ACTIVITIES FOR ACCELERATION OF RADIOACTIVE ION BEAMS AT VECC, KOLKATA*

Alok Chakrabarti#, VECC, 1/AF Bidhan Nagar, Kolkata-64, India

Abstract

An ISOL type RIB facility is being built around the K130 cyclotron at VECC with the aim to accelerate 1.3 MeV/u beams. Presently 289 keV/u stable isotope beams are available from the facility and acceleration to around 415 keV/u is expected shortly. Design and development of a 10/50 MeV, 100 kW superconducting electron linac photo-fission driver has also been started.

Present status of developments of various accelerators including the e-linac, the R&D programs that are initiated using stable heavy-ions from the facility and our efforts towards acceleration of RIBs would be presented.

INTRODUCTION

VECC has undertaken the task of developing a Radioactive Ion Beam (RIB) facility with energy up to 1.3 MeV/u [1]. The acceleration scheme is linear accelerator based. The first post-accelerator is a RFQ Linac [2,3] that accelerates beams up to about 100 keV/u. Subsequent acceleration will take place in six IH Linacs [4]. The RFQ and three Linac tanks are already installed and the 4th Linac is under fabrication. Presently the facility delivers A/q=14 stable isotope beams up to an energy of 289 keV/u at the end of LINAC-2. The third linac module (LINAC-3) is ready for beam commissioning and shortly the beam energy will be raised to 415 keV/u.

PRODUCTION OF RADIOACTIVE IONS

Radioactive isotopes will be produced in nuclear reaction induced by proton or alpha-particle beams from the VEC K130 cyclotron. Radioactive atoms diffusing from the target(s) are ionized initially in an integrated 1^+ ion-source and then to higher charge state in an Electron Cyclotron Resonance (ECR) ion-source. This system is called a “charge breeder”. The 1^+ beam has to be decelerated to few tens of eV while ensuring that the beam get efficiently trapped in the ECR. To do this a gradual deceleration scheme and a large volume 6.4 GHz ECR has been designed [5]. This ECR has been operated for both gaseous and metallic beams. The 1^+ ion-source will be a coil-based 2.45 GHz ECR ion source that is presently being designed (see these proceedings, M. Bhattacharya et.al.).

Helium-jet ECR ion-source

A new R&D programme on Helium-jet coupled ECR ion-source has been started. This option is highly attractive especially for the fission production route. Transport efficiencies of 50-90% can be obtained from the *He-jet recoil transport method* for almost all elements [6]. In this method, the radioactive recoils coming out of the target are transported to a remote collection chamber via a thin capillary as shown in Fig. 1. The target chamber is filled with helium (at a pressure of about one atmosphere) and trace amount of organic compounds that capture the radioactive atoms and carry them along with helium in the form of clusters. The transport takes place by differential pumping of helium at the collection chamber by a roots pump.

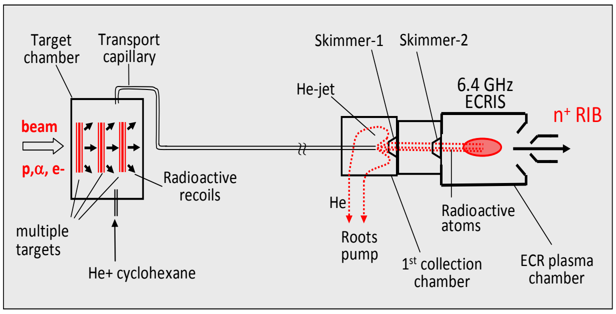

Figure 1: Conceptual scheme of He-jet coupled ECR.

The jet emerging out of the transport capillary passes through two successive skimmers having openings of 1.5 and 2 mm diameter respectively. The clusters being heavy pass through both the skimmers while the lighter helium-gas is pumped out. The radioactive atoms are finally stopped in the ECR plasma chamber. A photograph of the He-jet two-stage skimmer system is shown in Fig. 2.

