pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.17, No2, (2015), pp.36~40
http://dx.doi.org/10.9714/psac.2015.17.2.036

Comparison analysis of superconducting solenoid magnet systems for ECR ion source based on the evolution strategy optimization

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(Received 23 February 2015; revised or reviewed 10 June 2015; accepted 11 June 2015)

Abstract

Electron cyclotron resonance (ECR) ion source is an essential component of heavy-ion accelerator. For a given design, the intensities of the highly charged ion beams extracted from the source can be increased by enlarging the physical volume of ECR zone [1]. Several models for ECR ion source were and will be constructed depending on their operating conditions [2-4]. In this paper three simulation models with 3, 4 and 6 solenoid system were built, but it's not considered anything else except the number of coils. Two groups of optimization analysis are presented, and the evolution strategy (ES) is adopted as an optimization tool which is a technique based on the ideas of mutation, adaptation and annealing [5]. In this research, the volume of ECR zone was calculated approximately, and optimized designs for ECR solenoid magnet system were presented. Firstly it is better to make the volume of ECR zone large to increase the intensity of ion beam under the specific confinement field conditions. At the same time the total volume of superconducting solenoids must be decreased to save material. By considering the volume of ECR zone and the total length of solenoids in each model with different number of coils, the 6 solenoid system represented the highest coil performance. By the way, a certain case, ECR zone volume itself can be essential than the cost. So the maximum ECR zone volume for each solenoid magnet system was calculated respectively with the same size of the plasma chamber and the total magnet space. By comparing the volume of ECR zone, the 6 solenoid system can be also made with the maximum ECR zone volume.

Keywords: Coil performance, ECR ion source, evolution strategy, superconducting magnet, length of solenoids, volume of ECR zone

1. INTRODUCTION

There are some demands for increased intensities of highly charged heavy ions, which leads to higher performance electron cyclotron resonance (ECR) ion sources. Strong confinement by highly charged ions is required for this system, and superconducting magnets are needed in 28 GHz ECR ion source [6].

Plasma is produced in ECR ion source. In a high magnetic field, outer electron of gas in plasma chamber will conduct cyclotron motion (Larmor gyration). When cyclotron angular frequency is equal to microwave angular frequency, resonance happens and plasma is formed [7]. For an ECR source, it is convenient to describe the magnetic field strength relative to B_{ECR}, which is the magnetic field in tesla for electron cyclotron resonance. If the frequency is 28 GHz, B_{ECR} becomes 1 T [6].

In order to produce more ion beams, plasma diffusing to plasma chamber wall must be prevented. To avoid diffusing, magnetic fields are used to provide a force in the transverse direction to confine plasma. In this way, charged ions becoming getting close to the center of the axis. The magnetic fields are also used to reflect electrons back into the plasma chamber.

Magnetic field mainly plays two roles in the discharge process. One is to provide an electron cyclotron resonance and the other is to confine electrons and ions. The confinement is mainly generated from the appropriate distribution of magnetic field in the plasma chamber.

Plasma is confined by making the magnetic field B minimum at the center of the plasma chamber, and this structure is called by minimum B structure. In the minimum *B* structure, magnetic field from sextupole is superimposed for radial confinement. For the axial confinement, asymmetry displacement of solenoids can be used to realize the confinement. Two groups of optimization based on the 3, 4 and 6 solenoid system are introduced in this paper.

2. ECR ZONE

2.1. Introduction of ECR Zone

The confinement fields in an ECR ion source provide closed surface, and the magnetic field on this closed surface is equivalent everywhere. On the closed surface where the ECR condition is satisfied, the electrons can be heated by rf power through electron cyclotron resonance. The physical region over which the ECR condition is satisfied is called as ECR zone [8]. By using Opera-3d^{TM} program, the ECR zone was visualized in Fig. 1. The center part in the magnets represents the ECR zone.

The microwave power can be coupled to the plasma only in ECR zones which occupy a small percentage of the ionization chamber volume and leave the remainder of the plasma chamber as "unheated" zones, as shown in Fig. 2. Therefore, the absorptivity of the plasma region is not

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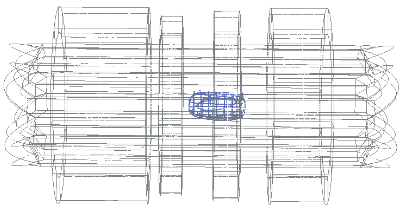
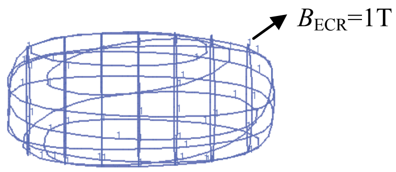


(a) ECR zone in ECR magnet



(b) Enlarged view of ECR zone.

