RADIOACTIVE ION BEAMS PROGRAMME AT VECC-KOLKATA, INDIAN EFFORTS

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Abstract

An ISOL type Radioactive Ion Beam (RIB) facility has been built at VECC with *K*130 cyclotron that delivers proton and alpha particle beams as the driver accelerator. So far ion beams of $A/q \leq 14$ have been accelerated up to 414 keV/u using a Radio Frequency Quadrupole (RFQ) linac and three IH-Linacs. Two more IH Linac modules are being added to increase the energy to 1.0 MeV/u. A few RIBs have been accelerated with typical intensities of 10^3 to 10^4 pps at the separator focal plane.

In the next phase, the plan is to construct a new facility called ANURIB (Advanced National facility for Unstable and Rare Isotope Beams) at the upcoming new campus of VECC at New Town in Kolkata. ANURIB aims to attract a wider user community in nuclear physics, nuclear-astrophysics, and materials science and is being built as a national facility. There will be two primary accelerators in ANURIB aimed at producing both neutron-rich and proton-rich beams. One is a 50 MeV 100 kW superconducting electron linac photo-fission driver that is being developed in collaboration with TRIUMF Canada and the other a 50 MeV proton injector to be developed indigenously. To be built in phases starting from low energy of few keV/u in Phase-I to a final energy of 100 MeV/u in Phase-II, ANURIB will be a combined ISOL and PFS type facility.

INTRODUCTION

It was in the mid-nineties that the idea of developing a Radioactive Ion Beam facility took shape at VECC, prompted by exciting physics opportunities in study of exotic nuclei that led to activities world-wide for construction of RIB facilities. It was realized that this would need design and development of advanced accelerators, ion-sources and detector systems. It was decided: a) to proceed in small R&D steps to acquire the capability, and b) to collaborate with an international laboratory that has already started working in this field and has the experience of designing and building advanced accelerators.

To meet these objectives and to keep the budget small, it was decided to use the existing *K*130 room temperature cyclotron as the driver or the primary accelerator and construct an ISOL type RIB facility around the same [1-3]. A collaboration agreement with RIKEN, where RI Beam Factory project was just about to start, was signed in 1996. The VECC RIB project received some seed money in 1998 for design of the facility. Funding for construction of accelerators was made available in 2003 and again in 2007. These have led to development of a number of linear accelerators [4-10], the physics designs of which were mostly done in collaboration with RIKEN. Also, facilities for material science and laser spectroscopy of exotic nuclei have been built. Proton and alpha particle beams from the cyclotron have been used to produce rare isotopes using suitable targets. Using a gas-jet recoil transport coupled ECR technique [11, 12] radioactive atoms, ion beams of ^{14}O ($t_{1/2}$=71 sec), ^{42}K ($t_{1/2}$=12.4 hrs), ^{43}K ($t_{1/2}$=22.2 hrs), ^{41}Ar ($t_{1/2}$=109 min) have been produced at the facility. RIB of ^{111}In ($t_{1/2}$= 2.8 d) has been developed in the off-line mode.

ACCELERATOR DEVELOPMENT

A layout of the facility is shown in Fig. 1. The scheme is to produce rare isotopes using a suitable target in alpha/proton induced nuclear reactions, ionize the reaction products in two ion-sources in tandem [2, 6], mass separate the reaction products to choose the rare isotope of interest and finally accelerate the beam in a series of linear accelerators. The charge breeder is an ECR ion-source operating at 6.4 GHz. The post- accelerators are – a Radio Frequency Quadrupole (RFQ) linac that accelerates heavy-ions of $A/q \leq 14$ to 100 keV/u, followed by five IH linac tanks for further acceleration to 1 MeV/u. Two superconducting QWR modules to boost the energy to 2 MeV/u are also planned.

First, a 1.7 metre long RFQ [4, 5, 8] was constructed with the aim to study machining and fabrication aspects and conduct comprehensive beam tests. Commissioned in September 2005 this was the first RFQ to be built in India and was a major milestone in the RIB project. Operating in CW mode at 33.7 MHz, this RFQ accelerates ion beams from energy 1.38 to 29 keV/u. Typical measured beam transmission is 85%. This RFQ is now a part of the material science beam-line (Figure 1). A second RFQ (Fig. 2), operating at 37.8 MHz and 3.4 m long has been commissioned in year 2008 [9]. The high power RF sources for RFQ and linacs have been developed indigenously in collaboration with SAMEER, Mumbai. The critical components of the RFQ viz. the copper electrodes and supporting posts have been machined at Central Mechanical Engineering Research Institute, a CSIR laboratory at Durgapur, 200 km from Kolkata. Other components have been made in Indian industry.

