SIMULATED NEW CUSP FIELD CREATED BY PERMANENT MAGNET FOR AN 18 GHz ECRIS

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Abstract

A cusp magnetic field (CMF) configuration is robust in achieving more plasma confinement than a traditional minimum-B field. Earlier the classical CMF was used to design an ECR ion source (ECRIS) [1] 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) 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 [2] and to achieve denser plasma than in traditional ECRIS. This will initiate the quasi-gas-dynamic confinement of the plasma, which will decrease the loss of plasma particles further. It consists of two end-plugs and several permanent magnet (PM) rings discarding the power supplies, cooling system etc. It can be designed for high-B mode operation of the cusp ECRIS of as high as 18 GHz microwave frequency for producing multiply charged heavy ions. It can provide low/ highly charged light/ heavy ions for extracting high current narrow beam for particle accelerators or broad beam for ion implanting devices useful for industry, academy or Sc. research.

INTRODUCTION

Geller's group pioneered constructing ECRIS like MAFIOS and its variants [3, 4, 5] at Grenoble in 1970's and later. The ECR plasma and its property have been described well by him [6] 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. Henceforth, it will be referred to as the traditional magnetic field (TMF) configuration. A vacuum chamber in such ion source is filled with rarefied gas, microwave power and magnetic field lines. The cold electrons with some initial kinetic energy gyrate about a magnetic line of force, that is field line (FL) with f_G(gyro-frequency) $\propto$ B(magnetic field). At resonance condition, $f_G \approx f_{RF}$, electrons get energy from the RF wave.

Improvement of ECRIS is done using higher B and f_{RF} to generate more intense ion beam of more common or rare species with higher charge state (Q). It helps to achieve higher value of $n_e\tau_i$ for generating intense HCI beam. The prevalent techniques [7] to improve the performance of advanced ECRIS include proper gas mixing [8], multiple-frequency plasma heating [9], placing negatively biased disk [10], chamber surface coating by Al_2O_3 [11] and improved plasma confinement with higher B [12]. The high vacuum, dense fast electrons (n_f) and long confinement time (τ_i) are favourable for generating high density of HCI's. The plasma density n_e is deduced from $n_e \leq \varepsilon_0 m_e \omega_{RF}^2/e^2$ and given in per cc by $n_e \leq 1.11\times10^{10} f_{RF}^2$, where the equality sign corresponds to the critical plasma density and the microwave frequency, f_{RF} is in GHz. The critical density *vs.* frequency plot is depicted in Fig. 1.

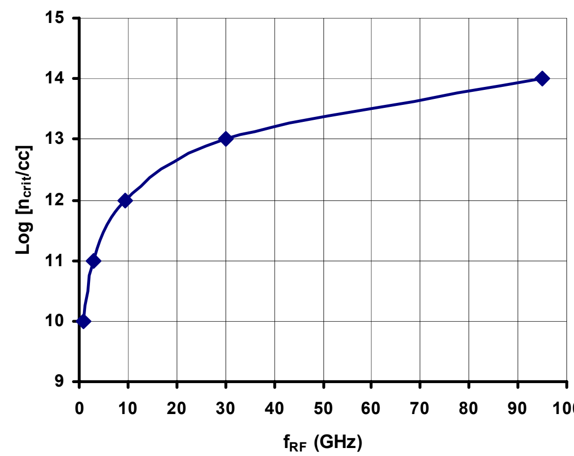

Figure 1: Critical plasma density vs. RF frequency plot.

Traditional ECRIS have axially asymmetric plasma along the length, complicated magnet system, small plasma volume, limited injection and extraction regions. In this paper it has been attempted to alleviate some problems by employing CMF configuration which is herein created by PM. 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. The standard model, based on the experimental results for constructing a superb ECRIS, is essential to meet the following criteria concerning the magnetic field achieved in the plasma chamber [13, 14, 24]; $B_{inj} \geq 2B_{ECR}$, $B_{inj} \geq B_{wall}$, and $B_{ext} << B_{inj}$, where $B_{ECR} = (f_{RF}/2.8)$ kG and f_{RF} is in GHz; B_{inj} and B_{ext} are the field at the injection and extraction end of the chamber respectively. From empirical scaling laws of ECRIS [6, 16] $\langle Q_{op} \rangle \propto \mathrm{Log}(B_{max})$ and $I^{Q+} \propto (f^2 n_e V_p)/(A_i^{\alpha} \tau_i)$, where V_p and A_i are the plasma volume and the ion mass number respectively.

