Indian J. Phys. **66B** (5 & 6), 629 – 637 (1992)

Status of VEC ECR heavy ion source

D K Bose, G S Taki and R K Bhandari
Variable Energy Cyclotron Centre, Department of Atomic Energy,
1/AF Bidhan Nagar, Calcutta-700 064, India

Abstract : An Electron Cyclotron Resonance (ECR) heavy ion source, basically a hot electron plasma machine having B-minimum field configuration is going to be operational soon at this centre. The source which is indigenously built will act as a heavy ion injector for the Variable Energy Cyclotron (VEC) replacing the existing penning (PIG) internal light ion source. This programme was undertaken to facilitate acceleration of multiply charged heavy ions (MCHI) in the cyclotron. The heavy ions, substantially energetic compared to the light ions will be utilised to initiate new fields of research with heavy ions The present ECR source is expected to produce fully stripped light heavy ions and partially stripped heavy ions. It will be suitable for metallic ions also. Radio frequency (rf) power is transferred to the ionising electrons in this source at a frequency in resonance with the electron cyclotron frequency (ECR). VEC ECR source is a two stage, room temperature heavy ion source, "Stage-1 acts as an injector for the stage-2", the main stripping stage which has a B-minimum magnetic field configuration. Powerful samarium-cobalt sextupolar permanent magnet generates the radial field of the second stage. The resonance frequency of operation is same for both stages and is 6.4 GHz. Two commercially available 6.4 GHz, 3 KW microwave generators have been procured to supply the rf power. The source has been partly assembled in the ECRIS laboratory of VECC. A vacuum of 1×10^{-7} torr in the source and 5×10^{-8} torr in the analysing line have been obtained. A charge analysing system comprising two 45° normal entry and normal exit dipoles and four quadrupoles (QDQ QDQ system) has been built. The fabrication work of entire injection line comprising optical elements, beam transport lines, radio frequency buncher, beam inflector, etc. coming in the phase-2 programme shall start immediately after the source commissioning.

Keywords ECR, acceleration, multiply charged heavy ions, plasma, B-minimum, injection line.

PACS No. : 25.25 Ni

1. Introduction

The Variable Energy Cyclotron (VEC) at Calcutta is being utilised efficiently since 1981 for research and applications. So far, light ions mostly alpha particles, have been accelerated using internal Penning (PIG) light ion source. The achievable energy from VEC is given by

$$E = 130\, Q^2/A \text{ MeV}, \tag{1}$$

where Q is the charge number and A is the mass number.

Equation (1) gives 130 MeV as the maximum energy for alphas which have $Q = 2$ and $A = 4$.

For fully stripped comparatively heavier ions, for example O^{8+} and A^{18+},

$$E(O^{8+}) = 520 \text{ MeV}$$

$$E(A^{18+}) = 1053 \text{ MeV}.$$

It is clear that by accelerating highly stripped heavy ions in the cyclotron, there will be significant gain in energy per nucleon. These energetic ions in turn when used as projectiles can dump large amount of energy on target giving rise to many new phenomena. In fact heavy ion capability of cyclotron will open up new fields of research in many branches of nuclear physics. MCHI beams from ECR source can also be utilised for offline research in atomic physics.

1.1. Consideration in favour of ECR source :

The present internal PIG source is incapable of producing MCHI beams. Modified PIG heavy ion source [1] can produce low charge state heavy ions and has the major drawback of having only 2/3 hours cathode life time. In present days, electron beam ion source EBIS [2] and electron cyclotron resonance ion source ECRIS [3-6] are well known advanced types of heavy ion sources. EBIS has the disadvantage that it involves ultra high vacuum technology and it is basically a pulsed device. On the other hand, ECRIS requires only high vacuum technology and produces continuous beam of heavy ions. The latter is an electrodeless discharge which takes place by very efficient ECR mechanism with microwave power. Its other merits are capability of working stably over days together and having low phase space area (emittance) ion beam. Because of these advantages ECR heavy ion source is the best choice for cyclotron application.

