Proceedings of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 2003

Design of a 14 GHz minimum-B Electron Cyclotron Resonance Ion Source for Flexible Operations

Hyun-Jong You and Kyu-Sun Chung

Hanyang University
17 Haengdang, Seongdong, Seoul, Korea 133-791

Jong-Seo Chai

Korea Cancer Center Hospital
215-4 Kongreung, Nowon, Seoul, Korea 139-706

Abstract

A 14 GHz minimum-B ECR ion source with movable extraction system and biased disk has been designed. This will be used as an ion source for heavy ion accelerator, for applications in atomic physics research, and for further physical understanding of electron cyclotron resonance (ECR) plasmas. To meet diversities in beam parameter and to optimize the system under the various conditions, the source is designed to be operated in flexible magnetic structures and extraction system. The designed magnetic field is minimum-B structure which is generated by two main yoked coils and 12 segmented permanent magnet. By using the central coil and by axially shifting the whole magnet system, the magnetic field structure can be changed to different profiles: therefore, the mirror ratio can be adjusted from 2.5 to 4, and the tuning of ion source can be facilitated under the various magnetic field geometries. The rectangular waveguide for RF injection is directly inserted to the source to make its radial position lie along the resonance surfaces so that it can ensure the maximum power coupling.

1. Introduction

Electron cyclotron resonance ion sources (ECRIS’s) are devices designed for intense highly charged ion beam production. They are mirror machines where a plasma is heated by high frequency waves, usually with frequencies between 10 and 18 GHz. A resonant coupling between the wave and the electrons occurs when electrons cross a particular magnetic surface where the cyclotron frequency w_{ce} is equal to the wave frequency w. It leads to an increase of the perpendicular velocity relative to the magnetic flux lines, and the heated electrons are trapped in a minimum-B structure.[1)]

During the last decade, electron cyclotron resonance ion sources (ECRIS) have transformed heavy ion physics. Because ECRIS can generate substantial currents of very high-charge-state ions, the size and the cost of new heavy ion accelerators have been reduced considerably and the energy of old machines has been increased dramatically. The unsurpassed reliability of ECRIS is also attractive in an industrial environment. ECR ion sources operate comfortably for hundreds of hours on feed gases that ruin arc discharge ion sources. In some ion sources the hot cathode is now replaced by a small ECR plasma which works as a nondestructive electron donor. Thus ECR plasma supplants little by little the arc plasma in many fields.[2)] In Korea 6 cyclotrons are being operated now. For more extended applications these accelerators are planed to be transformed to heavy ion accelerators in near future. Now arc discharge source such as penning ion source and duoplasmatron is used as an ion source in these accelerators. These ion sources have some limitations: their plasma is difficult to be confined, and due to the erosion of the electrodes, they are not very reliable. For generation of highly charged ions these sources must be replaced by more reliable and long lifetime ion source. ECRIS seems to be the very promising source to overcome these limitations of these arc discharge sources.

Recently, ECRIS has also opened up new areas of atomic research in the low-energy, i.e. without an accelerator, by offering many kinds of highly charged ion collisions. This research has provided basic data of a diagnostic technique in fusion machines (temperature and impurity distributions), and has initiated the study of the interaction of slow highly charged ions with surfaces. This interaction is closely connected to the observation of Coulomb explosion at the surface and of multiply charged ions and atoms[3)], and is related to nano-structuring of material surface. This atomic research also boosted other basic studies[4)]. Then ECRIS is very essential device for these basic studies and applications.

The development of ECRIS is still continuing. Despite increased extracted particle density by several improvements such as stronger magnetic fields, higher radio frequency, biased disk, mixing gases and afterglow mode, the optimization of ECRIS is not fully accomplished due to the complexity of ECR plasma concepts. Because all exceptional properties of ECRIS depend on the ECR plasma concepts, the more systematic understanding of ECR plasma in ECRIS must be needed.

