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The radioactive ion beam project at VECC, Kolkata – A status report

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Abstract. A project to build an ISOL-post accelerator type of radioactive ion beam (RIB) facility has been undertaken at VECC, Kolkata. The funding for the first phase of the project was approved in August 1997. This phase will be the R&D phase and will be completed by December 2003. The present status of development of the various sub-systems of the RIB facility will be discussed.

Keywords. RIB facility; ISOL; thick target; post acceleration.

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1. Introduction

A project to develop an ISOL-type radioactive ion beam (RIB) facility has been undertaken at the Variable Energy Cyclotron Centre, Kolkata [1]. The activities started early in 1998 after receiving the formal sanction in late 1997. The progress that has been achieved in the last four years will be presented here. The total plan of the project is schematically shown in figure 1. Since the development of a RIB facility is highly R&D intensive in nature, the activities have been planned in phases. The first phase is planned so that the basic design of all the critical components, accelerators and subsystems and the R&D needed to arrive at these designs are completed during this phase. The aim has been to complete by the end of 2002 the physics design and the fabrication aspects of all the subsystems of the RIB facility and to actually develop subsystems from the target chamber up to the first tank of LINAC. This status report aims at bringing out the progress till date.

The basic scheme, as mentioned above, is schematically shown in figure 1. Radioactive atoms will be produced inside a thick target using proton and α-particle beams from the $K = 130$ variable energy cyclotron at VECC. The radioactive atoms diffusing out from the thick target will be ionized to $q = 1^+$ in the integrated target-ion-source and then transported to an on-line ECR ion-source where $q > 1^+$ RIB will be produced in the novel 'two-ion-source' mode. Alternately, in the case of inert gases and other gaseous activities, the radioactive atoms will be directly transported to the ECRIS by means of a transfer tube. The He-jet transport with skimmer assemblies offers another possibility of injecting the radioactive atoms into the ECR ion source. After extraction from the ECR ion source the desired RIB with an energy of 1 keV/u and $q/A > 1/16$ will be separated from other products in the low energy beam transport line and will be ultimately transferred to RFQ.

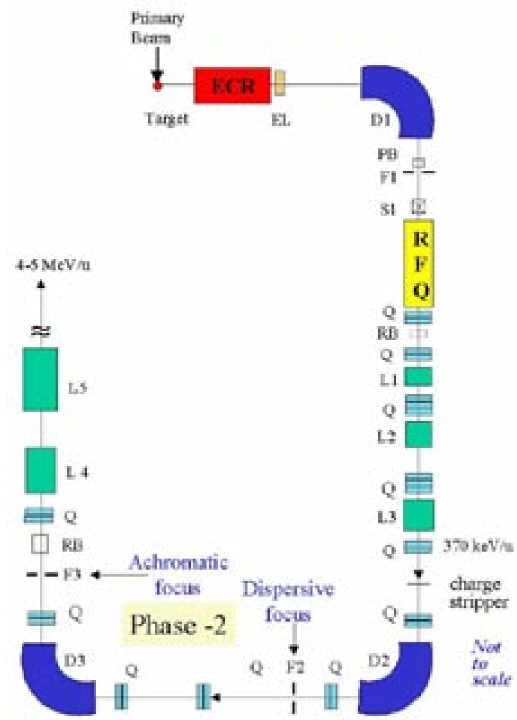

Figure 1. Schematic lay out of the VEC-RIB facility.

In RFQ the RIB will be accelerated to about 90 keV/u. Subsequently the RIB will be accelerated to the desired final energy of about 4 MeV/u in a series of IH-LINAC tanks.

2. Thick target R&D and the nature of RI beams obtainable from the RIB facility at VECC

The RIB intensity is proportional to the thickness of the target, that is, on the number of target atoms per unit area of the target. Proton induced reactions are often used for production of radioactive atoms. At energies in the range 30 to 100 MeV, the typical target thickness is of the order a few gm/cm^2, while at around 500 MeV proton energy the typical target thickness is of the order a few hundred gm/cm^2. The incident energy, the threshold energy for the reaction of interest and the energy deposition in the target are some of the parameters considered for deciding the optimum target thickness in a particular case. The choice of target material is done considering the temperature.

