflection coefficient, $R_{coeff,l}$, of the electron at a point is given by

$$R_{coeff,l} = 1 - (\Omega_l/2\pi) = \cos(\alpha_{apex\ l}). \quad (5b)$$

But as soon as the plasma comes into picture, the loss cone is affected by it tremendously through stepwise ionisation of atoms and binary or collective, elastic or inelastic scattering and multiplication or recombination of electrons in the chamber.

According to the expression of loss cone, mirror ratio solely decides value of the loss cone. The source should have sufficient mirror ratio to ensure the minimum loss cone angle. The field configuration in the chamber should confirm it such that the magnetic field surface for electron cyclotron resonance is sufficiently far off the inner surface of the chamber for the accelerated electrons to get sufficient length of flight for incessant change of position to take place by some physical means like scattering, diffusion *etc.* The local mirror ratio at certain point on that surface should be sufficiently high to get the lowest possible local loss cone to get the electrons reflected avoiding loss on the chamber surface on hitting it.

The mirror ratio is not less than ~3.0 on the surface of the plasma (resonance). An optimised plasma surface and volume were obtained for the 14.4 GHz ion source. The electrons on ECR region get transverse energy over a small axial distance while in interaction with rf-wave, so the $P_\perp$ component of the momentum increases. The electrons conserve the momentum acquired while in resonance for a few microseconds and subsequently it remains perpendicular to the magnetic field line. A strong anisotropy of momentum components $P_\perp/P_\parallel > 1$, will occur. Downstream from the interaction region, the energised electrons are magnetically confined and can ionise the background gas. The experimental observations show that it becomes more stringent in the case of decreasing gas pressure and thermalisation of electron is not reached instantly. Overall effect of this phenomena is to push the electrons outside the purview of the loss cone thereby increasing the mirror effect The measurements in noiseless min-B ECRIS proved that for given value of plasma frequency (ω_p) the loss cone depends excessively on Spitzer collisions (collective long range Coulomb collisions) because all other collision were negligible. The loss cone data exceeds those expected for electron-particle collisions in simple ECRIS without min-B because the collective electron collision frequency is higher than ω_p [6].

Evaluation of the loss cones taking into account the major cause of effects in the whole space of the plasma chamber gives very significant information about the plasma confinement and loss of electrons. Further, it can give a figure of merit or qualitative value of efficiency of an ECR ion source.

References

[1] M H Rashid, D K Bose, C Mallik and R K Bhandari *Int. Symp. Nucl Phys (DAE)* Vol. 43(B) BARC (Mumbai) p 516 (2000)

[2] G Caivola and S Gammino *Proc. of the EPAC 94* Vol. 2 p 1421 (1994)

[3] J Vamosi and S Biri *Nucl. Instrun. Meth.* B94 297 (1994)

[4] S Biri and J Vamosi *Proc. of the EPAC 94* Vol. 2 p 1432 (1994)

[5] S R Seshadri *Fundamentals of Plasma Physics* (New York American Elsivier Publishing Company) p 184 (1973)

[6] R Geller *et al Proc. of the 12th Int. Workshop on ECR Ion Source (Riken)* p 4 (1995)