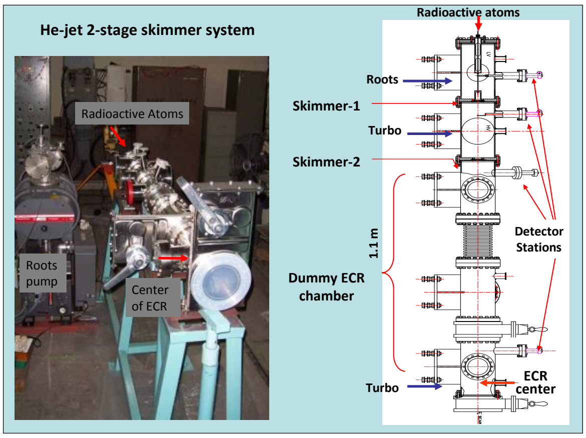

Figure 2: He-jet 2-stage skimmer system.

On-line experiments using alpha-particle beams are underway to test the He-jet skimmer system. Vacuum in 2nd skimmer and dummy plasma chamber is typically $2X10^{-4}$ mbar and $3X10^{-6}$ mbar respectively. About 10-15% of the reaction products have been found to reach the ECR plasma chamber (dummy). Along with the stand-alone He-jet ECR the option of He-jet coupled ECR based Charge Breeder is also being pursued.

*DAE/Govt. of India project

#alok@vecc.gov.in

The multiple-target chamber

Since excitation functions for typical (α/p, xnyp) reactions span around 18 to 20 MeV energy window, one could use multiple thin-targets and obtain production yields almost equal, or even higher in case of refractory elements and metals, to thick target yields. This together with reasonably good ionization efficiency of ECR ion-source for many elements makes the multiple-target ECR a key R&D programme for RIB production.

A 3-d view and photograph of the he-jet multiple target system is shown in Fig.3. In a recent study aimed at testing the he-jet multiple target system, collection and transport efficiency for multiple (ten) foil targets was measured and compared with that for single target. Yields for ^{60}Cu ($T_{½}$=23 min.) produced in $^{58}Ni(\alpha,pn)$ reaction were measured. The observed yield enhancement was almost eight times that of single target yields. Further experiments using various gases such as Argon and Nitrogen with varying gas pressures for optimum stopping and collection of recoils are underway.

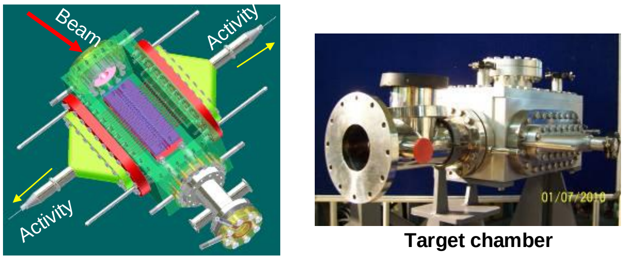

Figure 3: Multiple target chamber for He-jet ECR.

On-line studies on composite targets

Available intensity of RIB crucially depends on efficient and fast release of radioactive atoms from the target. This has to be achieved while maintaining the integrity of the target under high beam power. With this aim an extensive target R&D programme is being pursued for past few years. High porosity composite targets have been developed by coating few micron thin layers of refractory target compounds on graphite matrix by various methods. This way the surface-to-volume ratio of the target gets enhanced multiple times. In a previous study we had experimentally observed for ^{38}K($T_{½}$=7.6 min.) produced from composite Al_2O_3 target that measured yield was almost ten times higher as compared to thin aluminium foil target of equivalent thickness [7]. The density of the base matrix on which the target compound is deposited is also a crucial parameter. In a recent experiment using 40 MeV alpha-particle beams, composite targets of ZnO deposited on a matrix with compression of 1x and 6x were studied. The release efficiency of ^{66}Ga produced in $^{64}Zn(\alpha,2n)$ reaction was studied and ZnO-1x was found to be more efficient. More experiments are planned in this direction.

POST-ACCELERATION

The RIB facility from the ECR to a portion of the beam-line leading to LINAC-3 is housed in an existing 23m x 15m experimental cave. The LINAC-3 will be placed in the adjacent cave (see Fig.4.) whereas remaining Linacs and the experimental facilities are to be housed in a new annexe building that is under construction.