The release of activity from the target should be fast and efficient. As such no atoms practically comes out from deep inside a thick target. The trick is therefore to achieve the given thickness with the maximum possible surface area. One way of achieving this is to use a large number of thin targets stacked together instead of one thick target. But the typical thin foils do not allow the radioactive atoms to diffuse easily. One thus considers low-density target materials like grains, fibres, etc. in which the diffusion time is mainly governed by the grain size and the temperature. Target materials often deposited on graphite matrices that can withstand very high temperature have sufficient porosity to allow radioactive atoms to diffuse out and allows very reactive atoms like oxygen to diffuse out in the form of CO.

In nuclear reactions such as fission, projectile fragmentation (spallation to a great extent) a single target can produce a large number of products. But to produce *p*-rich nuclei through low energy CN reactions, one needs a large number of targets since the reaction products are only a few atomic and mass number away from those of the target. Thus a single target usually turns out to be optimum for the production of only a few RIB. For example the LiF target has been used at Louvain-la-Neuve for the production of ^{6}He, ^{15}O, ^{18,19}Ne.

To build a versatile RIB facility around a cyclotron delivering light ions up to 100 MeV or a little less, the development of a large number of thick targets is of key importance. The targets should be able to sustain beam irradiation for at least a week, allow good release efficiency uniformly over the entire beam run and with the minimum possible release time.

The beam intensity of RIB in an ISOL-type facility is limited by several factors: maximum primary beam intensity that the mother accelerator can supply, the maximum power density the target can sustain without losing its physical integrity and without compromising the efficiency of the ion-source, rate of diffusion of radioactive atoms from the target, loss of atoms during transport to ion-source from the target, ionization efficiency and the loss due to separation and post-acceleration. The maximum temperature and therefore the maximum beam power in a target is limited by the vapor pressure of the target which should not be much above 10^{-4} torr in order that the ionization efficiency of the integrated surface ionization source is not adversely affected. However, higher temperatures are preferable for faster diffusion of radioactive atoms from inside the target to outside and for minimizing the loss due to surface adsorption. More often it is these considerations of vapor pressure, physical integrity, etc. that limit the maximum usable beam current/power and for a large number of targets this limit is only a few microamperes!

The target material should preferably be refractory in nature (so that it can withstand high temperature) and should be in a form such as powder, fibre, thin disc or even liquid that allows high permeability for the radioactive atoms to diffuse out. The choice of target material and target matrices are therefore very much limited. The development of each target is therefore a very complicated exercise.

Using the existing $K = 130$ cyclotron at VECC, one can produce *p*-rich nuclei that are four to five neutron deficient with quite high cross-sections of a few tens of milibarns. Using light ion (α/proton) induced fission reaction one can also produce a large number of neutron-rich nuclei in the range $28 \leq Z \leq 50$. Neutron-rich nuclei with $A/Z \sim 2.5$ can be produced with cross-sections as high as a few tens of millibarns in the fission of Th/U induced by α/proton. For the production of *n*-rich nuclei in the fission product range, high power electron LINACS delivering electron beams of energy of about 30 MeV is becoming a very cheap and popular option. A fission rate of about 10^{13}/s can be obtained with about 100 kW of beam power. As compared to 20 μA 30 MeV proton beam, the electron LINAC can produce *n*-rich nuclei of $A/Z \sim 2.5$ with a yield which is nearly one order of magnitude higher. The advantage is more in the case of products that are more neutron-rich. The e-LINAC option (in addition to the existing accelerator) for the acceleration of very *n*-rich RIBs such as ^{132}Sn would be given a serious consideration once RIB up to about 1 MeV/u are successfully accelerated at VECC. The commissioning of the $K = 500$

superconducting cyclotron at VECC would also offer an additional possibility. A large number of both neutron-deficient and neutron-rich light nuclei $(A \leq 70)$ can be produced via projectile fragmentation reaction using a thick graphite target in which the fragments are also stopped for subsequent diffusion, ionization, etc.

