SIMULATION OF SUFFICIENT SPINDLE CUSP MAGNETIC FIELD FOR 28 GHz ECRIS

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Abstract

A cusp magnetic field (CMF) configuration is proposed for achieving more plasma confinement. It is an improved version of CMF compared to the classical one used earlier to design arbitrarily ECR ion source (ECRIS) of low frequency. The CMF has been reconfigured here adopting a simple, novel and cost-effective technique to shrink the loss area and to achieve denser plasma than in traditional ECRIS. It consists of a mid-iron disk, two end-plugs and a pair of superconducting magnet coils cooled by cryo-coolers. It is designed for high-B mode operation of the cusp ECRIS of as high as 28 GHz RF frequency for producing an intense beam of highly charged heavy ions. The electric current in the coil at the extraction end can be manipulated to optimize the operation to achieve high extracted beam current of highly charged ions.

INTRODUCTION

Significant developments took place in fabrication of ECRIS after its invention in Grenoble, France by the ion source group led by Geller in 1970's. They built early ECRIS'es, MAFIOS and its variant [1, 2] and show their superb feature in terms of charge state of ions achievable and ion beams extractable. The salient features of the ECR plasma including its production and confinement in minimum-B field and techniques to improve further the workings of an ECRIS have been described in detail [3]. With special design of superconducting magnets for as high frequency as 28 GHz of powerful microwave, Gammino et al [4] explored the possibility of constructing third generation ECR ion source called GyroSERSE, which opened the way to a new operational domain having the highest plasma densities, ~10^{13} cm^{-3}.

The electrons crossing the iso-Gauss surface, B_{ECR}, gain energy due to transfer of energy from the EM wave to electrons through ECR process when electron gyration is in resonance with RF ($f_G = f_{RF}$). A magnet system for a conventional source using higher microwave frequency is complex, consume more electric power and more complicated forces act on the coils and coil bands. Thus, the magnet system becomes complex. The scaling laws for ECR ion source design are well known [3].

The motivating factors of the present study are i) constructing a simple and compact but superb ECRIS of higher RF frequency, ii) producing dense large volume of plasma consisting of high charge state ions (HCI's), iii) more confinement of electrons for heating the electrons electromagnetically through ECR process, iv) sufficient confinement of ions for further step-wise stripping and v) shorter magnetic cusp line of plasma loss region. Some earlier attempts were taken to understand theoretically the plasma confining feature of the simulated sufficient spindle CMF for lower frequencies [5]. After we are satisfied for higher and higher frequencies in generation and confinement of high density plasma theoretically, we should go for experimental test of the superior CMF principle and proposed design. There is an on-going effort by the LPSC-IN2P3 group at Grenoble for development of a 60 GHz ECRIS based on shouldered CMF configuration. They produced the required magnetic field [6] related to the frequency using helix-coils in agreement with the scaling laws. Here we are proposing field design for 28 GHz RF frequency in a larger chamber volume immersed in the CMF.

SUPERIOR SPINDLE CMF

We assume that axial length and diameter of the chamber are 2L. The radial ($B_r(r,z)$) and axial ($B_z(r,z)$) field components on the point cusp (PC) and ring cusp (RC) are of magnitude B_0; they are given by Eqs. 1 and 2 respectively derived from A_θ in Eq. 3 to maintain field symmetry and effective mirror action.

$$B_r(r,z) = -Gr - 3\Pr z^2 - Qr^3 \quad (1)$$

$$B_z(r,z) = 2Gz + 2Pz^3 + 4Qr^2 z \quad (2)$$

$$A_\theta(r,z) = -Grz + Pz^3 r + Qr^3 z + C \quad (3)$$

Where *G, P*, *Q* and *C* (say 0) are constants. The magnetic field is taken to be that of vacuum and the plasma current effect is neglected. The constants G, P and Q are evaluated adopting three constraints. The first constraint, must be satisfied as there is no electric current inside the chamber, which sets the constant Q = - (3/4)P. Another two boundary constraints B_r (L,0) = -B_0 and B_z (0,L) = B_0 set the constants G = ($11B_0$)/ (14L) and P = ($-2B_0$)/ ($7L^3$). Thus, A_θ and desired field components are defined, in general, to generate symmetric and spindle CMF. The theoretically obtained field for L=16 cm and B_0=40 kG can be numerically reproduced in reality as under.

PROPOSED CMF ECRIS DESIGN

Earlier, application of old CMF of low and asymmetric magnetic field to confine plasma was limited because of huge plasma loss mainly at the RC position. Some crucial attempts to understand the features and associated problems of the old CMF have been reported recently. The papers [5] deal with the technique to get an improved configuration of CMF for microwave frequency 14.4 and 18.0 GHz. Superconducting coils can be used to achieve it corresponding to higher microwave frequencies. Here a design is described for f_{RF} =28 GHz and B_{ECR} =10 kG with improved field mainly at the RC, which at least is

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approximately equal to the field at the PC positions to assert field symmetry.

