

AN ECR ION SOURCE FOR MULTIPLY-CHARGED HEAVY IONS AT 14 GHz

M. Sekiguchi, Y. Ohshiro, M. Fujita, T. Yamazaki
Institute for Nuclear Study, University of Tokyo, 3-2-1 Midori-cho, Tanashi-shi,
Tokyo, 188, Japan

Y. Yamashita, Y. Isoya, T. Yamada
Research Center for Advanced Technologies, the Japan Steel Works, Ltd., 1-3 Takanodai, Yotsukaido-shi,
Chiba, 284, Japan

and

A. Kitagawa
National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba-shi,
Chiba, 263, Japan

ABSTRACT

An ECR ion source for multiply-charged heavy ions was designed and constructed by using a 14.25-GHz microwave power source based on our experiences obtained by development efforts on other sources. In addition to the high frequency, it has high axial and radial magnetic field strengths over 10 kG. The diameter of the plasma chamber is 50 mm and the diameter and length of the ECR zone is 30 mm and 70 mm, respectively. Preliminary tests show good performance. The ion yield turned out to be 36 $e\mu A$ for O^{7+} , 1.5 $e\mu A$ for Ne^{9+} , 350 $e\mu A$ and 190 $e\mu A$ for Ar^{8+} and Ar^{9+} , respectively, without using special technique such as electron injection or electron repeller. This paper describes the design concept and preliminary performance.

1. INTRODUCTION

Many ECR sources for multiply-charged heavy ions have been constructed and are working at various heavy-ion accelerators. The basic structure has been developed by R. Geller and his collaborators at Grenoble.¹⁾ Among them, one of the best performance has been attained, to the authors' knowledge, by the CAPRICE²⁾ and its modifications.³⁾

At the Institute for Nuclear Study, University of Tokyo, we developed four sets of ECR ion sources in these five years. The first was SF-ECR for the SF cyclotron of our institute working at 6.1 GHz microwave frequency, now serving for experiments.⁴⁾ The second was a test machine developed in collaboration with Tokyo Institute of Technology, named HiECR, without its own microwave and coil power supplies.^{5,6)} The third one is a 10-GHz source for heavy-ion medical accelerator complex at the National Institute of Radiological Sciences(NIRS). This source was designed at NIRS and tested at our institute according to a collaboration program between the two institutes.⁷⁾

The source reported in this paper is the fourth one developed at our institute, named HyperECR. This was designed, constructed and tested in collaboration with

the Research Center for Advanced Technologies, the Japan Steel Works, Ltd..

According to the experiences based on the development of the above mentioned sources, ECR sources of any design can surely produce beams, but we are not certain why one source works well and another not. Moreover, we can not predict how much beam a source of a certain design can produce before testing it. In the design of the present source, we have made efforts to make the design principle as clear as possible so as to evaluate each item after testing. The primary aim is to construct a compact and powerful source at low cost.

2. DESIGN AND CONSTRUCTION

We started our design based on an existing microwave amplifier purchased from a Japanese company, which has a frequency of 14.25 GHz and a maximum output power of 2.0 kW. According to the Geller's scaling law,¹⁾ the higher the frequency is, the better the performance. In addition, we assumed that both axial and radial magnetic field should be as high as possible at a given frequency in order to make the confinement of the plasma better.

Since the frequency is rather high and, consequently, the ECR field is high, the diameter of the plasma chamber was chosen to be 50 mm in order to produce a high sextupole field by using permanent magnet material commercially available. We adopted Nd-Fe-B alloy with a trade name NEOMAX35, whose maximum BH product is about 280 kJ/m³. This diameter is one of the smallest one ever used in ECR sources but still more than twice of the wavelength of the microwave.

From our experience concerning other ECR sources,⁵⁻⁷⁾ the ECR surface was designed to be 10 mm apart from the wall of the plasma chamber. We searched for a magnetic configuration which makes the diameter of the ECR surface less than 30 mm. The distance between the two coils was determined mainly from this requirement. The ampere-turns of the coils were determined to produce as high peak fields as possible on the axis with sizable coils and power supplies.