1.2. Physics of ECR heavy ion source :

Multiply charged ions with reasonably good amount of yield are efficiently produced in ECR source by successive ionization of species by hot electrons. The equilibrium charge states distribution (CSD) is determined by the balance between ion production rate and loss rate. Two important quantities in regard to production of high charge states are the product $n_e\tau_i$ and electron temperature T_e in the plasma. Here n_e is the ionising electron density and τ_i is the ion confinement time in the plasma. T_e is to be 3 to 20 KeV or more and n_e to be 10^8–10^{10} for totally stripped light heavy ions. For fully stripped heavy ions of the high mass numbers, T_e and $n_e\tau_i$ should be higher. Since critical electron density in a plasma is proportional to the square of the rf frequency and electron temperature is proportional to the power of rf, it is beneficial to go to higher frequencies and higher power to achieve high yield of high charge states.

1.3. Mechanism of ECR source :

ECR heavy ion source essentially produces a hot electron plasma in a B-minimum configuration inside a plasma chamber. Axial mirror B_z field is produced by solenoids and radial stabilising B_r field by a set of sextupole. In this field configuration, there is a ellipsoidal surface (Figure 1) where magnetic field B satisfies the resonance condition, *i.e.*

corresponding to this B, the electron cyclotron frequency equals the applied rf frequency. Plasma chamber dimension is so chosen (multimode cavity) that there always exists component of E field perpendicular to the B field. As a result, on the ellipsoidal resonance surface, efficient power transfer takes place from E-M wave to the electrons. At a given pressure (≈ 10^{-6} torr) plasma electrons oscillating back and forth between the mirror points are heated up stochastically to quite a few KeV by crossing the resonance surface large number of times. These hot electrons (3–20 KeV) are responsible for the production of high charge state ions by successive ionisation.

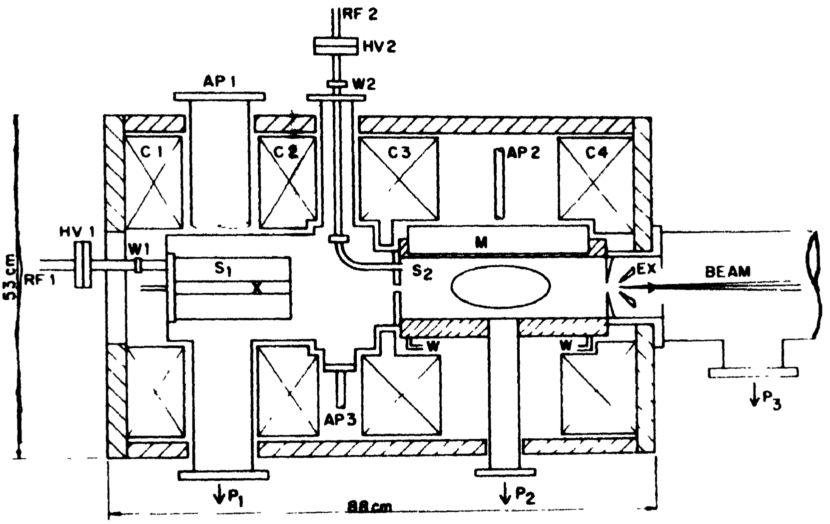

Figure 1. Layout of the VEC ECR source, RF1, RF2, microwave power feeds, HV1, HV2 high voltage isolator, W1, W2 microwave windows, S1 stage 1, S2 stage 2; C1-C4 solenoid coils, M sextupole magnet, AP additional port; P1, P2 : pumping ports

Achievement of high charge state is favoured by operation at low pressure which restricts charge-exchange loss with neutrals and the yield is substantially increased by addition of a first stage. That is why most ECR sources are a two stage device [6]. Main purpose of first stage is to supply electrons together with low charge state ions into the main stage.

2. Design of VEC ECR source

In this regard the foremost work was to fix up the requirements. These lead us to arrive at a suitable design of the source [7,8] to be developed within the fixed time period. It also included selection of microwave frequency. The ECR programme is a quite complex one and it involves many techniques and fabrication works like—

(1) Fabrication of high power solenoids for generating the axial magnetic fields.