Fig. 1. ECR zone (for f=28 GHz). The isopotential lines of 1 T constitute the outline of ECR zone.

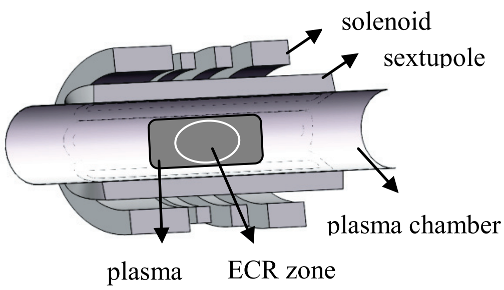


Fig. 2. A structure for ECR ion source.

controlled by the size of the plasma, but by the size of the ECR zone. Hence, the ECR zone is one of the key elements to increase the intensity of highly charged ion beams.

2.2. Calculation of ECR Zone Volume

The volume of ECR zone V_{ECR} can be calculated approximately by using the magnetic field. On the surface of ECR zone, the magnetic field B is equal to B_{ECR}, while inside of ECR zone B value is less than B_{ECR}. We can calculate V_{ECR} with Matlab™ and Opera-3d™ program in rectangular coordinate system or cylindrical coordinate system. In the rectangular coordinate system, the volume of each unit V_r is calculated by

$$V_r = x_{step} \cdot y_{step} \cdot z_{step} \quad (1)$$

where x_{step}, y_{step} and z_{step} indicate the unit distance along x, y and z axis directions. In the cylindrical coordinate system, per unit cylindrical arc is shown in Fig. 3 and its volume V_c is calculated by

$$V_c = \rho_{step} \cdot \phi_{step} \cdot z_{step} \cdot \rho_i \quad (2)$$

where ρ_i is the i^{th} radius of per unit cylindrical arc; and ρ_{step}, $\rho_i \cdot \phi_{step}$ and z_{step} indicate the unit distances along ρ, ϕ and z axis directions.

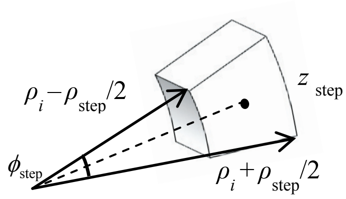


Fig. 3. Per unit cylindrical arc.

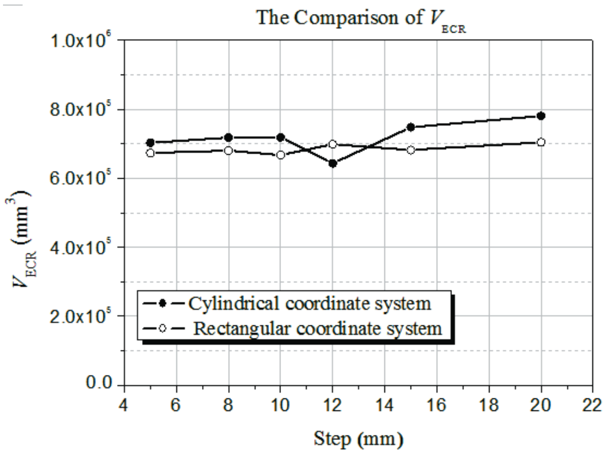


Fig. 4. Comparison of V_{ECR} with different steps between two methods.

TABLE I
COMPARISON OF V_{ECR} AND CALCULATION TIME WITH DIFFERENT STEPS.

ρ_{step} (mm)	Cylindrical coordinate system		Rectangular coordinate system	
	V_{ECR}	Time(m)	V_{ECR}	Time(m)
5	702352	15.60	673000	17.51
8	717670	5.09	679936	6.32
10	717932	3.08	667000	4.97
12	642755	2.20	698112	3.36
15	747502	1.62	681750	2.50
20	780372	1.18	704000	2.02

The calculation time of V_{ECR} with two kinds of coordinate systems was also checked. The results and diagram about different steps in two coordinate systems are respectively shown in Fig. 4 and table I.

In considering of the accuracy of V_{ECR} and calculation time, the cylindrical coordinate system is used to get the ECR zone volume. V_{ECR} volume is more accurate with smaller ρ_{step}, ϕ_{step} and z_{step}. In this paper, ρ_{step}=z_{step}=8 mm and ϕ_{step} =0.05π are used.