In this paper the design features of the ECRIS source with flexible operating conditions are presented, including source description (2), magnetic field design (3), and RF injection (4), in order to be used as an ion source both for heavy ion accelerator and for applications in atomic physics research.

2. Source Description

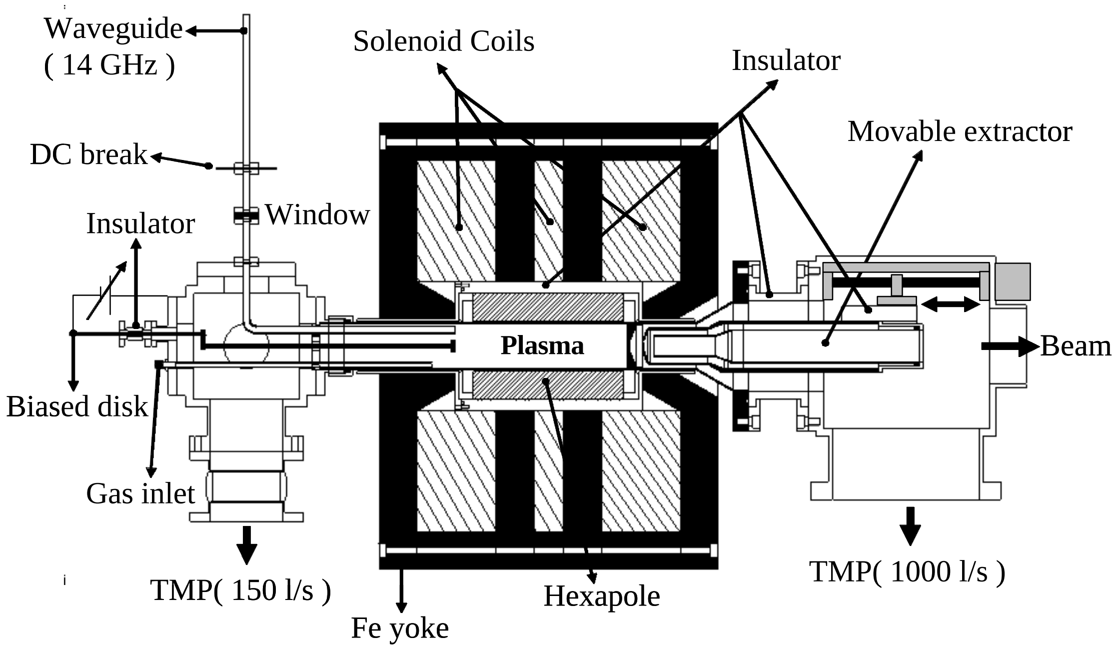

Fig. 1 Schematic sectional view of the new ECRIS

The schematic structure of the source is illustrated in Fig. 1. The source consists of magnet system, Al plasma chamber, RF injection part, beam extraction part and a stepping motor controlled mechanism. The magnet system consists of three coils, Fe magnetic flux return yoke and NdFeB hexapole permanent magnets. The hexapole magnets for radial confinement are positioned within the cylindrically symmetric insulator. The Al plasma chamber is electrically insulated from the ground so that the source can be operated at a rather high extraction voltage: therefore, high energy ion beams can be directly obtained. The RF injection part includes rectangular waveguide for 14 GHz microwave injection, gas feeding line and biased disk. The biased disk can be adjusted to optimum positions during operation. The beam extraction part is movable three-electrode accel-decel extraction system, which is required for space charge compensation of the extracted beam. The stepping motor controlled mechanism is used to adjust the axial positions of the whole magnet system with respect to the plasma chamber. The source vacuum system is maintained with two turbomolecular pumps. One is 150 l/s, the other 1000 l/s. The 150 l/s pump is located at the injection part, and the 1000 l/s pump is at the extraction part. The plasma chamber is 58 mm in inner diameter. The outer diameter is 61 mm. This leaves 2.5 mm between the hexapole and plasma chamber. The place is used for water cooling of the plasma chamber by thin copper tubes soldered on the plasma chamber.