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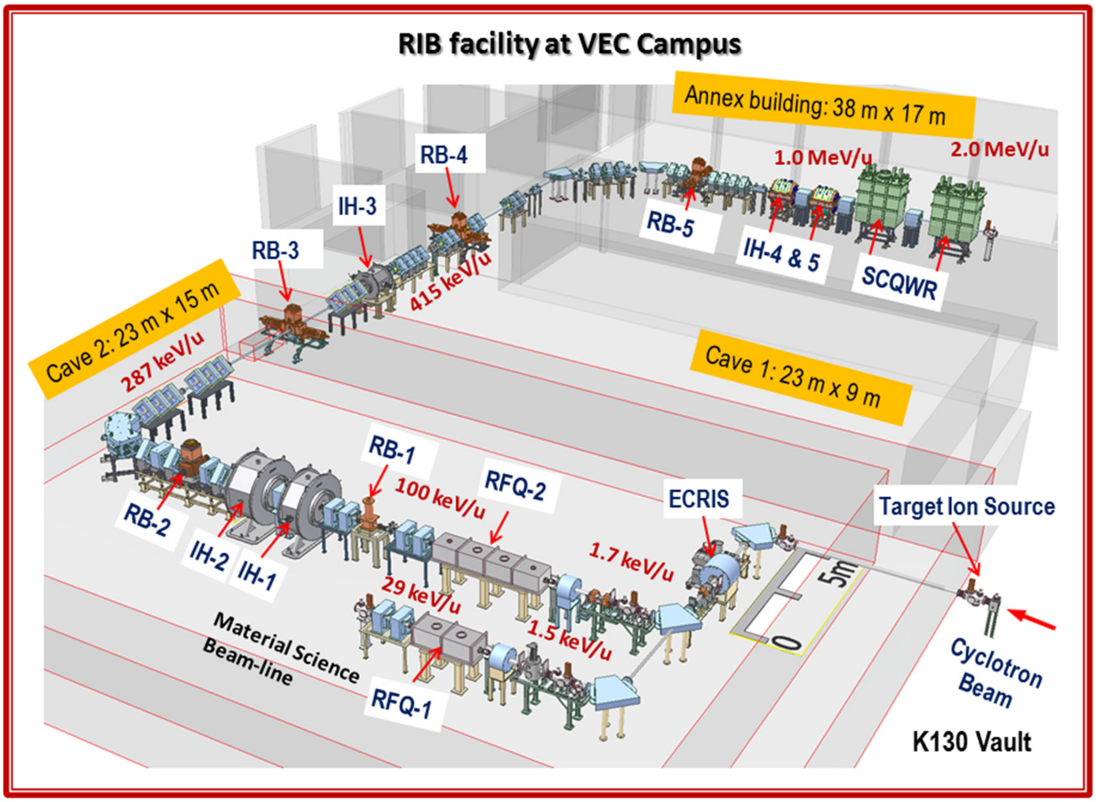

Figure 1: Layout of the RIB facility at VECC Kolkata.

The first three Linac modules have also been designed and built indigenously. Facility up to third linac (Linac-3) has been successfully commissioned by accelerating $^{14}N^{4+}$ beam to 414 keV/u (5.8 MeV) in year 2010 [7].The first two Linacs operate at 37.8 MHz and the subsequent ones, third to fifth, operate at 75.6 MHz. After the third Linac (Fig. 3) a charge stripper would be used for obtaining *A/q* of 7 needed for Linac 4& 5.

Linacs 4 & 5 have already been fabricated and are awaiting installation in a 20 m long beam line [10] that additionally has several quadrupoles, di-poles and bunchers. These are to be housed in a new annex building which is almost complete. The 1.0 MeV/u beam after Linac-5 will be accelerated further to about 2 MeV/u in two super-conducting heavy-ion QWR modules. The design and development of the Superconducting QWR linacs is now in progress in collaboration with TRIUMF.

A good deal of R&D effort has gone into designing targets for RIB production, ion sources, and for trying out various techniques for RIB production. Apart from these studies, the stable ion beams from the facility have been regularly used for material science research especially for ion beam induced nano-structure formation and studies on room temperature ferro-magnetism in ZnO and other oxides. Also a laser spectroscopy hut has been set up for pursuing quantum optics studies relevant to photo-ionization and for measurements of atomic hyperfine splitting and isotopic shift of exotic nuclei using collinear laser spectroscopy.