3. COMPARISON ANALYSIS

Evolution Strategy (ES) optimization method was adopted for the 2 groups of comparison analysis. All the current density in the optimization was set as 100 A/mm^2 in solenoids and 270 A/mm^2 in sextupole. In addition, the size of each sextupole for each case is equivalent. The confinement conditions is given as

$$\begin{cases} B_{\text{inj}} \geq 3.5B_{\text{ECR}} \\ B_{\text{ext}} \approx (1.8 \sim 2.3)B_{\text{ECR}} \\ B_{\text{min}} \approx (0.4 \sim 0.8)B_{\text{ECR}} \\ B_{\text{r}} \approx 2B_{\text{ECR}} \end{cases} \tag{3}$$

where B_{inj} is the axial magnetic field at injection part, B_{ext} is the axial magnetic field at extraction part, B_{r} is the radial magnetic field at chamber wall, and B_{min} is the minimum axial magnetic field [4] .

The radius of solenoids can be defined as matrix **A**, and the depth of solenoids can be defined as matrix **B**.

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \end{bmatrix}$$
$$\mathbf{B} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \end{bmatrix} \tag{4}$$

where the general components of matrix **A** and **B** are defined as a_{ij} and b_{ij} respectively. For a_{ij}, i means the inner and outer radii. j means the j^{th} solenoid. In matrix **A**, the first row indicates the inner radius of solenoid and the second row indicates the outer radius of solenoid. In matrix **B**, the first row indicates the lower position of solenoid and the second row indicates the larger position of solenoid in the z axis. These parameters are shown in Fig. 5. The total solenoid number is defined as N, which is the maximum value of j. And N is equal to 3, 4 and 6 respectively for the 3, 4 and 6 solenoid system.

The solenoids can be designed in the area which is shown by the dashed line in Fig. 5. We assumed L=1000 mm and W=600 mm and used them to determine the range of variables. So the range of parameters are

$$a_{1j} < a_{2j} < W, \ |b_{1j}| \leq L/2, \ b_{1i} < b_{2j} \leq L/2. \tag{5}$$

To make the size of plasma chamber constant, a same constant was used for the first row in matrix **A**.

3.1. Coil Performance

To increase intensity of ion beams, we had to enlarge the ECR zone under the confinement field. Meanwhile, the total volume of solenoids must be reduced to save material. Based on this idea, the object function 1 was defined as (6).

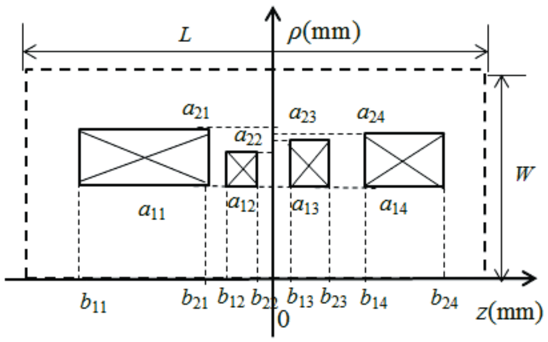


Fig. 5. Parameters for solenoid systems.

TABLE II
CONFINEMENT FIELDS FOR COIL PERFORMANCE.

N	B_{inj} (T)	B_{min} (T)	B_{ext} (T)
3	3.5002	0.4231	1.8371
4	3.5041	0.4139	1.8141
6	3.5128	0.4020	1.8006

TABLE III
OPTIMIZATION RESULTS FOR COIL PERFORMANCE.

N	V_{ECR} (mm^3)	V_{coil} (mm^3)	$V_{\text{ECR}}/V_{\text{coil}}$	object function 1
3	818563	34433278	0.02377	46.65
4	858977	36070784	0.02381	47.71
6	1138372	38304303	0.02972	47.09

$$\begin{aligned} \text{object function 1} &= c_1 \cdot V_{\text{coil}} + c_2 \cdot \frac{1}{V_{\text{ECR}}} \\ &= c_1 \sum_{j=1}^{N} V_j + c_2 \frac{1}{V_{\text{ECR}}} \end{aligned} \tag{6}$$

where V_j is the j^{th} solenoid volume, c_1 is the weight value for V_{coil}, and c_2 is the weight value for V_{ECR}. c_1 and c_2 can be decided by the importance of two factors. In this paper, c_1=10^{-6}, c_2=10^{7} was used to make V_{coil} and $1/V_{\text{ECR}}$ same order of magnitude. Hence, we can consider the values of V_{coil} and V_{ECR} equally. If V_{ECR} is more important, the weight value of V_{ECR} could be enlarged, and vice versa. In the optimization process for coil performance, (6) was used as object function, (3) is some constraints for design variables (4) and equation (5) is upper/ lower boundaries of design variables (4).