The RFQ accelerates 1.75 keV/u, A/q=14 beam from the ECR to 99 keV/u, and was commissioned in the year 2008. It will be operated in CW mode. In a first of its kind study, effect of vane modulation on the rf-characteristics has been calculated for the RFQ. For this purpose the 3-d model of RFQ from CATIA was exported to ANSYS workbench and used for rf simulation. The resonance

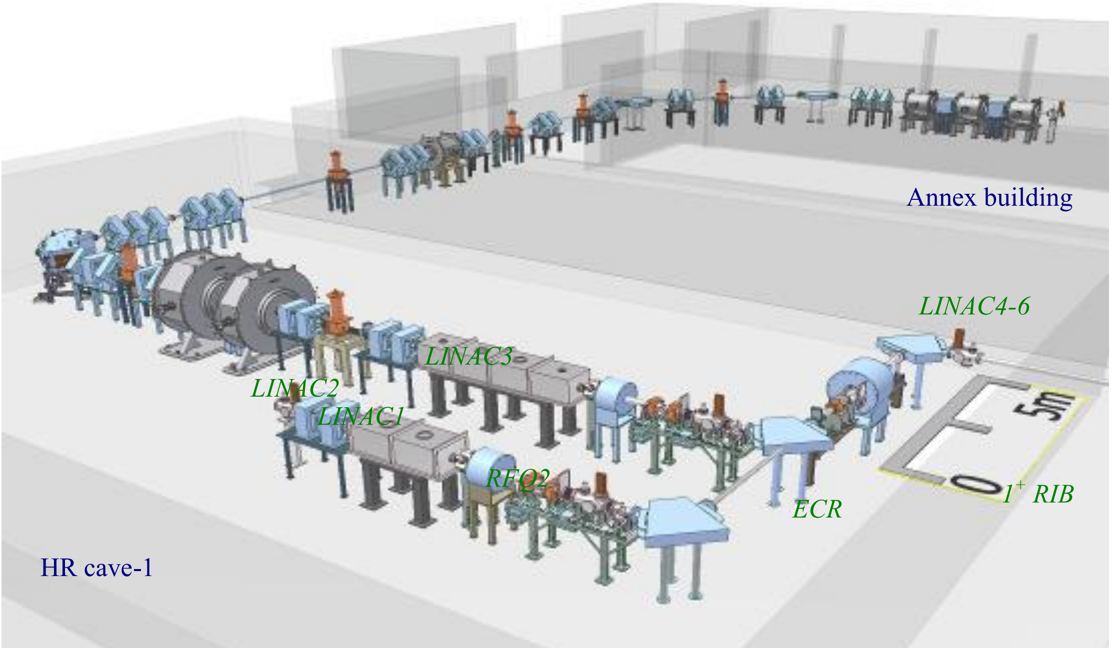

Figure 4: Floor layout of the upcoming RIB facility.

frequency and Q-value with the modulated vanes come out to be 37.66 MHz and 8026 respectively whereas the R_p is 65 kΩ. For the un-modulated vanes these numbers were 37 MHz, 9763 and 78 kΩ respectively. The effect of modulation on the resonance frequency and the shunt impedance is therefore found to be quite significant.

The RFQ is followed by two Linac tanks that together take the energy further to about 289 keV/u. For low beta and low A/q beams IH-LINAC is the preferred structure. The beam energy after LINAC-1 is 187 keV/u and 289 keV/u at the end of LINAC-2. The RFQ, LINAC-1 and the LINAC-2 operate at 37.8 MHz. respectively while LINAC 3-6 have been designed for 75.6 MHz. LINAC-2 was commissioned in the year 2010. Beams have been accelerated through LINAC-2 with an overall efficiency of 60% as measured for $^{16}O^{5+}$ beam. The RF power during the beam test was 700 W (CW) and the vacuum of the cavity was 1.2 x 10^{-6} mbar. Necessary steps to improve the transmission efficiency further are being taken. A photograph of the RIB project site showing RFQ on the left corner and first two Linac modules on the top-right is given in Fig. 5.

