Rare ion beams – the new road to understand the universe

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The last three decades have seen enormous progress in our ability to produce new nuclei. Driven by the first construction of powerful heavy-ion and light-ion accelerators and more recently, with the advent of rare isotope beams – also called radioactive ion beams (RIBs), the field of low energy nuclear physics is now vibrant with new possibilities. On one hand, the community now understands the nucleus and its central role in the creation of elements in the universe with more confidence, while on the other, new and surprising discoveries of nuclear halo, new magic numbers and regions of deformation, to name a few, entice us to probe for more. RIBs with their promise of making accessible hitherto unexplored regions of the nuclear chart and enhanced intensity for already synthesized nuclei has clearly emerged as the frontier of low energy nuclear physics. Apart from nuclear physics and astrophysics, RIBs open up new areas in materials research and biology, and provide an alternative route for medical isotope production. Further, the accelerator technology needed for producing these beams has led to the development of particle therapy machines for treatment of cancer and ion beam applications in industry. This article reviews the present scenario of physics and technology of RIBs and discusses VECC's efforts and contribution in this field and future plans vis-à-vis the upcoming ANURIB project.

Keywords: Accelerators, ion source, linac, nucleosynthesis, radioactive ion beams.

RARE isotope beams or radioactive ion beams (RIBs) represent the latest trend in nuclear physics[1,2]. Availability of these rather exotic beams would allow us to understand the many-body system called the atomic nucleus, the limits of nuclear stability, neutron star – the largest atomic nucleus in nature, and nucleosynthesis or the process of element creation in stars that provides direct clue to our 'cosmic connection'. RIBs would also allow us to test the deviation from *V–A* theory of beta-decay and some of the fundamental symmetries of nature, such as the time-reversal symmetry. RIBs are thus necessary to understand the world around us, be it the stars and the galaxies, our Sun and the planet we live in, or life itself.

North America, Europe led by Germany and France, and Japan have constructed RIB accelerators and are planning for more powerful next-generation facilities, whereas China and Korea are planning mega billion dollar RIB facilities. In India, the Variable Energy Cyclotron Centre (VECC) at Kolkata has made a beginning a decade ago, albeit on a modest scale, to develop a low energy RIB facility. Built with extensive R&D and indigenous effort, ably supported by Indian industry and national as well as international collaborators, a number of state-of-the-art accelerators have been built and we have successfully accelerated first radioactive ion beams in the year 2012. The VECC facility continues to be a test bench for new R&D on RIB physics and technology while we embark on a new journey towards construction of the next generation facility in the country, named ANURIB (Advanced National Facility for Unstable and Rare Ion Beams). The physics with RIB and technological issues related to accelerators for producing RIB are discussed in this article.

The physics case of RIB

There are close to 300 isotopes available in nature. In the *N–Z* chart (Figure 1), these are represented by black dots. These isotopes are either stable with respect to beta-particle decay (heavier ones undergo alpha-particle decay) or have half-lives that are comparable with the age of the Earth, which is 4.5 billion years. Together these black dots form in *N–Z* chart, the so-called valley of beta-stability. Mass formulae, however, predict existence of more than 6000 stable (nuclear force allows them to remain bound) nuclei, which decay only because of the existence of weak interaction. These nuclei undergo beta decay and since this is a weak interaction process, they

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have half-lives long enough, from a few microseconds to several years. Their finite life-time allows one to produce energetic beams of these nuclei, called RIBs.

The experimental studies over the last three decades on rare isotopes lying away from the valley of beta-stability – the so-called exotic nuclei, clearly reveal that our understanding of atomic nucleus based on beta-stable nuclei is grossly inadequate. The exotic nuclei display many unusual and surprising properties, quite different from the nuclei closer to the valley of beta-stability. Completely new phenomena like nuclear halo[3], nuclear skin, exotic shapes[4] and decay modes, new magic numbers[5–7] (at $N = 16$ and 32) and weakening of shell structure at conventional shell closures have been discovered.