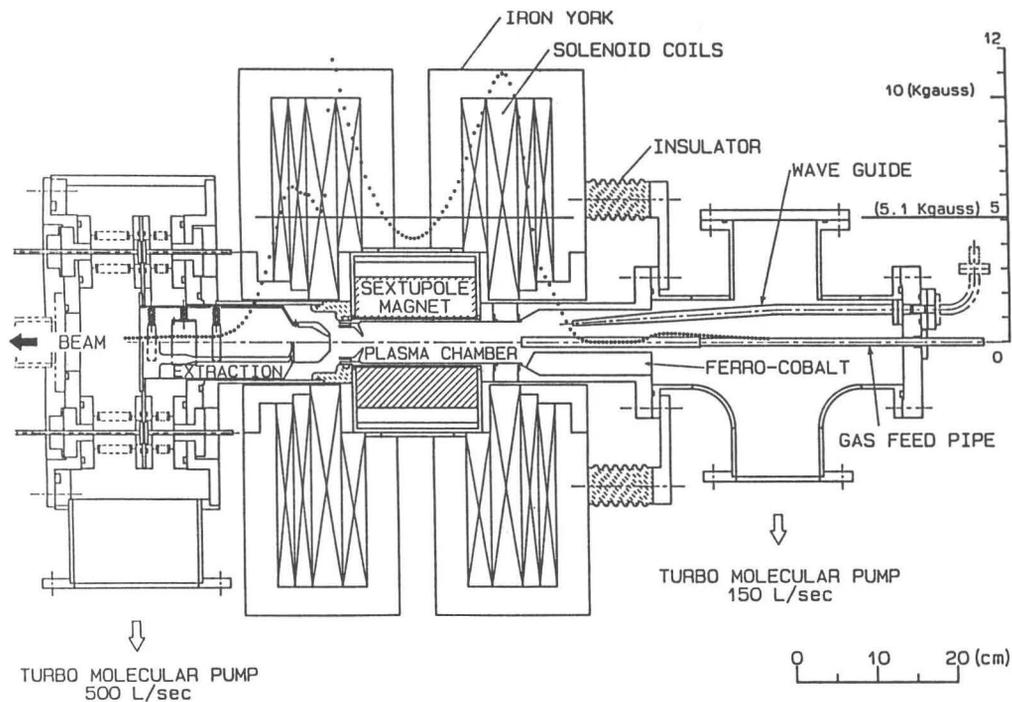


Fig. 1. Schematic drawing of the HyperECR and the measured axial-field distribution on the axis.

In order to increase the field on the axis, *pole tips* are used near the axis to guide the lines of force of the magnetic field. Various shapes of magnetic material can be inserted at both ends of the plasma chamber to tune the axial field distribution. In addition, the vacuum chambers outside the sextupole magnet and extending the plasma chamber into both directions are made of iron, while the plasma chamber itself is made of copper. These iron chambers also contribute to collect the magnetic lines of force on the axis.

Taking into account that at a high magnetic field above 10 kG iron might saturate locally and could not produce the field shape intended, the return yokes for the mirror coils were made from pure iron 4 cm thick. A ferro-cobalt alloy was used as the material of the *pole tips* where the lines of force concentrate.

Magnetic material such as yokes and *pole tips* inserted near the axis to increase the axial field reduces the conductance of the pumping. We assumed that the working pressure in the plasma chamber should be less than 1.0×10^{-6} Torr. The conductance for pumping was made as large as the above-mentioned conditions permit; for example, the *pole tips* were made axially asymmetric in order to provide space for pumping, and for inserting a wave guide and a gas feed pipe. In this context, we did not employ the axial injection of microwave power as is done in CAPRICE: the microwave power is led into the plasma chamber through an ordinary wave guide set a little off-axis.

The effective pumping speed for the plasma chamber is estimated to be about 10 l/s although two turbomolecular pumps evacuate the chamber from its both ends and some efforts are paid to make the conductance large.

The resultant size of the expected ECR zone turned out to have a diameter of less than 30 mm and length of 50 mm, as shown in Table 1. In addition, the mirror ratio has been made variable by varying the distance of the two mirror coils, reaching a value of about 3 at the largest.

Field measurements after assembling the parts have proved that field calculations with the computer code PANDIRA predicted well the strengths of the fields, although some difference has been found concerning the details, because some local saturation points appear due to the sharp edges of the ferromagnetic material, which the calculations could not predict accurately; further, the program cannot calculate the axially asymmetric field.