(2) Technique of launching high power microwave into the plasma.

(3) Very high vacuum technology (10^{-7} torr in the source and a few times 10^{-8} torr in

(4) Fabrication of plasma chambers — stage 1 and main stripping cavity (stage 2).

(5) Handling of powerful and fragile rare earth permanent magnets (B_{re} = 9000 gauss) and fabrication of sextupoles with these magnets.

(6) Precautions against microwave and X-ray radiations.

(7) Isolation of pumps, wave guides, magnet coils, etc., from the source at high voltage.

(8) Fabrications of charge analysing system.

(9) Fabrication of an advanced external injection system [9] comprising optical elements, rf bunching system, diagnostics, beam inflector etc.

Schematic diagram of VEC ECR heavy ion source is shown in Figure 1. Some of the technical details are given in Table 1.

Table 1. Technical details of VEC ECR heavy ion source

i	Length of the source	88.0 cm
ii.	Outer diameter of the yoke cyclinder	53.6 cm
iii	Number of solenoid coils	4
iv	Frequency of operation	
	- Stage 1	6.4 GHz
	- Stage 2	6.4 GHz
v	Plasma chamber diameter	
	- Stage 1	94.0 mm
	- Stage 2	108.0 mm
vi.	Sextupole magnets	
	- Length	305.0 mm
	- Field diameter	118.0 mm
	- Field on the pole tip	4.0 KGauss
vii.	Estimated solenoid power	
	- For 6.4 GHz operation	25.0 KW
	- For 10.0 GHz operation	52.0 KW

2.1. *Plasma chamber and vacuum requirements :*

VEC ECR source is a room temperature compact two stage device. The entire source is enclosed in a 25 mm thick iron cylinder acting as the yoke for the return flux. Four sets of coils C1, C2, C3 and C4 held within the yoke cylinder generate the resonance and mirror fields in both the stages. Additional sextupol magnet is provided for producing radial field in the second stage.

Stage 1:

Plasma chamber S1 is made of 94 mm internal diameter (I D) copper tube and has a co-axial 20 mm I D quartz tube inside it. On the left side there is a slot cut on the copper end-flange for connecting WR-137 wave guide and a vacuum window. It is also having connection for gas inlet.

Stage 2 :

The second stage plasma chamber S2 is made out of a solid oxygen free high conductivity copper billet. This chamber has ID 108 mm, and length 345 mm and forms a multi mode cavity for rf. This chamber is water cooled and carries 305 mm long rare earth sextupole magnet bars externally. Three radial ports are provided for vacuum gauge, diagnostics and oven connections.

At 6.4 GHz microwave frequency ECR discharge takes place at a pressure of about 1×10^{-3} torr in the quartz tube of stage-1 plasma chamber. This stage injects electrons and low charge state ions into the main stripping stage by diffusion. In this stage, more powerful ECR discharge occurs at a pressure of about 1×10^{-6} torr or lower. The plasma which is stabilised in B-min configuration, has high energy electrons which by stepwise ionisation, produce highly stripped heavy ions. Heavy ions are extracted through a 8 mm hole in the copper emission electrode with the help of a shaped stainless steel puller electrode. The puller is placed 25 mm away from the emission electrode and has a 10 mm aperture at the centre. The source first stage and the extraction chamber are pumped by two 600 litre per sec diffstak pumps. Second stage is mainly pumped by the plasma itself. Additional pumping is provided through the extraction side. A pressure of 1×10^{-7} torr in stage 1 and extraction chamber is routinely obtained in absence of gas leak. The beam analysing part of the transport line is pumped by a 1500 litre per sec cryopump producing a pressure of 7×10^{-8} torr. A pressure of about 1×10^{-7} in the beam transport line is needed for transport of MCHI beam with negligible loss by charge exchange.