The atomic nucleus is a finite many-body system of nucleons, whose properties are determined by a delicate interplay of three fundamental interactions – the strong, electromagnetic and weak forces. The inadequacy of the theoretical models to predict the properties of exotic nuclei not only limits our understanding of the atomic nucleus but also that of stellar evolution and nucleosynthesis, where exotic nuclei play an important role. To achieve the goal of developing theoretical models that would be able to predict the properties of nuclei spanning the entire nuclear landscape, the first step would be to create a substantial data bank on exotic nuclei (properties such as masses, half-lives, excited states, decay properties) and their reaction rates with proton, neutron and alpha particles, which the theory should be able to reproduce.

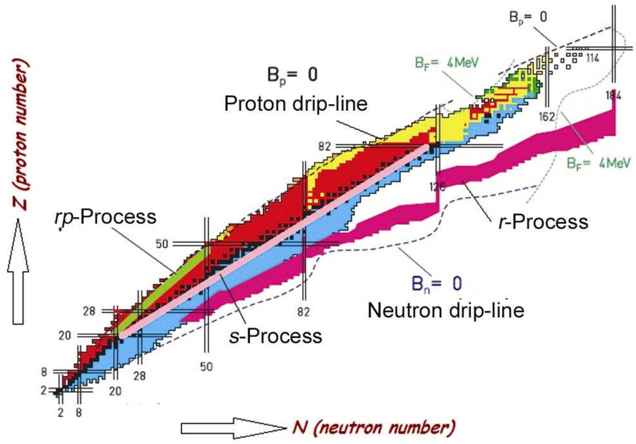

Figure 1. The N–Z chart or table of nuclides representing a map of the isotopes (courtesy: The Physics Case for EURISOL; http://pro.ganil-spiral2.eu/eurisol). The neutron number is plotted on the x-axis while the proton number that identifies an element is plotted on the y-axis. Black dots represent beta-stable nuclei and their locus is called the valley of beta-stability. On the left of the valley are proton-rich (p-rich) nuclei that undergo β^+ decay (red) or α-particle decay (yellow), while on the right are neutron-rich (n-rich) nuclei that decay by β-emission. The dotted lines show the limits of particle stability, i.e. on these lines the one proton (neutron) separation energy B_p (B_n) = 0 and beyond these limits the nuclei are no longer bound. The white region between the drip-lines represents nuclei yet to be synthesized. The nuclides participate in a network of nuclear reactions leading to element synthesis in the universe. Some major nucleo-synthesis processes depicted on the chart are rapid proton capture process (rp-process – green) and rapid neutron capture process (r-process – magenta) that involve nuclei close to the drip-lines, many yet to be synthesized in the laboratory. The slow neutron capture process (s-process – pink) involves beta-stable or close to stability nuclei. High neutron flux for low energy neutrons is needed for the study of s-process.

We are made up of elements that were created and are getting continuously created in various stellar environments[8]. Element creation started microseconds after the big bang. After a few minutes of the big bang, the universe was left with mainly hydrogen and helium, and a very small amount of heavier nuclei such as Li, Be, B, etc. Nucleosynthesis stopped thereafter and started again in stellar interiors after a long gap of a few hundred million years when stars were born from hydrogen nebulae. Hydrogen, helium and the tiny fraction of other heavier elements produced during the first 15–20 min after the big bang provided the seed for the synthesis of heavier elements.

The creation of elements in stars takes place via a network of nuclear reactions or nucleosynthesis processes[9]. For light nuclei up to iron, fusion is the predominant reaction because of favourable energy balance, while nuclei heavier than iron are created in neutron-capture (s- and r-process), proton-capture (rp- and p-process) and alpha particle capture reactions (Figure 1). Weak interaction plays a crucial role in the formation of alpha particle and hence carbon. Also in s- and r-process nucleosynthesis, nuclear beta decay leads to the creation of heavier elements. Short-lived neutron-rich (n-rich) and proton-rich (p-rich) isotopes play a key role in rapid neutron capture (r-process) and rapid proton capture (rp-process) respectively that can take place only in explosive stellar events such as a type-II supernova explosion, X-ray bursts, etc. Without these rapid processes, it is impossible to understand the origin of elements in old stars and in our solar system.