3. Magnetic Field Design

The design goal is to provide a flexible geometry with optimum magnetic configuration accomplished. Fabrication cost was also taken into accounted in the design. The axial magnetic field was produced by 3 Coils and iron yoke, and the radial field was realized by a hexapole permanent magnet. The computer codes employed in this study were the POISSON group of codes[5)] and TrapCAD[6)]. The former is used to model the static magnetic fields, and the latter is used to reconstruct the 3D magnetic fields.

A. Axial Magnetic Field

The structure has been designed modular and consists of 12 coil elements, two in the central coil and five in outer coil. The surrounding Fe yoke consist of 4 iron disks and two end pieces (see Fig. 1). This modular design favored upgrading to the other types of ECRIS later (e.g. volumetric ECRIS with a uniformly distributed resonant plasma volume[7, 8)]). By using the central coil or by axially shifting the whole magnet system the magnetic field structure can be changed to different profiles. Fig. 2 shows the axial mirror field distributions along the axis of the source under the various conditions. The A curve indicates the axial magnetic field distribution calculated when the whole magnet system is shifted to the extraction side by 5 cm. This shifting of the magnetic structure can provide a reduced magnetic confinement at extraction side. The maximum magnetic field on axis is 1.05 T. These configurations can provide mirror ratios of 2.5~4 and resonant zone lengths of 60~100 mm. The main parameters of axial magnetic field are summarized in Table 1.