We can approximate the strength of the mirror field near the axis in the center of the two coils as

$$B_z = B_0 + az^2,$$

where B_0 is the minimum field, z is the length along the axis and a is a constant. The sextupole field can also be approximated as

$$B_r = br^2,$$

where b is the field gradient and r is the radius. The length (L) and the diameter (D) of the ECR zone can

Table 1. Design and measured values of the ECR zone parameters.

	Designed	Measured
min. field B_0 (kG)	4.21	4.13
mirr. field grad. a (kG/cm ²)	0.129	0.074
sex. field grad. b (kG/cm ²)	1.34	1.30
length of ECR zone L (cm)	5.34	7.35
dia. of ECR zone D (cm)	2.96	3.00

be expressed as

$$L = 2\sqrt{\frac{B_{ECR} - B_0}{a}}$$

and

$$D = 2\left(\frac{B_{ECR}^2 - B_0^2}{b^2}\right)^{1/4}$$

respectively, where B_{ECR} is the ECR field for 14.25 GHz.

The design and measured values of these parameters are summarized in Table 1. The design values were calculated by the program PANDIRA and the measured values were taken from one of the configurations in which the beam intensity was optimized. It should be noted that the design value of the diameter agrees very well with the measured one, while the agreement for the length does not have much meaning since the mirror ratio is adjustable.

An example of the measured field distributions is shown in Fig. 1 and the main parameters of this source are summarized in Table 2. The field distribution on the axis has a sharp peak between the anode and the extraction electrode. This is a result that the extraction electrode is made of soft iron. In the design stage, we tried to set the position of this peak just on the anode, but it was unsuccessful. This may be due to the iron configuration near the axis. An additional peak in the extraction electrode is also a result of using iron for this electrode and we don't believe it plays any essential role on the performance.

It should be remarked that the surface field strength of the NEOMAX was measured to be 11.8 kG on the average when it was virgin; after putting it in the mirror field of about 12 kG, however, the strength was reduced to 10.6 kG on the average, resulting in about a 10 % reduction. It is supposed to be one of the initial effects, because no remarkable reduction has been noticed ever since.

The two coils, the plasma chamber and a vacuum box containing the extraction electrode and an einzel lens are mounted on an accurate common rail, so that the position adjustment of these components along the axis can be easily made. The axial position of the extraction electrode is adjustable without breaking the vacuum. All components of this source, namely, the plasma chamber,

Table 2. Main parameters of HyperECR.

Microwave power source	
frequency	14.25 GHz
max.power	2.0 kW
Plasma chamber	
diameter	50 mm
length	190 mm
Multipole magnet	
multipolarity	Sextupole
Field strength on the surface	10.6 kG
material	Nd-Fe-B
inner diameter	57 mm
length	150 mm
Mirror field	
Max.field strength on axis	12 kG
max.Current	600 A
max.Power	72 kW
Turbomolecular pumps	
	500 l/sec
	150 l/sec

the vacuum chamber on both sides of the plasma chamber, the coils, the extraction electrodes and sextupole magnet, can be easily disassembled and replaced to make the system highly flexible for future modification.

3. PRELIMINARY PERFORMANCE

The beam test started in February, 1992. Argon ions were chosen as a target at first; we have obtained so far 350 μA of Ar^{8+} and 190 μA of Ar^{9+} , for example, with 20 kV extraction voltage without such special technique as electron injection⁸⁾ and electron repeller.⁹⁾

Some different behaviours have been found on this source from those of other sources we have tested. Firstly, the best performance is obtained when the diameters of the anode hole and the extraction electrode are 18 mm and 14 mm, respectively. These are larger than those of other sources(10mm to 12 mm). This may be related with the field distribution on the axis: the peak of the mirror field is just between these two electrodes.

Since a large extraction hole usually results in a large emittance of the beam, we tried to estimate it by measuring the beam spread after a thin slit. The width of the beam 30 cm downstream of a 2-mm slit was found to be about 2 cm. Although this measurement is rough, we can say that the emittance is not worse than other sources.

Secondly, the gas flow rate required for the best performance is very small: it is of the order of 0.001 atm-cc/min. This is consistent with the value estimated from the observation that the gas flow increases the vacuum pressure by about 5×10^{-7} Torr and the estimated pumping speed of about 10 l/s. The gas flow rate affects

Table 3. Examples of ion yield.