2.2. *Microwave :*

For the present application, 6.4 GHz has been chosen as the ECR frequency. It has been planned to use a single 3 KW microwave generator to feed both the stages by making internal or external power division. Microwave power will be injected in both the stages parallel to the axis. Teflon microwave windows have been used to isolate wave guide at atmospheric pressure from the part in high vacuum. Two 3 KW 6.4 GHz commercially available microwave generators have been procured and tested with dummy load.

2.3. *Magnets :*

As is common with conventional ECR source two types of magnets are used. One type is solenoid magnets for axial mirror fields and $SmCo_5$ permanent magnets for sextupolar fields in the main stage.

Four solenoid coils C1–C4 comprise 27 pancakes. Each pancake is made of 6.3 mm square copper conductor having 3 mm central hole for water cooling. The conductor is covered with thin insulating tape while winding. Wound pancakes are epoxy casted to make their outer diameter concentric with the inner diameter which help alignment inside the iron yoke of 486 mm internal diameter. There are two types of pancakes as shown in Table 2.

Table 2. Types of pancakes.

Pancake Type	I D (mm)	OD (mm)	Numbers of turns/layers	Thickness (mm)
A	190	485	21	14.8
B	240	485	17	14.8

Figure 2, gives an example of solenoid fields obtained using Poisson code. The lower curve corresponds to 6.4 GHz operation and upper one for 10.0 GHz operation of both stages. It is also possible to generate working field configurations without exciting the first coil, that is no mirror field in stage 1 as shown in Figure 3.

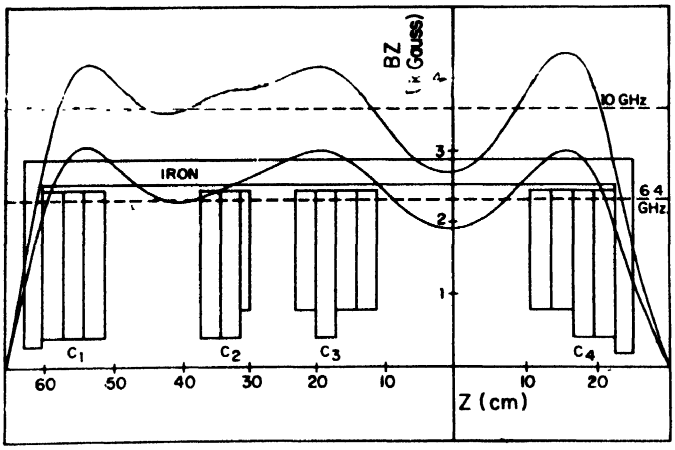

Figure 2. Axial magnetic field due to the solenoidal coils. Upper curve corresponds to 10 GHz and lower curve to 6.4 GHz operation.

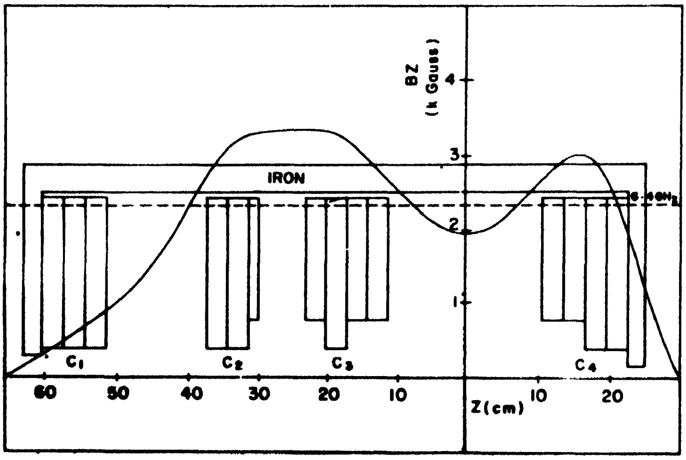

Figure 3. Axial magnetic field of the solenoidal coil with falling field configuration in stage 1 for 6.4 GHz operation.