CMF PRODUCED BY PM

The CMF is generated merely using shaded single PM ring (Fig. 2) with radial magnetization. The FL, PC and RC are field lines, point cusp and ring cusp respectively. The variation of the field components B_z and B_r along Z (central axis) and R (on z=0 plane) are depicted by dashed and dotted curves respectively. The density of the FL's decreases towards the magnetic centre defined by the zero

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magnetic field. The vector potential generated in the CMF configuration is given by $A_\theta(r,z)$=G rz, where G=$B_0/(2z_0)$ and B_0 is the magnetic field at z_0 on the central Z-axis. The field components are given by B_r=-Gr and B_z=2Gz. The |B| increases all around from the magnetic centre, which is the characteristic of a minimum-B field and due to 0 field at the centre, it may be called zero-B field. Even under magnetic mirror action plasma as a fluid is able to flow across the FL's because of inter-particle continuous collisional diffusion. The variation of plasma pressure, $P_{par} = n_e k_B T_e$, along the FL's depends on the magnetic pressure, $P_B=B^2/(2\mu_0)$. The gravitation-like inward force because of the nature of FL's in the CMF produce a MHD-stable configuration.

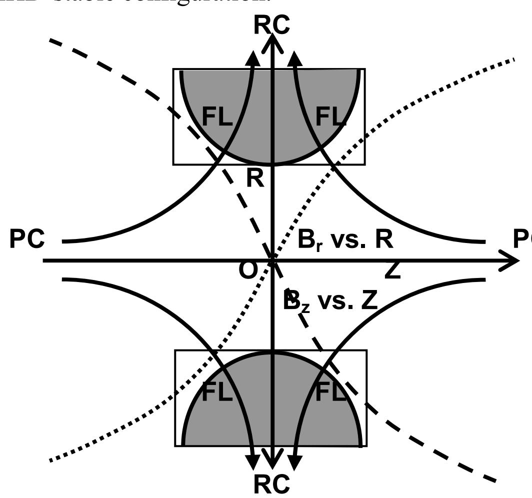

Figure 2: A scheme to produce new CMF due to PM ring. It may be a rectangle-ring instead of the shaded one.

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 the collisional regime. The quasi-gas-dynamic confinement of plasma takes place [17] 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 averaged electron velocity distribution function remains isotropic in the filled loss cone. Then the non-adiabatic motion of electrons at the magnetic centre is insignificant [18, 19].

Some initial results of CMF computation were reported in the InPAC [20] showing that a TMF 14.4 GHz ECRIS [21] can, on paper, be split into two CMF ECRIS'es; one using the same coils and the other using the same PM after rearrangement to generate the required improved CMF. The all-PM TMF ECRIS'es are constructed and operated at various laboratories from the 1980's. Very recent development of such ECRIS took place in China and it is believed that LAPECR2 [22] is the largest TMF ECRIS of 14.5 GHz ever constructed using strong PM's. Nowadays, Nd-Fe-B magnets are used in accelerators and ion sources because of their high remanent field (B_{rem}), coercive force (H_{cor}) and energy product, $(BH)_{max}$. It is now feasible to generate field using such material (Table 1) to design PM cusp ECRIS of as high as 18 GHz f_{RF}.

Table 1: The available Nd-Fe-B strong PM parameters.

Material (energy product in MGOe)	**B_{rem} (kG)**	**H_{cor} (kOe)**
VACODYM 745HR (50)	14.4	14.0
NEOMAX 5563 (55)	15.0	13.5

Design of 18 GHz cusp ECRIS

Optimization of the PM position and geometry of the PM's and plug P was done to achieve the final geometry shown in Fig. 3 in which both the length and diameter of the plasma chamber is 12 cm containing total plasma volume of 1.44 litre. The scale of 5 cm length has been shown in the axial and radial direction for estimating the magnet-size. Each of the rectangular blocks represents a ring in cylindrical geometry. The numbered areas have PM's with magnetization angle 20N degree with respect to the radius, where N is the number in the interested area. The CMF so generated is shown in the 3D field plot in Fig. 4. It is very important to assess the magnetic field mainly at the cusp positions owing to the magnetic end-iron, E and plug, P. They were replaced by air regions in the problem geometry and re-computation of the field was done keeping the other components same. It was found that the magnetic field at the RC and PC positions decreased by 7.2% and 25.4% giving ~12.7 kG and ~9.7 kG field respectively. The contribution of the E and P is important and so their placement is very crucial.