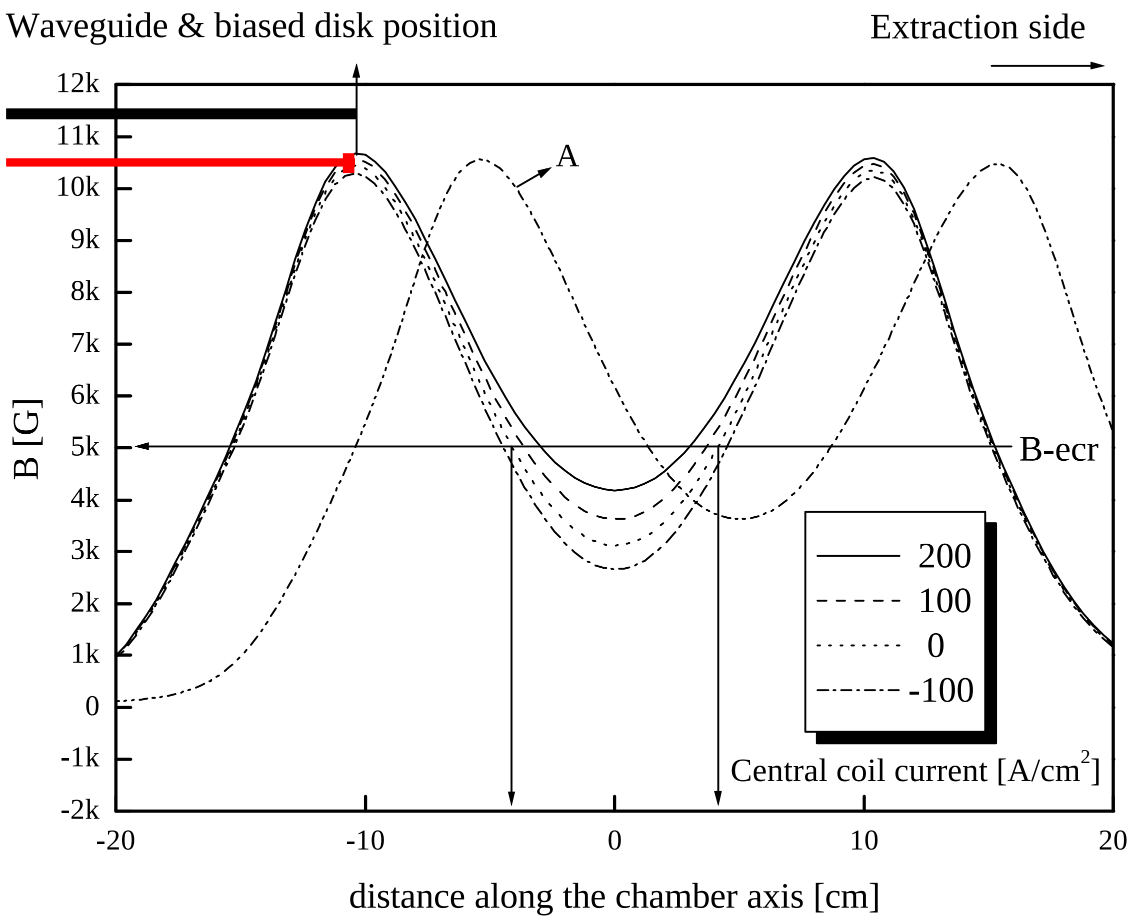

Fig. 2 Axial magnetic field distribution along the chamber axis: The A curve is the axial magnetic field distribution calculated when the whole magnet system is shifted to the extraction side by 5 cm. The axial positions of the waveguide and the biased disk are also displayed near the maximum magnetic field.

B. Radial Confinement Field

The hexapole magnet for the radial confinement field is 200 mm in length, 66 mm in inner diameter and 142 mm in outer diameter, and is consist of 12 segments. Fig.3 shows the hexapole structure and the calculated hexapole field distribution. The angle of magnetization axis of the segments varies by 60 degrees from one segment to the next. Hexapole field strength is 1.1 T at the plasma chamber wall (at r=29 mm), and the distance from resonant surface to the plasma chamber wall is 8.5~12 mm. The main parameters of radial confinement field are also summarized in Table 2.