The second stage has a B-minimum field configuration. This is needed for plasma stabilisation against MHD instability. Plasma stabilisation is important for achieving high ion confinement time (τ_i). The radial stabilising field is produced by a sextupole of length 305 mm and field radius 59 mm and pole tip field 4 KGauss. Each pole is made up of five individual blocks of samarium cobalt ($SmCo_5$) rare earth magnets of size 61 mm by 38.1 mm by 50 mm and magnetised to a residual magnetism of 9 KGauss. Calculated field plots for the sextupole is shown in Figure 4.

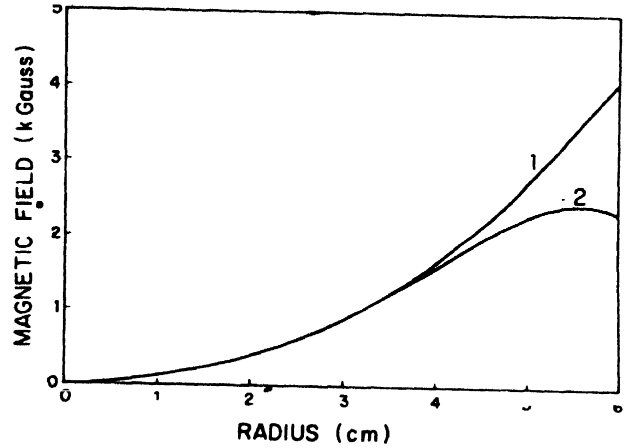

Figure 4. Radial field due to sextupole magnet. Curve 1 : along the radius going into the pole centre; Curve 2 : along the radius going between two adjacent poles.

2.4. *Charge state analyser and external injection system* [9] :

Heavy ion beam extracted by a potential difference of 10 KV is composed of ionic species of various charge states. This beam with the help of two glasers (magnetic lenses) LM-1 and LM-2 [10] is injected into the 90° charge analysing system (Figure 5). It consists of two unit cells each cell comprising two quadrupole (QT) magnets and a 45° dipole magnet (MT) [11].

The magnetic rigidity $B\rho$ (B = field in pole gap, ρ = bending radius) is about 20 KGauss cm for 10 KV deuteron beam. And the resolution $R = Q/M = 1/20$ for full (20 mm) object slit opening. This can be improved further by reducing the slit width.

The beam after charge state selection is to be injected into the centre of the cyclotron for acceleration which is the end use of heavy ion beam produced by the ECR source. The scheme of the injection system is shown in Figure 5. The beam after the analyser is transported to the centre of the cyclotron telescopically with the help of four magnetic lenses LI-1 to LI-4 and finally by a glaser LI-5 on to the 45° electrostatic mirror inflector. Inflector inflects the beam into the cyclotron for subsequent acceleration by the rf fields. The inflector is a copper electrode placed at an angle of 45° to the vertical and is applied with an ion-repelling voltage of about 10 KV. The inflector electrode is enclosed in a grounded copper tube having a slit for beam exit. There is a wire grid placed in front of the inflector for creating desired electrical field in between. Apart from the lenses mentioned above there is a beam rotator (BRI)—a solenoid magnet which can impart a rotation to the beam. This rotation may be needed for maximum transfer of beam from the inflector to the cyclotron. There is also a rf buncher system in the vertical line. The continuous low intensity MCHI beam passing throuth the buncher is bunched in time for increasing the intensity. This is done by accelerating the slower ions and slowing down the faster ones in the rf cycle of the buncher. Since cyclotron accepts ion beam only over a small time interval of the rf cycle, bunching helps to increasing the intensity of the heavy ion beam number of times compared to the unbunched beam.