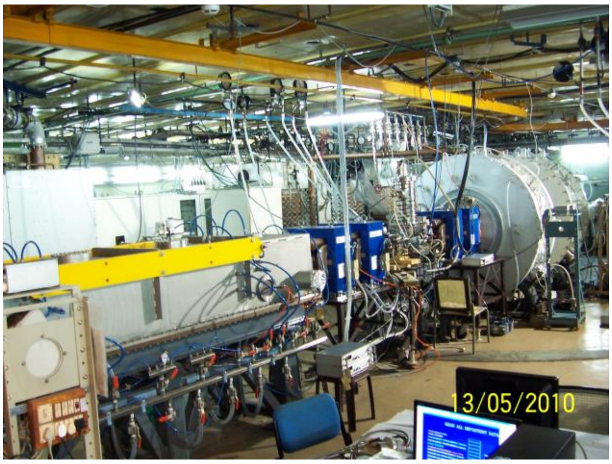

Figure 5: Photograph of RIB site.

Recently, LINAC-3 (Fig.6) that will accelerate the beam to 415 keV/u, has been commissioned and is being readied for beam tests. It is a 0.8 m diameter, about 1m long octagonal cavity made from copper cladded steel, same as for LINAC-1 and LINAC-2. After the third linac a charge stripper will be used and there-after the A/q=7 beams will be finally accelerated to about 1.3 MeV/u in LINACs 4-6, which defines the present scope of the RIB project. The physics design of these linacs has been completed and fabrication of LINAC-4 is underway.

Medium Energy Beam Transport (MEBT) line between LINAC-2 and LINAC-3

The MEBT line is designed to achieve a robust solution for matching the parameters of beam from LINAC-2 with transverse and longitudinal acceptance of LINAC-3. The RFQ has its vanes placed at 45 degree with respect to the conventional co-ordinates. Thus ion beam coming out of RFQ has X & Y rotated by 45 degree as compared to conventional coordinates. The transverse force for IH-Linac and Re-buncher cavities being symmetrical does not have any sacrosanct direction to be identified as X & Y. However, the dipole magnet has the magnetic field perpendicular to the median plane resulting in a deflecting force on the charged particle in the defined X plane of conventional beam coordinate.

Figure 6: LINAC-3 with front-cover removed.

Thus in beam optical parlance the LINAC-2 beam matrix (sigma matrix) has non-zero coupling elements (σ_{13}, σ_{23}, σ_{14}, σ_{24}) in dipole magnet reference frame. Therefore we need to decouple the LINAC-2 beam in dipole reference frame. Once the beam is decoupled all the subsequent beam elements, such as quadrupoles can be placed in the conventional way. We have designed the MEBT line to achieve all these requirements, viz, decoupling of X-Y motion, dispersion suppression and transverse and longitudinal beam matching at LINAC-2 entry [8]. Robustness of the design with respect to orientation of initial beam ellipse has also been ensured.

ION BEAM BASED STUDIES

Material science research programme has been started using ion-beams from the RIB facility [9, 10]. At present stable isotope beams of helium, oxygen, nitrogen, carbon, argon and iron as well as molecular beams of oxygen and nitrogen are being used from the facility. Low energy beams are available after the ECR with typical extraction voltage of up to 25 kV and beam currents ranging over several tens of micro amperes. Oxygen, argon and iron beams of energy 99 keV/u (e.g. 1.58 MeV for ^{16}O) are available at the end of the 3.4m RFQ. A new beam-line where the 1.7m RFQ delivering 29 keV/u beams has been re-installed is getting ready for experiments.

In recent experiments ion beam induced nanostructure formation and its basic mechanism has been studied [11]. Nano ripple structures on ZnO thin films were created by 16 keV O_2^+ ion beam and their growth mechanism characterized. Magnetic nano stripes have been made on both Si (100) and ZnO thin film by implantation of Fe ion on prefabricated ion induced nano structures. To investigate the origin of ion induced nanostructure formation the effect of mass, molecular and chemical effect of the projectile has been studied. For this experiment, we bombarded cleaned Si(100) surfaces with He^+, Ar^+, N^+, N_2^+ O^+ and O_2^+ projectiles keeping the ion beam energy (10 keV) and fluence same. The data for above experiments is being analysed at present.