	4	5	6	7	8	9	10	11	12	13	14
N	315	300	57								
O	480	330	245	36							
Ne	240	195	115	65	32	1.5					
Ar					351	195	-	43	13	11	2.2

the beam intensity so much that its control is very difficult with our present regulator. The third point is that this source can produce large drain current: it sometimes reaches more than 5 mA while others do not exceed 2 mA. The third one may also be related to the large holes mentioned above.

The fourth point of the difference is that the gap between the anode and the extraction electrode for optimum operation is smaller than our other sources: it is about 30 mm while it is more than 40 mm in other sources. The best axial position of the anode was searched and found to yield larger drain current exceeding 6 mA and higher ion yields at an inner position than the designed. The best performance has not been attained, however, due to the limited current capacity of our present high-voltage power supply.

The axial field near the design value turned out to give the best performance although some fine adjustment was needed, but the distance between the two coils seems to be larger for better performance. This fact suggests that a longer ECR zone is better.

A list of ion yield obtained in the preliminary survey is shown in Table 3.

4. DISCUSSIONS

The HyperECR ion source has been proved to have a high performance, although the results are still preliminary and the emittance has not been measured accurately. One of the reasons of this good performance is certainly attributed to the higher frequency of the microwave and the higher axial and radial magnetic fields. Various efforts to make them high resulted in a sharp peaks and valley of the axial field distribution keeping the diameter of the ECR zone within the reasonable size. In addition, this valley allows us to use an 18 GHz microwave frequency without changing the magnetic configuration, because the length and the diameter of the ECR zone are estimated to be 11.2 cm and 3.9 cm, respectively, according to the formulae in section 2.

The high peak axial field around the extraction seems to have effects on the ion yield. Rather large drain current is apparently inconsistent with the low gas flow rate: if all of the gas input of 0.001 atm-cc/min were to be ionized and extracted from the source, the drain current would be about 70 pμA. We must assume that a large amount of electrons should be injected into the high voltage side from the extraction electrode. If most

of the electrons pass through the anode hole and get into the plasma since the diameter of our anode hole is large, we are injecting electrons effectively without any special device for it. It is interesting to see if the electron injection improves the ion yield as reported in refs.^{8,9)} in our source.

Emittance measurement, metallic ion production, electron injection, injection of low-charge-state ions from another ion source and pulse operation to produce after-glow³⁾ are being prepared as well as searching for better working parameters.

5. REFERENCES

- 1) Geller, R., "ECRIS: The Electron Cyclotron Resonance Ion Sources," *Ann.Rev.Nucl.Sci.***40**, 15(1990).
- 2) Jacquot, B. and Pontonnier, M., "La source Caprice ..," *Nucl.Instrum.Meth.***A287**, 341(1990); *ibid* **A295**, 5(1990).
- 3) Sortais, P., "Pulsed ECR Ion Source using the After-glow Mode," *Rev.Sci.Instrum.***63**, 2801(1992).
- 4) Sekiguchi, M. *et al.*, "Design of the INS ECR Ion Source," in **Proc. Int. Conf. on ECR Ion Sources and their Applications** (NSCL Report #MSUP-47, 1987), pp.323-333.
- 5) Hattori, T. *et al.*, "Development of Higher Order Mode ECR (HiECR) Ion Source (Test of 6GHz Operation)," in **Proc. 7th Symp. on Accelerator Science and Technology** (Ionics, Tokyo, 1989), pp.71-85.
- 6) Sekiguchi, M. *et al.*, "INS ECR Sources for Accelerators," in **Proc. 12th Symp. on ISIAAT'89** (Ionics, Tokyo, 1989), pp.187-194.
- 7) Kitagawa, A. *et al.*, "Development of ECR Ion Source for the HIMAC Medical Accelerator," in **Proc. 8th Symp. on Accelerator Science and Technology** (Ionics, Tokyo, 1991), pp.58-60.
- 8) Xie, Q., Lyneis, C.M., Lam, R.S. and Lundgren, S. A., "Enhanced ECR Ion Source Performance with an Electron Gun," *Rev.Sci.Instrum.***62**, 775(1991).
- 9) Nakagawa, T. and Kageyama, T., "The Effect of an Electrode in the First Stage of RIKEN Electron Cyclotron Resonance Ion Source(ECRIS)," *Jpn.J.Appl.Phys.***30**, L1588(1991).