Magnetic Field Simulation

The magnet system has cylindrical symmetry, so 2D codes can compute the field due to associated coil and iron structure efficiently. There are two co-axial coils at the two ends of the plasma chamber separated by a gap filled by a cylindrical permeable iron plug, whose inner surface faces the plasma chamber closely. It is specially shaped to obtain sufficiently high field at the RC position. Input data of the geometry is fed into the POISSON code [7] to compute magnetic field distribution, magnetic force and stored energy. The magnetic lines of force (MLF) contours together with the geometry are depicted in Fig. 1(a). Solenoids have been decided to produce peak magnetic field of ≥40 kG at the injection end and on the inner cylindrical surface of the plasma chamber when the coils and the iron structure are symmetric about the mid-plane at z=0. The coils are capable of generating sufficient magneto-motive force (MMF) of ~1.6×10^6 amp-turns each. So, the total MMF in the present case is less by ~1.3×10^6 amp-turns than the total MMF of 4.5×10^6 amp-turns in the VENUS [8] to generate suitable maximum field. The MMF in the coil at the extraction side may be reduced to facilitate extraction of the HCI beam by decreasing the field at the plasma electrode and electrostatic extractor by shaping the mid-plug surface at the chamber and optimizing the current in the corresponding coil. This causes some change in magnetic field (B_{inj}) at the injection position and little reduction of magnetic field (B_{wall}) at the chamber surface in the mid-plane. The size and the structure of the mid-iron-plug (thick disk) and two iron-plugs at the two ends of the chamber are optimized properly as they play the crucial role in configuring and achieving the new CMF with sufficient and same field at the PC's and RC respectively. The modified magnetic field achieved at the injection end, B_{inj} chamber wall, B_{wall} and the extraction end B_{ext} are 42.8 kG, 38.0 kG and 36.0 kG respectively.

The minimum field on the chamber surface on the mid-plane and on the central axis passing through the centre is ≥40 kG. The 10 kG and 40 kG iso-Gauss contours '1' and '4' representing B_{ECR} and $4B_{ECR}$ surfaces are depicted. They represent saucer shaped oblate surface in this case unlike crudely approximated prolate surface in conventional ECRIS. The approximate ECR surface area and the volume of the spheroid formed is ~255 (~193) cm^2 and ~341 (~226) cm^3 in the Cusp (VENUS) ECRIS respectively. The surface plot of the optimized simulated magnetic field in the r-z plane covering the length and radius of the plasma chamber is depicted in Fig. 1(b). The field matched well with the requisite calculated field in the chamber using Eqs. 1 and 2. The main parameters of the conceptual design of the new advanced cusp ECRIS are shown in Table 1. The plasma chamber volume of ~25.7 lit in the present ECRIS is about ~3 times more than ~8.85 lit in the VENUS.

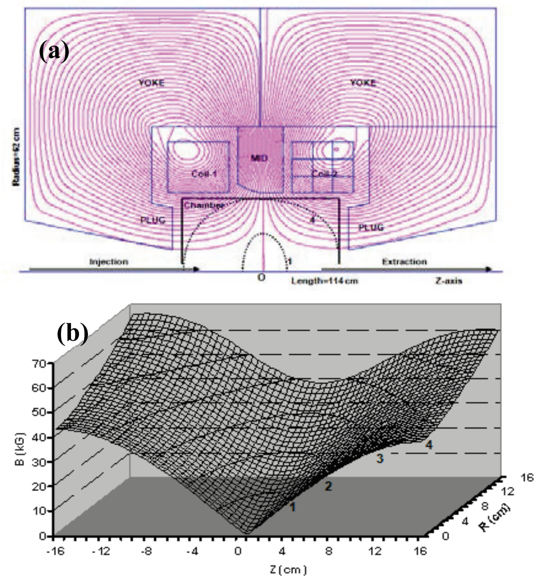

Figure 1: (a) Plot of magnetic lines of force, (b) plot of 2D magnetic field distribution, 1- 4 represent field in T.

Table 1: Cusp ECRIS parameters

Dimension	Chamber	Coil	Cryostat
ID (cm)	32.0	37.0	34.0
OD (cm)	33.0	61.0	68.0
Length (cm)	32.0	32.5	17.0
Width (cm)	0.5 (wall)	12.0	19.0