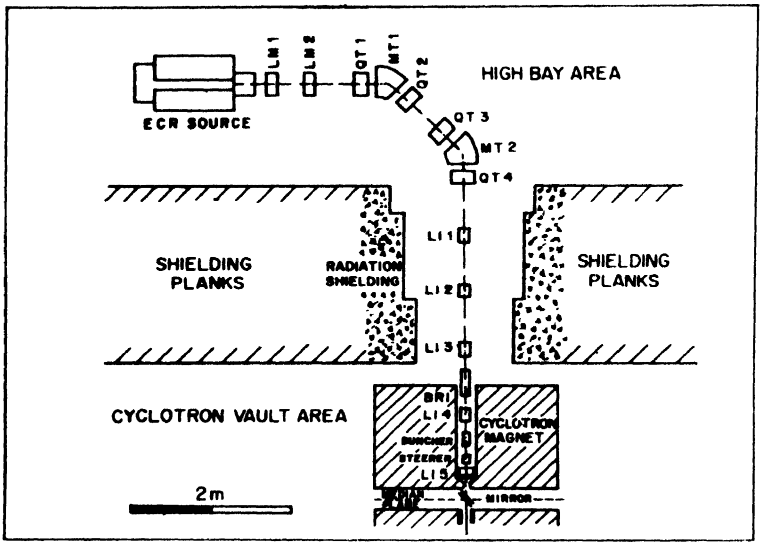

Figure 5. Scheme of external injection system. LM1, LM2 : glaser lenses; QT1–QT4 : quadrupole magnets; LI1–LI4 : solenoid lenses; BRI : beam rotator.

3. Present status

As on November 1990, the source component have been assembled in the laboratory with part of the charge analysing vacuum line. All the magnet coils have been installed inside the iron yoke cylinder, together with vacuum chambers, plasma chambers. High vacuum pressure 1×10^{-7} torr in the ion source and 5×10^{-8} torr in the part of the transport line have been obtained. Main stage OFHC copper chamber will be taken out to mount the samarium cobalt magnets for the sextupole. All the power supplies for the solenoid magnets have been commissioned. Arrangements are being made to shift the source to high bay area on the top of the cyclotron which is the location decided for the source assembly. The source is expected to go for trial run within a few weeks.

Acknowledgment

It is acknowledge with gratefulness the helpful discussions we had with T Antaya of Michigan State University, who also arranged a 250 mm diameter OFHC copper billet as a gift. We are also thankful to C M Lyneis and D Clark of Lawrence Berkeley Laboratory, University of California, for many helpful discussions. We acknowledge with thanks the efforts of J Reich which enabled us to receive as gift a set of samarium cobalt permanent magnet bars and OHFC copper rods from Internationals Bureau, Kern Forsehungs Anlaage julich. We are grateful to our Director Dr Bikash Sinha for his constant encouragement, support and advice. We also thank our colleagues N K Mukhopadhyay, C Mallik, P R Sarma, M H Rashid for their interest and support.

References

[1] D J Clark 1981 *Proc 9th Intl. Conf on Cyclotrons and their Applications Caen Sept* 7 **231**

[2] M P Stockli 1987 *Intl Conf on ECR Ion Source and Their Applications N S C L, East Lansing, Report* **MSUCP-47** 219

[3] R Geller, F Bourg, P Briand, J Debernardi, M Delaunay, B Jacquot, P Ludwig, R Pauthenet, M Pontonnier and P Sortais 1987 *ibid* 1

[4] C M Lyneis 1987 *Proc 11th Intl Conf on Cyclotron and Their Applications, Tokyo 1986* 707

[5] Y Jongen, C Pirart and G Ryckewaert 1982 *Proc 4th Intl Worshop on ECR Ion Source and Related Topics, Grenoble 3 1*

[6] T A Antaya and Z Q Xie 1986 *Proc 7th Intl.Workshop on ECR Ion Sources, Julich* **72**

[7] D K Bose and T Antaya 1987 *Intl Conf on ECR Ion Sources and Their Applications, NSCL, East Lansing, Report* **MSUCP-47** 371

[8] D K Bose, G S Taki, J Chaudhuri and R K Bhandari 1989 *12th Intl Conf on Cyclotrons and Their Applications, Berlin* **190**

[9] R K Bhandari 1988 *Proc Symp on Nuclear Physics (DAE BARC, Bombay)* **31(B)** 92

[10] M H Rashid, P R Sarma and R K Bhandari 1991 *Indian J Phys* **65A** 402

[11] P R Sarma 1988 (unpublished)