Development of thick targets and the associated R&D have been undertaken at the Target Lab in VECC. To start with the attempt will be limited to fabricate only a few targets and test them 'in beam' for RIB production and release. The targets which are being developed at present are LiF, BN, C (graphite), MgO, Al_2O_3, $CaCl_2$, ZnO, GeO_2, HfO_2, Th and U. A list of first few RIB that would be developed at VECC is given in table 1 along with the probable targets.

The design of the target chamber with integrated ion source has been completed. The target holder for various target types will not be exactly the same and the design of a few different types of target holders is being finalized (figure 2). The fabrication of a 600 A power supply for target heating is nearing completion. On-line experiments for the target characterization have been planned towards the end of this year.

Table 1. First few RIBs to be developed at VEC-RIB facility.

RIB	Production route	Target
^{11}C	^{11}B(p,n)	BN
^{13}N	^{13}C(p,n)	Graphite
^{17}F	^{14}N(α,n)	BN
^{18}F	^{16}O(α,n)	HfO_2,Al_2O_3
^{19}Ne	^{19}F(p,n)	LiF
^{34}Cl	^{35}Cl(p,pn)	$CaCl_2$
^{35}Ar	^{35}Cl(p,n)	$CaCl_2$
^{38}K	^{35}Cl(α,n)	$CaCl_2$
^{64}Ga	^{64}Zn(p,n)	ZnO
^{70}As	^{70}Ge(p,n)	GeO_2
^{78}Ga	^{232}Th(α,f)	^{232}ThO
^{80}Ge	-do-	-do-
^{83}As	-do-	-do-
^{85}Se	-do-	-do-
^{88}Br	-do-	-do-
^{90}Kr	-do-	-do-
^{93}Rb	-do-	-do-
^{118}Ag	-do-	-do-
^{123}In	-do-	-do-
^{133}I	-do-	-do-
^{135}Xe	-do-	-do-
^{138}Cs	-do-	-do-
^{140}Ba	-do-	-do-
^{143}La	-do-	-do-
^{145}Ce	-do-	-do-
^{148}Pr	-do-	-do-
^{150}Nd	-do-	-do-

Assuming η (target release+1st IS) $=$ 10% ; η (ECR, $q+$) $=$ 10%; η (separation and acceleration) $=$ 10%, expected average yields for the above RIB are $\sim$0.1 to 1×10^8 pps for 20 μA primary beam.

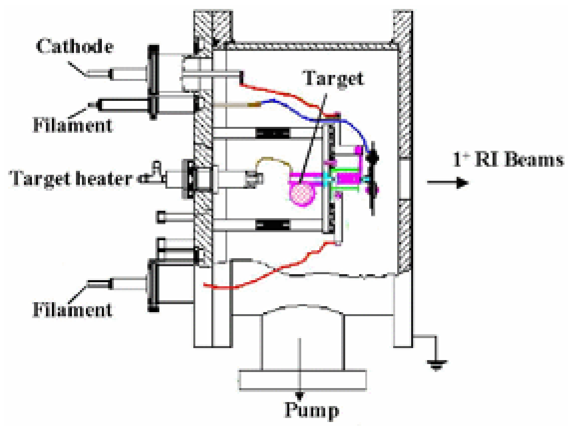

Figure 2. The thick target surface ion source.

3. On-line production of multiply charged radioactive ions

In the on-line ECRIS the aim is to produce high charge states of RIB with good enough efficiency in order to accelerate a wide mass range of RIB. Owing to the close vicinity of the target to the ion source, which is the case if a transfer tube is connected between the target chamber and the ECRIS, the residual gas pressure in the ion source cannot be kept low enough for efficient production of ions with $q > 1^+$. Although one can use long transfer tubes for the transfer of gaseous activity the same is not true for non-gaseous activity owing to huge transfer losses. Heating the transfer tube might minimize the transfer losses but the coupling of the hot transfer tube to the ECRIS is complicated. Also the high radiation environment close to the target may cause neutron damage to the permanent magnets of the ECR source thereby drastically reducing its life-time.