Experiments to study decay spectroscopy of short-lived nuclei are being planned / carried out using the low energy RI Beams. These efforts together with accelerator design and development have so far led to about 60 publications in Journals and 7 *PhD* theses.

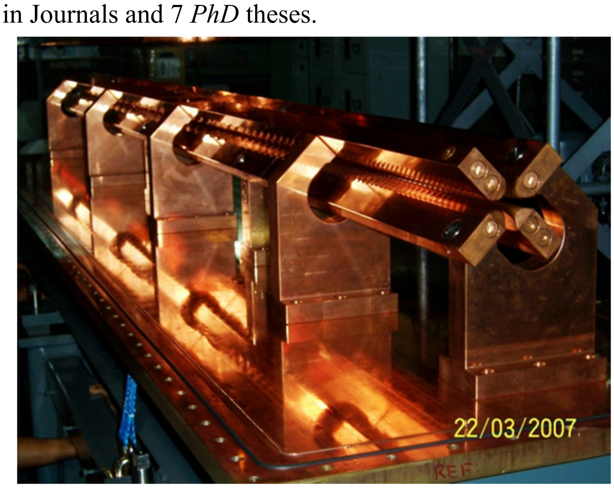

Figure 2: Photograph of the internal post-vane structure of 3.4 m long RFQ linac taken during installation at VECC.

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ANURIB – VECC'S UPCOMING FLAGSHIP PROJECT

The next step for us is to take up the development of an internationally competitive RIB facility, named ANURIB (**A**dvanced **N**ational facility for **U**nstable and **R**are **I**sotope **B**eams), as the flagship project of the centre [13, 14]. The ANURIB will be a green-field project and will be built at VECC's new 25 acre campus in New Town, Kolkata. An International Advisory Committee has been constituted by Department of Atomic Energy to review the ANURIB project proposal. The committee gave a favourable recommendation, accepted the entire proposal, and suggested several measures for speedy and successful implementation of ANURIB.

The RIB production and acceleration scheme in ANURIB is shown in figure 4. A 50 MeV, 100 kW cw electron linac and a high current proton accelerator would be the driver accelerators for production of neutron-rich & proton-rich isotopes. The facility has been planned such that experiments can be done at each stage of development. The physics opportunities that will open up at various stages are indicated in figure 4. After initial acceleration in RFQ and room temperature linacs, Superconducting Linac Boosters (SLBs) will increase the beam energy to around 7 MeV/u opening up the regime of coulomb barrier physics and production of Super Heavy Nuclei (SHE) using RIBs as well as Stable Ion Beams. For ANURIB a novel acceleration scheme using Asymmetric Alternate Phase Focussing will be employed in the SLBs that would allow simultaneous acceleration of multiple charge states of heavy-ions [15, 16].

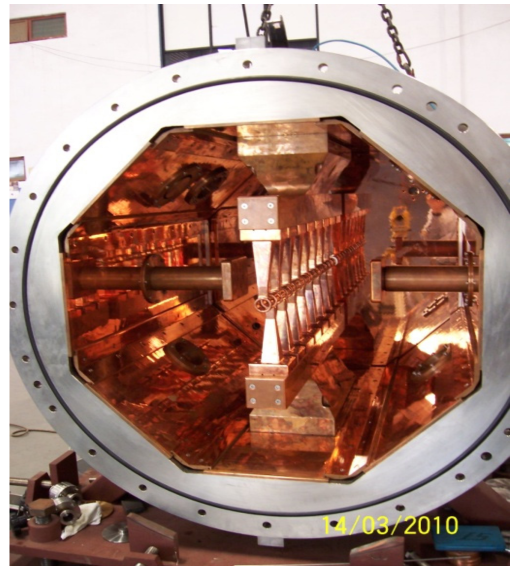

Figure 3: Photograph showing third heavy-ion Linac module with the front cover open. Designed at VECC this linac was fabricated in an industry at Bangalore.

A separated sector cyclotron will be used to accelerate 7 MeV/u beams after the SLB to about 100 MeV/u. The fragmentation of these RIBs in a secondary target is expected to produce highly exotic rare isotopes, which cannot be sufficiently produced through fragmentation of stable ion beams [17]. Also 5 to 7 MeV/u beams of p-rich nuclei are very effective in producing very exotic p-rich species using compound nuclear evaporation reactions.

