Commissioning of fifth heavy-ion Linac module and beam acceleration to 1 MeV/u

Successful acceleration of Nitrogen ion-beam to energy of 1 MeV/u was achieved recently in the VECC Rare Isotope Beam (RIB) facility. The design and operation of the heavy-ion accelerator for the ANURIB project has been validated on completion of the beam trials. The most critical part of the commissioning was time synchronized operation of eleven rf accelerator modules in phase matched condition at the required acceleration voltage. It may be mentioned that more than 90% of the components in the RIB facility are indigenously developed including the rf Solid State Amplifiers (SSA) that were used in the recent beam trials. The above exercise also has validated the SSA for site operating conditions.

Upstream of the fifth heavy-ion Linac module (L5), the RIB facility has a Radio Frequency Quadrupole linac (RFQ) which is the first post-accelerator that accelerates 1.75 keVu ion-beam from an Electron Cyclotron Resonance ion-source (ECR) to an energy of about 100 keV/u. Thereafter a total of five heavy-ion Linac modules (L1 – L5) and five rf rebunchers (RB1-RB5) are installed. A schematic of the RIB facility is shown in Fig.1 whereas Fig.2 shows a photograph of the high energy section beyond L3 (415 keV/u). The operating frequency of the RFQ, L1, L2, RB1-RB3 is 37.8 MHz whereas it is 75.6 MHz for L3-L5, RB4 and RB5. Beam energy for L4 is 715 keV/u, corroborated from the measurement of beam particles in a calibrated silicon detector.

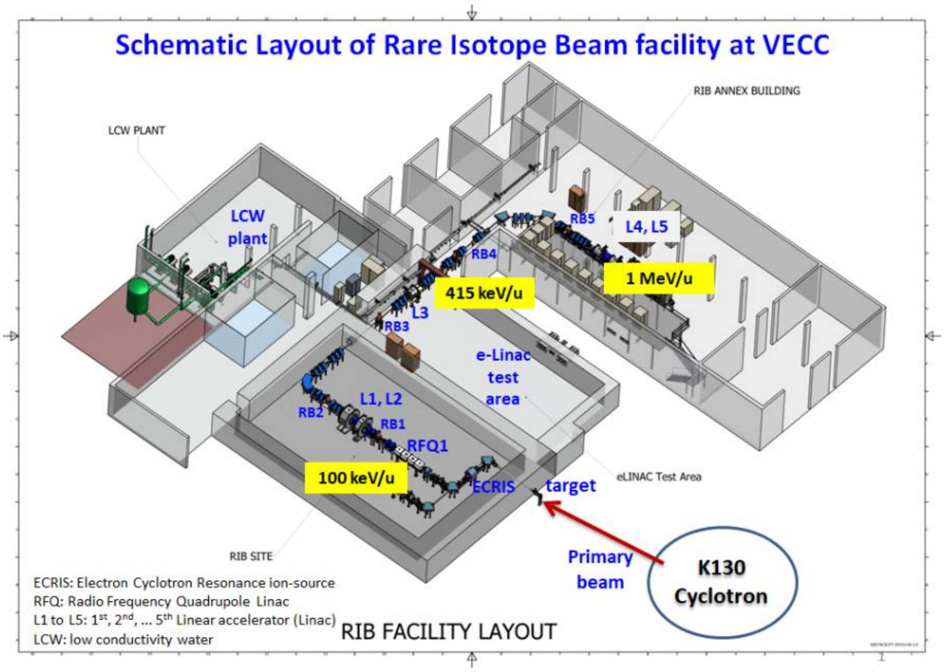

Figure 1. Schematic of RIB facility in VECC Kolkata.

Figure 2. A photograph showing the 4th and 5th heavy-ion linac module L4, L5 in the RIB facility.

During the beam trials, the 715 keV/u beam accelerated in L4 was further accelerated in the L5 energised to calculated rf power of 5.5 kW. The intermediate quadrupole magnets were tuned to values corresponding to the beam energy of 1 MeV/u. The beam current for the nitrogen beam accelerated through L5 measured in a Faraday Cup placed at the end of beam line was 20 nA. Using energy attenuation method through thin aluminium foils, the beam energy was first corroborated to be >920 keV/u through a 8.9 micron foil and subsequently through a foil of thickness 10.4 micron to be 1.04 MeV/u while the RF power and phase of the L5 was fine tuned. Earlier several RIB and SIB (stable isotope beam) such as ^{11}C, ^{14}O, ^{42,43}K, ^{111}In (RIB) and ^{11}B, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{40}Ar have been produced in the RIB facility. While the RIB has been developed for proof of principle technology demonstration aimed at ANURIB, the SIB is used as pilot beam for setting the parameters of the heavy-ion accelerator and also used in stand-alone mode for ion-beam based research.