After the optimization for coil performance, we got three optimized designs for ECR magnet for the 3, 4 and 6 solenoid system respectively. Since the weight values in objection function 1 can be decided for design purpose, the ratio of $V_{\text{ECR}}/V_{\text{coil}}$ was used as an intrinsic parameter for coil performance that means we used the object function 1as a tool for its process only to make the problem converge.

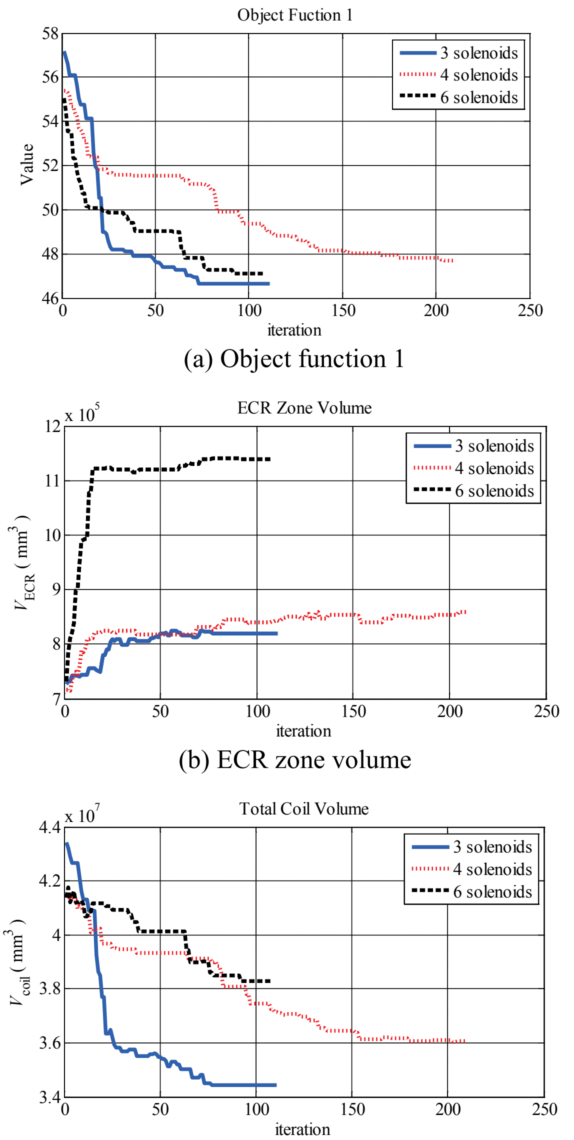
The decided confinement fields of each optimized model are shown in table II. And the final values results of V_{ECR}, V_{coil} and objection function 1are shown in table III and Fig. 6. By comparing the ratio of $V_{\text{ECR}}/V_{\text{coil}}$ in table III, the 6 solenoid system presents the highest coil performance.

3.2. ECR Zone Volume

The second analysis aims to get the maximum ECR zone volume without considering the coil volume within the given working space in Fig. 5. Based on this idea the objection function 2 was defined as (7).

$$\text{object function 2} = \frac{1}{V_{\text{ECR}}} \tag{7}$$

The same constraints and boundaries for coil performance was used in this optimization. After the optimization for ECR zone volume, we got three optimized