However, if the ions of $q = 1^+$ are produced in a thick target surface ionizer (integrated target-ion source) and then injected into an ECRIS after proper deceleration and focusing to ensure good trapping inside the ECR plasma zone, one can expect to get high enough efficiency for the production of high charge states for a large number of non-gaseous radioactive species. This technique allows the ECR ion source to be kept at a comfortable distance from the target and through differential pumping a pressure of 10^{-7} torr can be maintained in the ECRIS. The above 'two-ion-source' concept (charge breeder) has been tried out at Grenoble [2] for 1^+ to n^+ production of Ar, Rb, Zn, Pb and some other elements.

The 'two-ion-source' beam transport line between integrated target surface ionization source and the on-line electron cyclotron resonance ion source (ECRIS) for the production of multi-charged radioactive ions has been designed [3]. The schematic layout of the scheme is shown in figure 3. The 1^+ ions from the surface ionization source are decelerated to about 20 eV and focused into the ECRIS plasma so that they can be efficiently trapped there and further ionized to charge state $q > 1^+$. A scheme for stepwise and gradual deceleration of the 1^+ ion beam consisting of a multi-electrode decelerator and a tuning electrode placed before the ECRIS has been optimized. The 'two-ion-source' beam line along with the surface ion source has been fabricated and transported to RIKEN where the

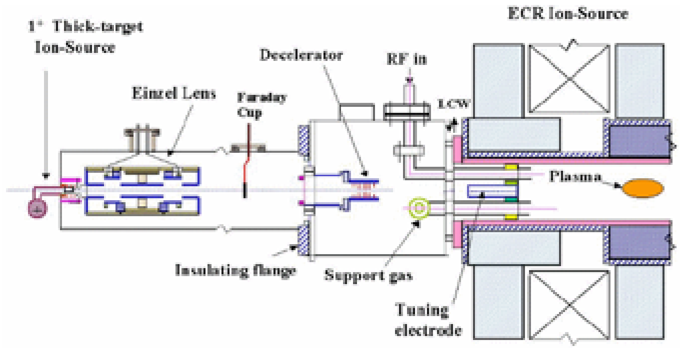

Figure 3. The two-ion-source scheme for production of multi-charged RIB.

Table 2. Parameters of the on-line ECR ion source for the VEC-RIB facility.

ECR parameters	Value
Frequency	6.4 GHz
rf Power (maximum)	3 kW
BECR	0.23 T
Axial magnetic field (Bz) (solenoid coils)	0.95 T (inj.)
	0.7 T (ext.)
Radial magnetic field at plasma chamber i.d. (Br)	0.7 T
NdFeB permanent magnet sextupole	
Mirror ratio	5.9 (inj); 4.375 (ext)
Plasma chamber ID	100 mm
ECR overall dimensions	0.98 m dia; 1m length
Power (both solenoid coils)	50 kW

concept has been experimentally tested at the 18 GHz ECRIS. The first tests have shown positive indication for K^{1+} to K^{3+} production. Further R&D to perfect the methodology will be conducted at VECC after the installation of the ECR ion source.

The fabrication of the on-line ECR ion source (ECRIS) designed for the RIB project is just completed. The main design parameters of the ECRIS are listed in table 2. It will be operated in the 'High B mode' having a peak solenoidal field of 1.0 T at the injection end and 0.7 T at the extraction end. The radial field at the surface of the plasma chamber is 0.7 T. The solenoid coils and permanent magnet sextupole for the ECR ion source have been fabricated and the field mapping tests completed. The installation of the mechanical assembly consisting of a double walled plasma chamber, injection and extraction chamber including a single stage Einzel lens is being carried out at present.

Apart from the two-ion-source methodology, the other possibility of injecting the activities in to the ECR ion source is the helium-jet recoil transport technique. The activities transported from the target chamber will be injected in to the ECR plasma chamber after passing through an intermediate two-stage skimmer. With efficient differential pumping, a vacuum reaching almost about 10^{-6} torr might be achievable in the ECR plasma chamber. This vacuum might be just enough for the production of heavy ions with $q/A \geq 1/16$. The concept, presently in the R&D stage, is shown schematically in figure 4.