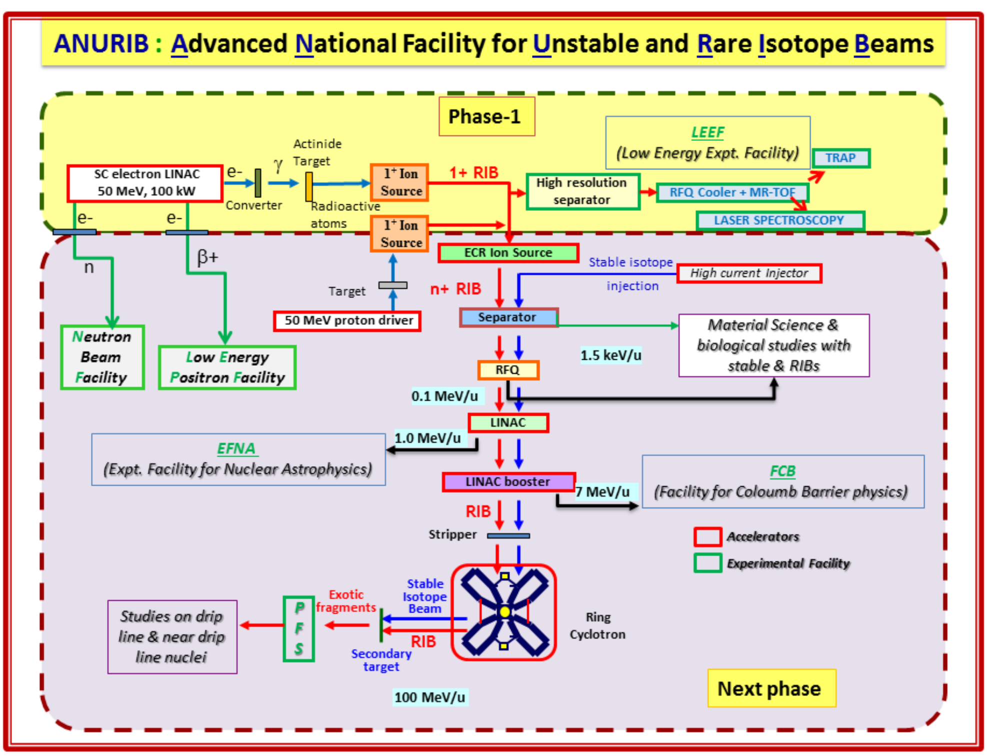

Figure 4: Schematic layout of ANURIB facility.

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ANURIB will be built in two phases with an estimated budget of Rs. 1200 crores and will need 12 years for completion. In 2013, the project has received funding for phase-1. In this phase (2013-2020) the electron driver accelerator, electron target module and low energy experimental facility (LEEF) will be built along with the phase-1 building. Facilities such as RFQ cooler and buncher, Multiple Reflection Time of Flight spectrometer, Penning traps, and Laser spectroscopy set up, are being planned for LEEF along with Neutron and the Positron beam lines for multidisciplinary research.

The superconducting electron accelerator (e-Linac) [18], presently under development jointly with TRIUMF, will be the main driver accelerators for ANURIB. An identical machine is being built at TRIUMF for the ARIEL-Advanced Rare Isotope Laboratory project. In the e-Linac, electron beam from a 300 kV thermionic gun will be accelerated first to 10 MeV in an Injector Cryo-Module (ICM) housing one 1.3 GHz, 2K 9-cell cavity. The 10 MeV electron beam would be then accelerated to 50 MeV in two Accelerator Cryo-Modules (ACM) each housing two 9-cell cavities. Last year in a test run at TRIUMF, electron beam has been accelerated to 23 MeV using the ICM and one nine cell cavity inside the ACM1. A second ICM meant for VECC is presently under construction at TRIUMF (figure 5.) and is scheduled to be tested in early 2016.

Figure 5: Injector Cryo Module for the VECC superconducting Electron Linac (e-Linac) at TRIUMF.

The electron accelerator will produce neutron-rich rare isotopes through gamma induced fission of actinides. The design and development of actinide target capable of handling high beam power is a challenging task, and is also being pursued jointly with TRIUMF.

The use of electron driver for production of *n*-rich RI Beams, combination of both ISOL and PFS methods, fragmentation and fusion reactions with RI Beams, and availability of intense stable heavy-ion beams together would make ANURIB an internationally competitive facility.

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