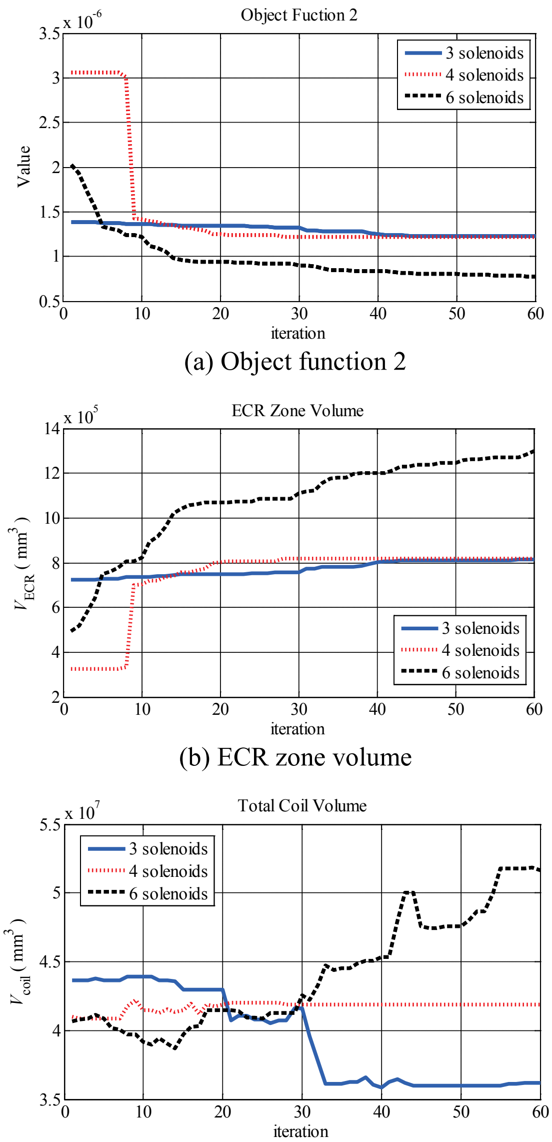


(a) Object function 1

(b) ECR zone volume

(c) Total coil volume

Fig. 6. Process of ES optimization for coil performance.



(a) Object function 2

(b) ECR zone volume

(c) Total coil volume

Fig. 7. Process of ES optimization for ECR zone volume.

designs for the 3, 4 and 6 solenoid system respectively. The decided confinement fields for each model are shown in table IV. And the results of V_{ECR}, V_{coil} and objection function 2 for each model are shown in table V and Fig. 7. According to the result, the 6 solenoid system shows the greatest ECR zone volume.

TABLE IV
CONFINEMENT FIELDS FOR ECR ZONE VOLUME.

N	B_{inj} (T)	B_{min} (T)	B_{ext} (T)
3	3.5454	0.4015	1.8028
4	3.6014	0.4614	1.9244
6	3.5329	0.4046	1.8497

TABLE V
OPTIMIZATION RESULTS FOR ECR ZONE VOLUME.

N	V_{ECR} (mm^3)	V_{coil} (mm^3)	V_{ECR}/V_{coil}	Object function 2
3	812733	36174552	0.0225	1.2304e-06
4	820212	41860113	0.0196	1.2192e-06
6	1298900	51674617	0.0251	7.6988e-07

4. CONCLUSION

In this paper, we have presented two kinds of optimization for ECR ion source. One is about the coil performance of solenoid system and the other is about ECR zone volume itself. Through these optimizations, we got the ECR ion source with 6 solenoid system has the highest coil performance and the largest volume of ECR zone at the same working space.

This result seems to be caused that the 6 solenoid system has more parameters to be controlled than those of other solenoid system. But practically, if the number of solenoid is increased, the things to be considered will be increased such as the number of power supply, etc. In addition, the sextupole in ECR ion source was not considered i.e. the value of parameters for the sextupole magnet is fixed in this paper. So the research about that must be the next.

REFERENCES

[1] G. D. Alton, Y. Liu, Y. Kawai, and H. Bilheux, “The ECR volume effect and its consequence,” *IEEE Conference Record – Abstracts*, Plasma Science, ICOPS, 2006.

[2] C. Lyneis, D. Leitner, M. Leitner, C. Taylor, and S. Abbott, “The third generation superconducting 28 GHz electron cyclotron resonance ion source VENUS,” *Review of Scientific Instruments*, vol. 81, pp. 02A201, 2010.

[3] S. Choi, Y. Kim, I. S. Hong and D. Jeon, “Superconducting Magnet for the RAON electron cyclotron resonance ion source,” *Review of Scientific Instruments*, vol. 85, pp. 02A906, 2014.

[4] J. Ohnishi, A. Goto, Y. Higurashi, K. Kusaka, T. Minato, T. Nakagawa, and H. Okuno, “Construction and test of the superconducting coils for RIKEN SC-ECR ion source,” *Proc. EPAC08*, pp. 43, 2008.

[5] Nikolaus Hansen, *The CMA Evolution Strategy: A Tutorial*, June 28, 2011.

[6] Claude M. Lyneis, D. Leitner, D. S. Todd, G. Sabbi, S. Prestemon,S. Caspi and P. Ferracin. “Fourth generation electron cyclotron resonance ion sources,” *Review of scientific instruments*, vol. 79, pp. 02A321, 2008.

[7] R. Geller, *Electron Cyclotron Resonance Ion Sources and ECR Plasma*, IOP, Bristol, 1996.

[8] G. D. Alton, J. Dellwo, and R.F. Welton, “Computational studies for an advanced design ECR ion source,” *Proceedings of the IEEE Particle Accelerator Conference*, vol. 2, pp. 1022-1024, 1995.