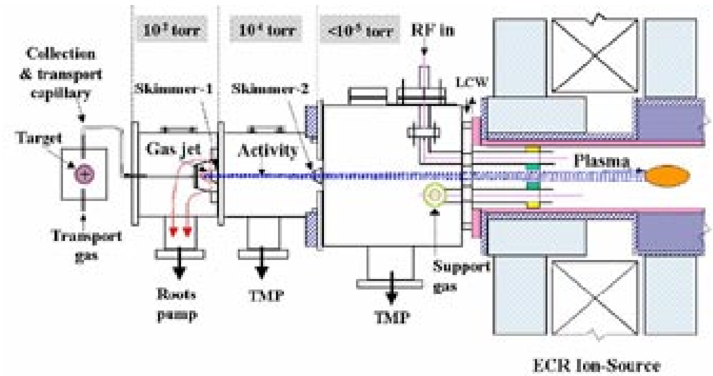

Figure 4. The helium-jet two-stage skimmer assembly.

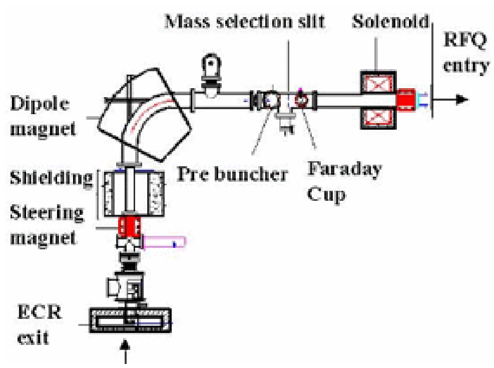

Figure 5. The lay out of ECR to RFQ beam line.

4. Low energy beam transport from ECR to RFQ

The extracted beam from the ECR ion source will be fed to the RFQ. Prior to injection into the RFQ the beam will pass through a single gap, sinusoidal pre-buncher placed about 80 cm upstream of the RFQ. The ECR to RFQ low energy beam transport (LEBT) line has been designed and fabrication of the majority of the components is already complete. The lay out of the beam line and its components is shown in figure 5. The main requirements of the LEBT line are:

- The emittance ellipse of the beam at the end of the injection line should be properly matched to the acceptance ellipse of the RFQ to avoid beam loss.
- The ion optics layout should provide reasonable mass separation to ensure beam purity to maximum extent possible.
- The total length of the layout should be minimized for space restrictions.

The emittance of the ion beam from the ECR ion source is taken to be 150 π mm-mrad. The half width of the beam at the exit of ECR is taken as ± 5.0 mm (the extraction hole of ion source is 1 cm ϕ) and divergence ± 30 mrad. Owing to the large divergence of the ion beam, an Einzel lens is placed just after the extractor to form a beam waist at a

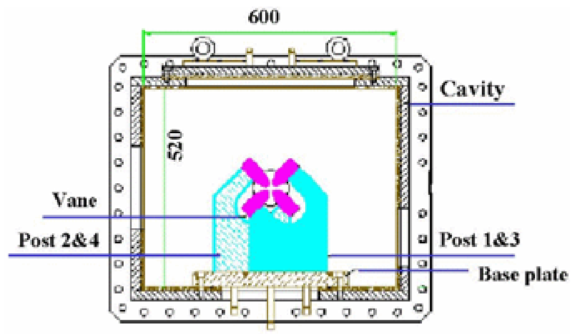

Figure 6. The cross-sectional view of the RFQ cavity.

distance of 0.6 m from the ECRIS exit, which acts as the object point for the subsequent part of the design. The next part of the layout uses properly optimized drift-dipole-drift combination to form an image where most of the unwanted reaction products can be filtered out. The final part ensures proper matching of the beam to the acceptance of the RFQ using a drift-solenoid-drift combination. The beam optics simulation has primarily been done using the code TRANSPORT but the results have also been verified using the code COSY INFINITY.

5. The heavy-ion radio frequency quadrupole (RFQ) and the first stage of RI beam acceleration

The radio frequency quadrupole (RFQ) LINAC is the most suitable linear accelerator for bunching, acceleration and focusing of low-β heavy-ion beams with low q/A. For the VECC-RIB project a RFQ LINAC has been designed for an input beam energy of 1.0 keV/u and $q/A \geq 1/16$. The output energy will be $\approx$ 80 keV/u for a 3.4 m long, 35 MHz structure. The intervane voltage will be 49.5 kV, which is 1.2 times the Kilpatrick limit.