Online development of $11C^{1+}$ RIB using gas jet coupled ECRIS

A 2.45 GHz electron cyclotron resonance (ECR) ion source coupled to a gas-jet skimmer system has been developed for the online production of radioactive ion beams (RIBs). Using radial injection of gas jet in the ion source, RIBs of $^{11}C^{1+}$, $^{11}CO2^{1+}$, and $^{11}CO^{1+}$ have been produced online with beam intensity up to about 9×10^3 particles per second for a 1 μA , 10 MeV proton beam from K = 130 Variable Energy Cyclotron Centre bombarding a nitrogen gas target. The production route utilised is $^{14}N\ (p,\alpha)^{11}C$ and half-life of ^{11}C is 20 min. Using Gas Jet Recoil Transport technique, radioactive gas jet was transported from production site at cyclotron vault to RIB experimental site using a long capillary and injected into a 2.45 GHz ECR ion source through a skimmer connected to its vertical port (shown in Fig 3). A porous catcher was placed projected into the plasma chamber where the recoils were stopped, release of recoils from the catcher was facilitated by the microwave applied to the plasma chamber.

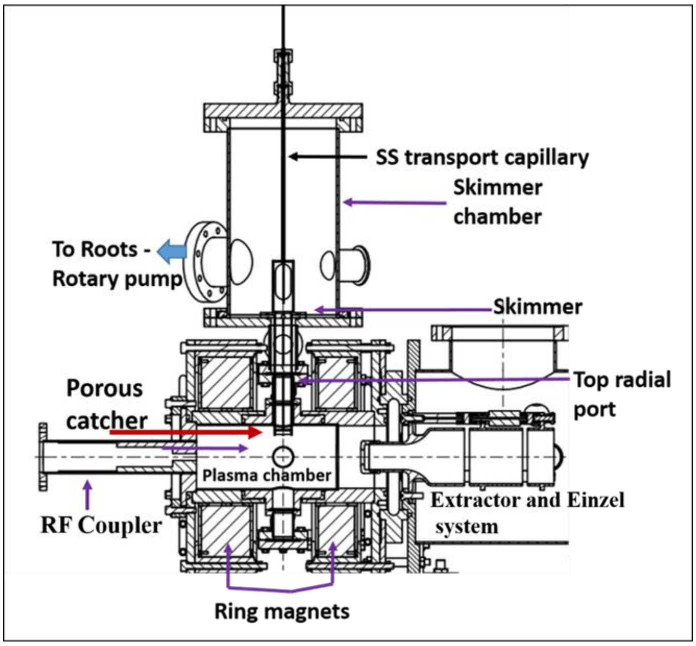

Fig 3. Cross sectional view of the 2.45 GHz ECR source showing the position of the catcher for stopping of the injected recoils

Analyser magnet downstream of ECR source was separately tuned for implantation of $^{11}CO_2^{1+}$, $^{11}C^{1+}$ and $^{11}CO^{1+}$ on an Al catcher after the magnet. HpGe detectors were placed near the skimmer, after the ion source (FC1) and after analyser magnet (FC2) during implantation of beam at the catchers placed at these positions (shown in Fig 4). Post implantation, catchers were offloaded from beamline and placed near a remote detector for measurement of the actual activity.

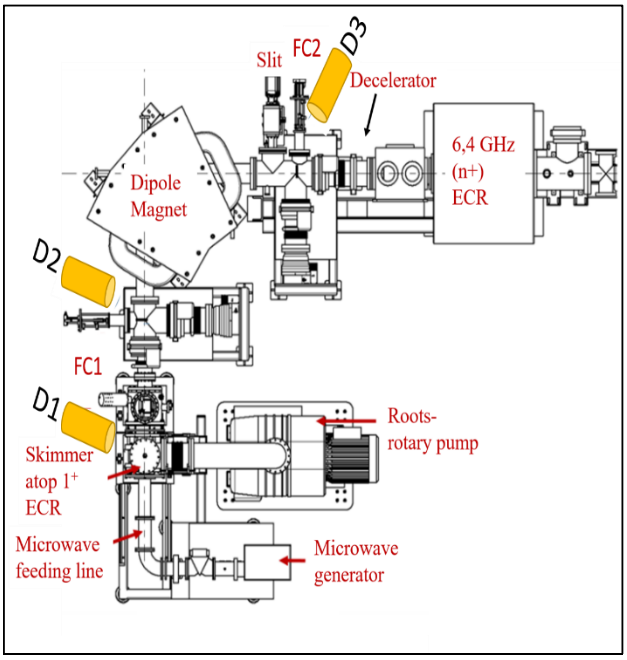

Figure 4. Layout of the components between the 2.45 GHz gas jet coupled ECR source to the 6.4 GHz ECR source. Position of the Faraday Cups and the HpGe detectors used in the experiment are shown

Intensity of $^{11}C^{1+}$ measured at various locations are tabulated below.