Feasible Magnet Structure

We will discuss the design using low temperature superconductor (LTS) only as they have already been used extensively in constructing many small and big superconducting magnets for ECRIS'es around the world. The specifications of a superconducting wire and the coils of LTS, NbTi are presented in Table 2. The critical current (I_c) at magnetic field 50 and 70 kG for the conductors Cd-1 and Cd-2 at 4.2K are also listed in the table. Some turns of the coils at the region of its innermost radius are immersed at ≤67 kG magnetic field at full excitation. Some turns beyond this region near the centre-plug experience magnetic field as low as ≤45 kG.. The critical points and the working points of conductors (Cd-1 and Cd-2) are depicted clearly in Fig. 2. We see that the working points are well below the critical points, which have been calculated by taking the corresponding magnetic field values for the conductors in the worst case, that is, some higher field than the field experienced by the respective conductors, Cd-1 and Cd-2. Thus, we are assured that the conductors are operating safely as there are enough margins of ~65% and ~48% for operation of Cd-1 in the outer low field region and Cd-2 in the inner high field region respectively. The Cd-2 is used in the inner coil at high field region to reduce the current density carried by the superconductor. The maximum charging current (I) is much below the critical values (see Table 2),

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so there is a minimum chance of any problem if the coils are clamped firmly. The coils may be wound on-to high conductivity copper former for supporting and providing a path for dissipated heat to be carried away quickly from the coils to cryo-coolers. The cryo-coolers can provide cooling of 45 W and 1.5 W at 50 K and 4 K temperature respectively when they are operated in close loop. The number of current leads in the designed magnet is only four, half the number in VENUS, so the heat leak through them is low when high T_c superconductor lead-connection can be used. Heat shield of the coils should be cooled by first stage of cryo-coolers. The design would incorporate an inner-diameter axial-solenoid winding to allow space for double-wall aluminium plasma chamber wrapped with thin W or Ta sheet to reduce plasma radiation heat. The magnet and cryostat structure is shown in Fig. 3.

The outer cylindrical wall and end flat walls of the iron yoke is designed to be thick enough to reduce the magnetic stray-field outside the yoke to <0.050 kG.. Mass of the iron yoke is ~8 tons. The iron yoke decreases electric current in coils by >30% to produce the same field and facilitates configuring the proper spindle cusp field. Though, the weight can be reduced further (by ~2 tons) by reducing the outermost diameter at the marginal expense of some of the advantages, which still will create appropriate CMF. Some interior parts of the iron yoke get saturated as the magnetic field inside the iron reaches 21.6 kG or beyond it. The saturated iron region contributes little in some of the above mentioned advantages. However, the shape and size of the saturated region strongly affect the CMF configuration.

Table 2: Superconductor Specifications

Cu/NbTi	Dim.(mm^2)	RRR	I_c(A)&L(H)	N_zxN_rxI(A)
4/1(Cd-1)	1.65x0.96	80	713&25.6	64x100x240
3/1(Cd-2)	1.9x1.0	200	608&11.3	59x72x377

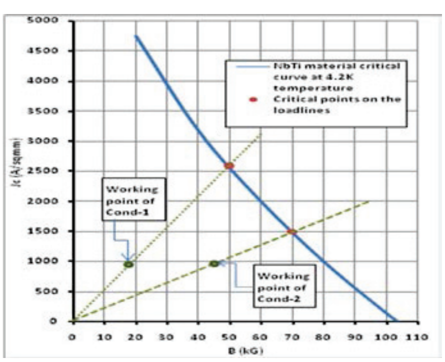

Figure 2: Working point of the NbTi LTS to be used.

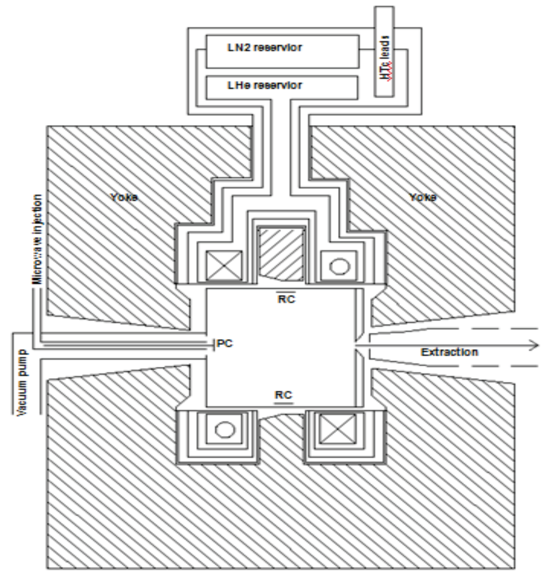

Figure 3:Cusp ECRIS magnet and cryostat structure.

CONCLUSIONS

The plasma loss is reduced because of high mirror field, shorter cusp line (2πL, where 2L is the chamber diameter), convexity of lines of force, electrostatic mirror action and secondary electron emission. A cusp ECRIS with higher microwave frequency will need more upgraded CMF, which can be generated using more powerful superconductor like Nb_3Sn. The cusp ECRIS is capable of accepting radioactive fragments or particles also from targets to produce and deliver intense ion beam of common and rare isotopes of heavy elements. It can work in continuous or pulsed modes. Some remarkable features like simple and compact structure with no sextupole coil and instability, stable CMF and comparable cost-effectiveness are attributed to the cusp ECRIS.

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