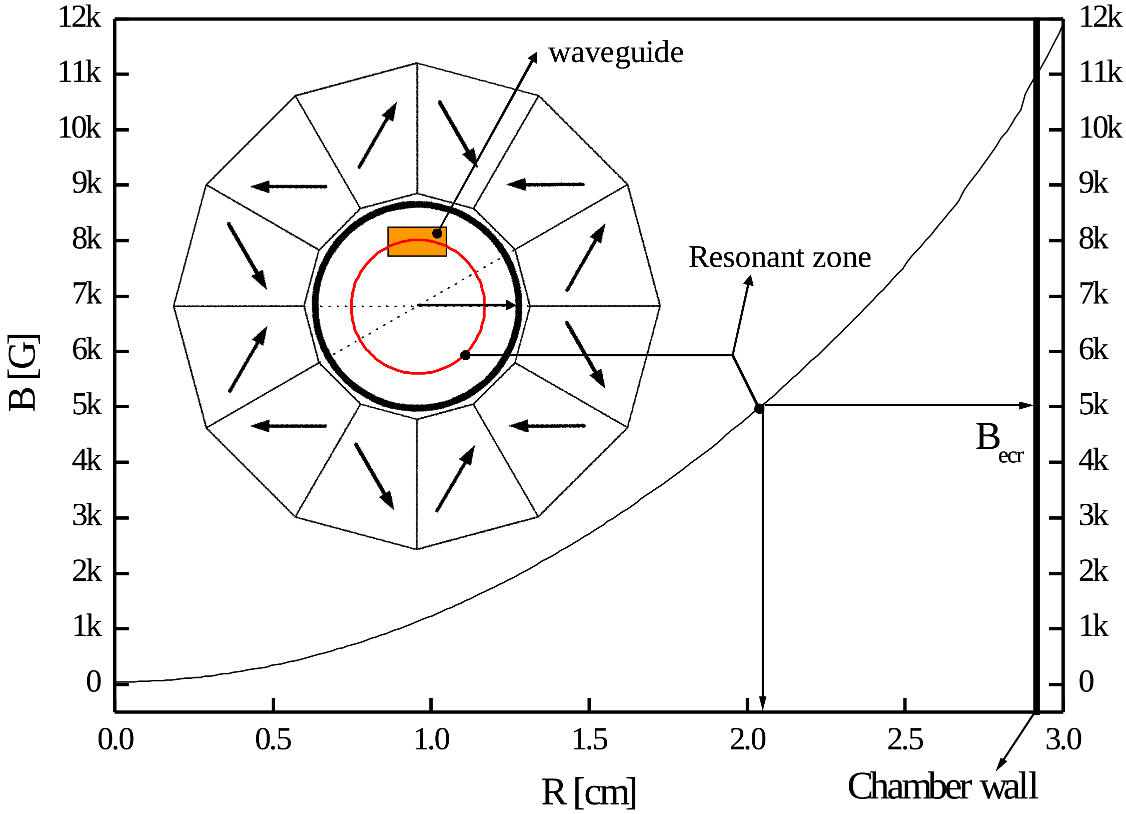

Fig. 3. The hexapole structure and the calculated hexapole field distribution: The positions of the waveguide and resonant zone are also shown.

Inner diameter	86 mm
Outer diameter	246 mm
Length	105 mm
Current density of the two main coil	600 A/cm^2 (24 kW)
Current density of the central coil	-200 ~ 200 A/cm^2
Coil conductor	6.5 mm × 6.5 mm with hole diameter of 3.5 mm
Cooling lines of each coil	14 lines
Pressure drop for temperature rise of 30 degrees	2.8 kgf/cm2
Maximum field strength	1.05 T
Mirror ratio	2.5~4
Resonant zone length	60~100 mm

Table 1. Main parameters of axial confinement field

Material (code)	NEOMAX-40, Sumitomo company (Japan)
Number of magnets/ cusps	12 / 6
Inner diameter	66 mm
Outer diameter	142 mm
Length	200 mm
B-field at chamber wall (at r=2.9 mm)	~1.1 T
Distance from resonant zone	6 ~ 10 mm