The cross-sectional view of the RFQ cavity is shown in figure 6. The resonant structure consists of four vanes supported on eight posts on a base plate. Each diagonally opposite pair of vanes are supported by four posts. The beam dynamics design of the RFQ has been done using the code PARMTEQ. More than 94% transmission efficiency could be achieved for 1 mA dc beam of $q/A \geq 1/16$. For the rf structure design the computer code MAFIA has been used. The Q-value and shunt impedance of the 3.4 m long accelerating structure comes out to be about 9100 and 70 kΩ respectively. The rf characteristics of the RFQ has been verified by fabricating a half-scale cold model. The experimental Q and the shunt impedance have been measured to be about 50% of the designed value. A 40 kW, 35 MHz rf transmitter, the rf source for the RFQ, has been procured and installed. The detailed design and other details on the RFQ is discussed in a local citation [4].

6. Heavy-ion LINAC post-accelerator for subsequent phases of post-acceleration

After the initial stage of acceleration in the RFQ LINAC the subsequent acceleration of RIB will be done in LINAC tanks. For these low-β and low q/A RIB the IH-LINAC

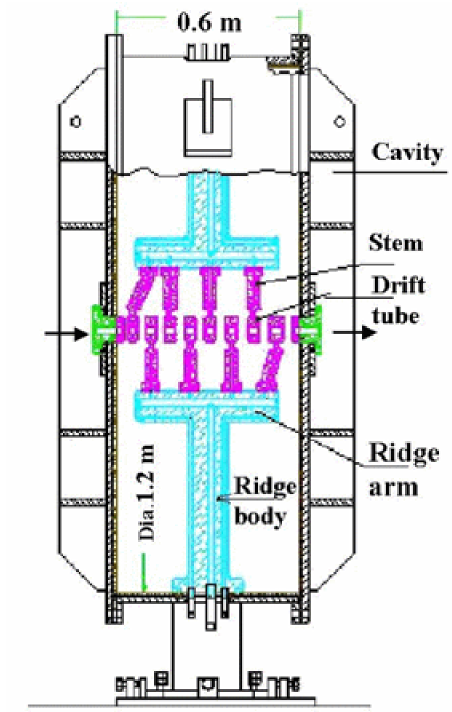

Figure 7. Schematic lay out of the LINAC tank 1.

structure is the preferred choice. In this type of structure, the LINAC cavities are excited in the TE mode. The IH structure offers quite high shunt impedance at lower frequencies. The transverse focusing will be taken care by placing quadrupole triplets in between the tanks.

The design of the first three LINAC tanks has been frozen and the fabrication drawings are nearing completion. The high power rf transmitters for the LINACS are being developed indigenously at SAMEER in collaboration with VECC. The first indigenously built 40 kW, 35 MHz transmitter will be ready for installation before the end of this year. This transmitter will power the first tank of LINAC. The RIB energy would be about 370 keV/u after the third tank of LINAC. The energy will be upgraded later to about 1 MeV/u and ultimately to about 4 MeV/u by adding more LINAC modules. The option of going in favor of superconducting LINAC structure for acceleration beyond 370 keV/u is being examined at present.

The first LINAC tank will be of about 1.7 m diameter and 60 cm long (figure 7). For such a large diameter, the distortion of the inlet and outlet flanges due to buckling under atmospheric pressure is a serious problem. The distortion needs to be corrected in order to avoid the perturbation to the resonant frequency and field distribution inside the cavity. The details of the beam dynamics and the rf-structure design for the LINAC and the critical mechanical aspects are discussed in a separate contribution in the local citation [5].

7. Conclusion

The development of an ISOL-type RIB facility is underway at VECC, Kolkata. In the last four years the design of all the subsystems from the integrated ion source to the third tank of LINAC has been completed. Fabrication of the two-ion-source including ECR ion source and the entire beam line from ECR to RFQ have been completed. The fabrication and testing of a RFQ cold model for rf structure studies and the fabrication of a test vane with 3d modulation have been completed. Fabrication of the final RFQ will be beginning shortly. We hope to install by middle of 2003, all the components up to the first tank of LINAC, delivering accelerated beams of energy 150 keV/u.

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