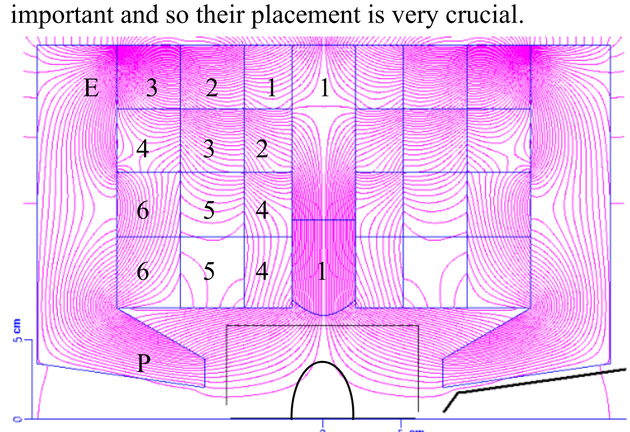

Figure 3: Schematic structure of the 18 GHz cusp ECRIS magnet and the field line contour plot.

The plug on the extraction side (at the RHS in Fig. 3) can be manipulated to decrease the magnetic field at the extraction region to widen and open up the loss cone for facilitating the extraction of the HCI to boost its intensity. This affects a little decrease of B_{wall} at the RC and pretty increase of the container field at the PC at injection side (at the LHS in Fig. 3). The ECR field surface corresponding to 18 GHz (6.43 kG) in the designed CMF is depicted by the vertical ellipse in the *r-z* plane (oblate spheroid in the *r-θ-z* three dimensions) in Fig. 3. The ECR surface spheroid (semi-axes a=b=3.82 cm and c=2.23 along x, y and z axes) are large to couple more energy to the electrons crisscrossing the surface. The density of the hot electrons increases in this way.

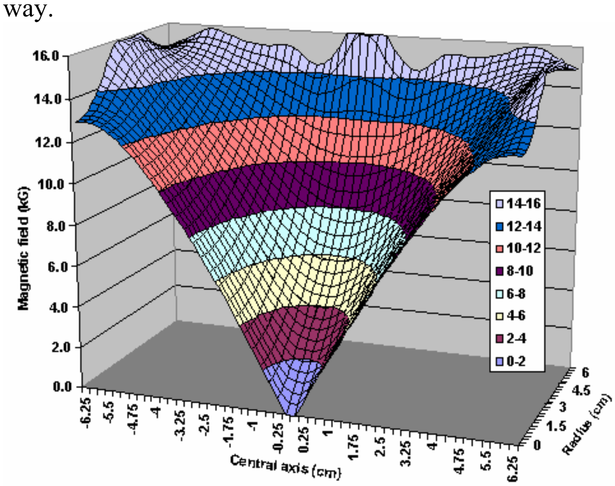

Figure 4: The 3D field plot of the 18 GHz PM cusp ECRIS.

Bent Magnetic Mirror

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 π/4 angle rotated PC-RC mirror [23]. The mirror ratio , R_m, 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 ($\alpha_{apex}= \arcsin(1/\sqrt{R_m})$) narrows down also. The electrons follow the FL's, which form a PC-RC mirror configuration. The electrons get bounced back and crisscross the ECR surface many times to be heated by the microwave to high energy successively. The confinement of these heated electrons is further increased because of the larger perpendicular velocity component ($v_{e\perp}$) than the parallel velocity component ($v_{e\|}$) with respect to the FL followed. These electrons come out of the loss cone area in the velocity space because of the anisotropic velocity components. They interact with the atoms and ions and boost the charge state in stepwise manner. Since the confinement of electrons becomes superb, so the confinement of ions too. This process helps to achieve very high density of contained plasma consisting of the HCI's in the whole large volume of the plasma chamber. It is possible now to extract intense beam of HCI's of desired species according to the current scaling laws. This may require some ingenious design of the extraction system with the combination of additional small PM or coil solenoid to reduce adequately by the reverse magnetic field produced at the position of extraction hole and to focus immediately the extracted beam also. It is also seen that the τ_i in the improved CMF ECRIS is more than in a TMF ECRIS [23] having similar magnetic field.

CONCLUSION

The designed CMF can be used to construct very cost-effective and simple CMF PM ECRIS, which requires a little running cost. The CMF has inherent property of MHD stability, so quiescent plasma is contained in such field. Since it does not need any sextupole for radial confinement of plasma, the volume of the plasma chamber increases, which will help in extraction of the intense beam of HCI's. It can be designed for lower RF frequency also. The EM energy can be injected to boost the source operation at several lower RF frequencies simultaneously. Plasma confinement can further be boosted by placing negatively (<-1.0 kV) biased disk and ring at PC and RC positions respectively. A metal-dielectric-disk at PC and ring at RC can act well too.

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