Table 2. Main parameters of radial confinement field

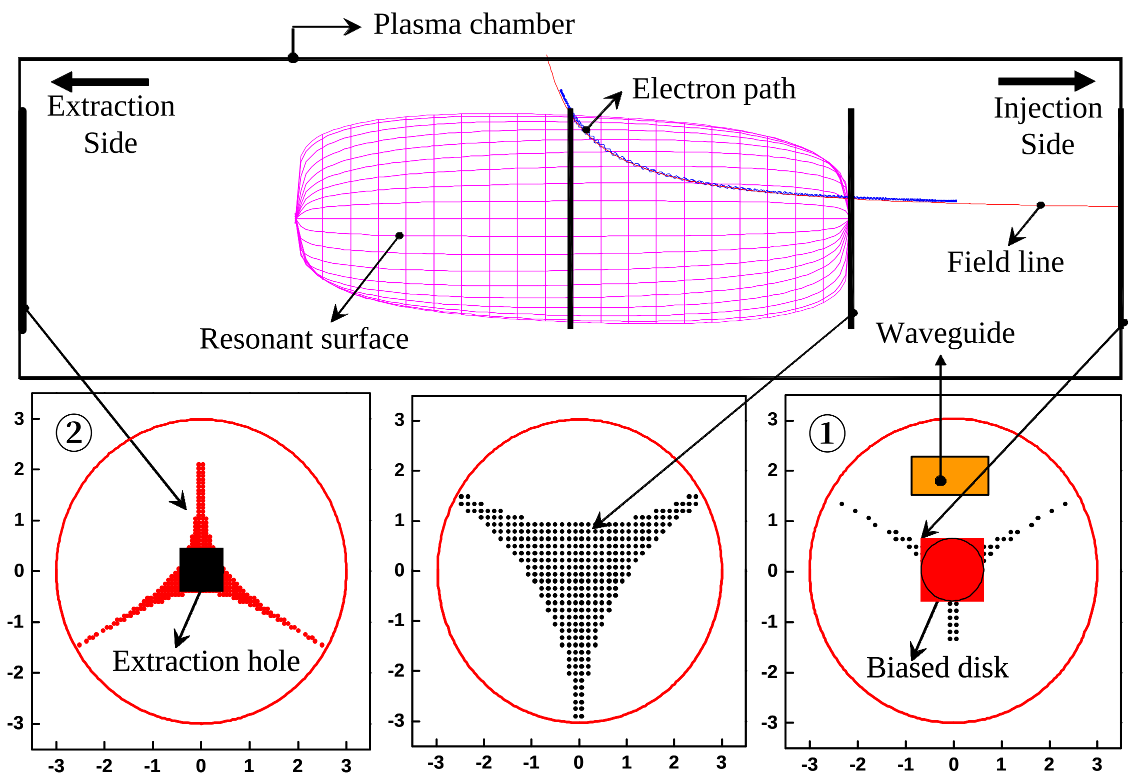

Fig. 4 The resonant zone (up) and cross sectional points of magnetic field lines (down) in the plasma chamber: electron moving with its magnetic field line is also shown.

To see the resonant zone shape and magnetic field lines at both waveguide position and extraction side the axial and radial confinement field data was superimposed by the TrapCAD code. Fig. 4 shows the resulting resonant zone in the plasma chamber and cross sectional points of magnetic field lines which crossed the resonant zone at different places. Electron moving with its guiding magnetic field line is also shown. Stars formed by the cross sectional points of magnetic field lines are very important, because these star patterns correspond to the plasma impact patterns. The star ① formed at the RF injection side was used in determining the azimuthal position of the waveguide, the shape and size of the biased disk. Similarly, the star ② at beam extraction side was used for designing the plasma electrode.

4. RF Injection

Interaction between plasma and wave is closely related to many types of propagation modes depending on frequencies, propagation directions and magnetic field etc. Unfortunately, the magnetic field geometry in ECRIS is very complicated, and ECR plasma in ECRIS has not been defined yet. In addition, no quantitative heating models presently are available in ECRIS. In this paper four qualitative theoretical results were used.[2)] The first is that the absorption of the right handed polarized wave is favorable on a magnetic beach, where the wave propagates from higher to lower magnetic field to the resonance $w_{ce} = w$. The second is that it may not be advisable to launch a wave from the magnetic cusp zones. This criteria is explained as follows: In a minimum-B ECRIS the maximum density is everywhere such that the plasma frequency w_{pe} is lower than the gyro frequency w_{ce}, then cutoff region for extraordinary wave can be quite broad. The third is that wave launching is done near the surfaces around the egg-shaped magnetic field surfaces at ECR. This is necessary for direct coupling of the launched wave to the ECR surface. By above three results the waveguide was positioned as shown in Fig. 2 (axial position) and Fig. 3 (radial position). The last is that one must consider accessibility for auxiliary system such as gas feeding, biased disk, additional waveguide for double frequency heating etc. When compared to coaxial types of wave launching method, the direct insertion of the rectangular waveguide (see Fig. 1) is more convenient for the introductions of these auxiliary systems.

5. Conclusions and Future Plan

A 14 GHz minimum-B ECR ion source for flexible operations has been successfully designed. This source will be used as an ion source for heavy ion accelerator, for applications in atomic physics research and for basic physical understanding of electron cyclotron resonance (ECR) plasmas. The source was designed to be operated in various magnetic structures. The magnetic structure can be changed not only by additional central coil but also by moving the whole magnet system axially.

These flexibilities make it possible to tune the system under the various conditions. This source will be fabricated, assembled, and then tested soon. In parallel with the source assembling diagnostic systems for ECR plasma and its beam also will be installed. After the assembling of the source and diagnostic systems we will investigate its applicability, and then study interrelations between the ECR plasma and the extracted beam. This relation is very important for understanding and upgrading ECRIS performances.

6. Acknowledgement

This work was supported by Korea Cancer Center Hospital. The authors wish to thank Dr. M. Sekiguchi for his helpful advices and discussions with him.

7. References

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