ELECTRON LINAC

Photo-fission of actinide targets is a highly promising route for producing neutron-rich exotic nuclei and radioactive ion beams. With this aim we have undertaken a programme on design and development of a 10/50 MeV, 100 kW, super-conducting CW electron linac to be used as a photo-fission driver for the RIB facility. VECC and TRIUMF laboratory, Canada will be collaborating on the e-Linac development. In the first phase, a 10 MeV injector will be jointly built.

Schematic layout of a 50 MeV e-Linac is shown in Fig.7. The e-Linac consists of *Injector* and *Accelerator* sections and is based on 1.3 GHz, 2K SRF technology. The *Injector* comprises of an electron gun, buncher, low energy beam transport line (LEBT) and an Injector Cryo Module (ICM) which is the most critical component of the e-Linac. The injector is followed by an Accelerator Cryo Module (ACM) consisting of two 9-cell Niobium cavities. Two ACM will be needed to reach 50 MeV.

The beam dynamics design of the e-Linac has been completed [12] and mechanical engineering design of the cryostat is underway. The Niobium cavities are being fabricated by TRIUMF at M/s PAVAC, Vancouver. The plan is to jointly design the e-Linac as well as to construct and test two ICMs, one for each institute, at TRIUMF to study all the engineering and beam acceleration related issues. The front end of the injector apart from the ICM is being separately built at VECC.

SUMMARY & OUTLOOK

The status of RIB project at VECC Kolkata has been presented. The facility is at present delivering stable heavy-ion beams. At the moment experiments can be performed at three experiment stations – one at the ECR mass separator focal point and the others at the end of the 1.7m and 3.4m RFQ. The post-accelerator is installed till LINAC-3. Beams have been accelerated to 289 keV/u and very soon beam commissioning of LINAC-3, taking the beam energy to 415 keV/u, is planned.

The present RIB facility is being built around the K=130 cyclotron. We are also planning to use photo-fission route for the production of neutron rich RIB. For this purpose we have undertaken a programme to develop a 10/50 MeV, 100 kW super-conducting electron Linac. In the first phase the 10 MeV Injector will be designed and developed. A memorandum of understanding has been signed between VECC and TRIUMF for technical collaboration on superconducting electron linac development.

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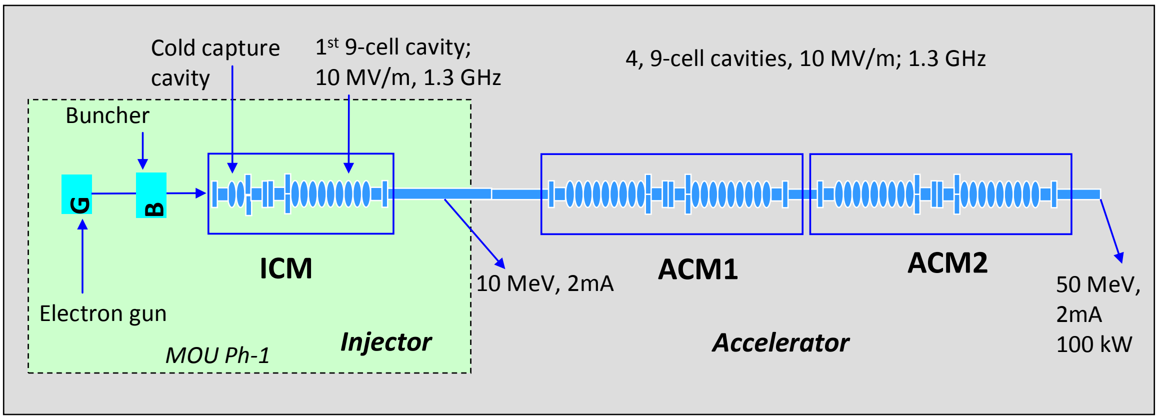

Figure 7: Block diagram listing the components of the 50 MeV superconducting electron linac.