TABLE I. RIB intensity at various locations.

(1) Intensity at skimmer (pps)	(2) Intensity at FC1 (pps)	(3) Intensity at FC2 (pps)		Efficiency (3)/(1) (%)
$(2.2 \pm 0.08) \times 10^5$	$(1.4 \pm 0.1) \times 10^4$	$^{11}C^{1+}$	$(6.6 \pm 0.4) \times 10^2$	6.3 ± 0.4
		$^{11}CO_2^{1+}$	$(8.9 \pm 0.7) \times 10^3$	
		$^{11}CO^{1+}$	$(4.3 \pm 0.2) \times 10^3$	

Development of Multi-charged ^{11}B using plasma induced heating

Boron ion beams in multiple charge states were developed using lithium tetrafluoroborate ($LiBF_4$) as a solid precursor in a 6.4 GHz electron cyclotron resonance (ECR) ion source. $LiBF_4$ pellet was axially inserted into the plasma chamber using a linear motion feedthrough, and plasma-induced heating was utilized for in-situ generation of boron ion beams without the use of an external oven with nitrogen used as supporting gas. Under optimized operating conditions, boron beams in charge states B^{+}, B^{2+}, and B^{3+} were produced and identified using a dipole magnet. Optimised parameters for efficient production for B^{2+} generation has been tabulated below.

Table 2. Optimised parameters for B^{2+} generation

Supporting gas	N_2	Ion source Extraction voltage	9.6 kV
Operating pressure	2.79×10^{-6} mbar	Einzel lens voltage	6.4 kV
RF Power	54 W		

Schematic layout of the 6.4 GHz ECRIS with solid $LiBF_4$ mounted and the current recorded for different charge state species after the analysing magnet are shown in Figure 5.

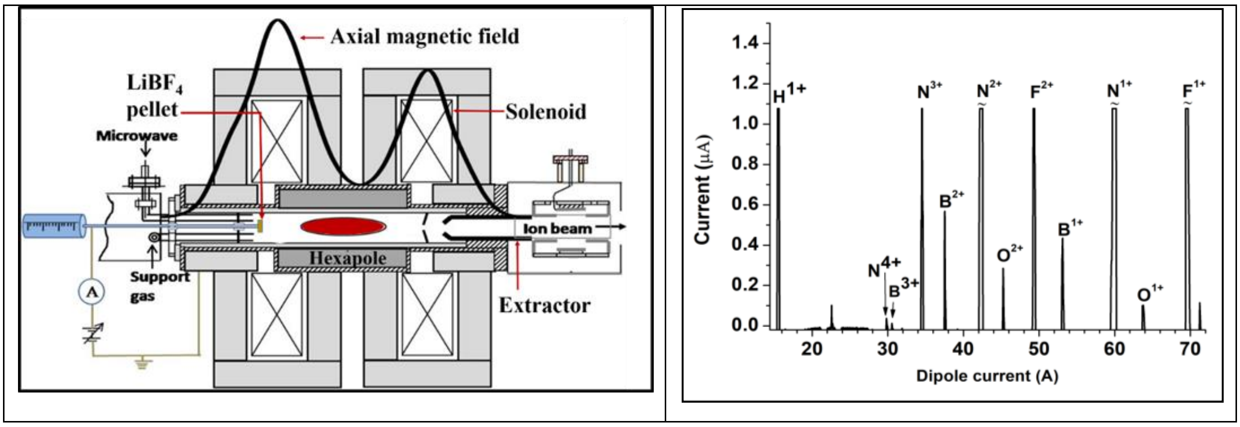

Fig 5. (a) The 6.4 GHz ECR ions source and the position of the LiBF4 sample inside plasma chamber (b) Multi-charged Boron peaks identified in the q/A spectrum after analyser magnet.

B^{2+} has been accelerated through downstream RFQ to 1.1 MeV and Linac I to 2.05 MeV. The current measured after RFQ and Linac I is 700 nA and 120 nA respectively. The motivation for the present endeavour is to develop pilot beam for RIB acceleration ^{11}C.