Apart from nuclear physics and astrophysics, RIBs have great potential for research in materials science[10]. Radioactive ions can be implanted at controlled depths, their decay introduces time-dependent changes in the sample and the emitted radiation becomes the courier for information about the lattice environment surrounding the implanted probe. Techniques like Mössbauer spectroscopy, Perturbed Angular Correlation (PAC), β-NMR and Emission Channelling (EC) are being used with rare isotopes for investigations of condensed matter systems. RIBs would also help in the creation of nuclear data crucial for advanced nuclear reactor design and also potentially produce varieties of radioisotopes for diagnostic and therapeutic purposes. Further, any RIB facility by default remains a powerful stable isotope beam facility. Thus the wide variety of beams in terms of ion species, beam energy and intensity from a RIB facility will open up great opportunities for multidisciplinary research and myriad applications.

Production of RIBs

Radioactive ion beams are energetic beams of radioactive isotopes that are produced through nuclear reactions between targets and energetic ion beams, both made of stable isotopes. The beam energy should at least be higher than the Coulomb barrier to allow nuclear reactions. Beams of radioactive ions are thus often termed as secondary ion beams. One can use different nuclear reaction routes such as the compound nuclear reaction (for *p*-rich isotopes), fission of actinides (for *n*-rich isotopes in the range $30 < Z < 60$), high energy proton-induced spallation, and high energy heavy ion projectile fragmentation reactions (for both *p*- and *n*-rich isotopes over a large region of the *N–Z* chart) to produce these isotopes. The projectile fragmentation and spallation reactions are the most versatile with larger reach in both *p*- and *n*-rich regions of the nuclear chart. Since any nuclear reaction produces a large number of isotopes, it is necessary to separate the isotope of interest from the rest. The isotopes produced in projectile fragmentation reactions are emitted in a small cone in the forward angle with almost the beam velocity. These fragments are often fully stripped, and can be separated in-flight in a Projectile Fragment Separator (PFS), which is essentially a long beam-line with multiple magnetic separation stages to effect a reasonably clean separation (Figure 2). The final focal plane usually contains the isotope of interest and a few other undesirable isotopes (cocktail beams). A clean separation is extremely difficult since isotopes are produced with large momentum spread and widely different cross-sections varying over almost six orders of magnitudes.

The other method (Figure 2) is called the Isotope Separation On Line (ISOL) method. In this method the reaction products are stopped inside the target, allowed to diffuse out of the target as neutral atoms, ionized in an ion source (usually in two ion sources used in tandem with an intermediate separation stage to boost the charge state to values suitable for acceleration), extracted from the ion source usually at a few tens of keV energies, mass-separated, and finally accelerated in linear accelerators or cyclotrons. In the ISOL method, because of the delay associated with the process of diffusion and ionization, the half-lives of rare isotopes that can be studied/accelerated are limited to a few hundred milliseconds, except for gases and alkaline earths, where the limit may be 10 ms. However, the beam is much pure (as opposed to a cocktail beam in the PFS method). In this method typically beam is accelerated to energy of around 5–10 million electron volt per nucleon (MeV/u) to enable physics experiments around Coulomb barrier, where most of the nuclear physics interest lies. The PFS method delivers a much higher energy beam with no limitation of half-life for the species. The ISOL and PFS methods are thus complementary and the latest trend is to build RIB facilities that include both these features.

The poor intensity of RIBs beams poses a great challenge to the facility developers as well as experimenters. Since nucleus is a tiny object, the total probability or cross-section for nuclear reactions is only of the order of a barn (b) (one barn = 10^{-24} cm^2) and individual isotopes are produced with cross-sections ranging from a few tens of millibarn (mb) to a few microbarn (μb) for isotopes closer to drip-lines. To compensate for the low cross-section one needs to develop very high intensity primary beams, thick targets that can withstand the high-power beam and maximum efficiency for all the intermediate stages necessary for delivering a reasonably clean beam of the isotope of interest to the experimenters.

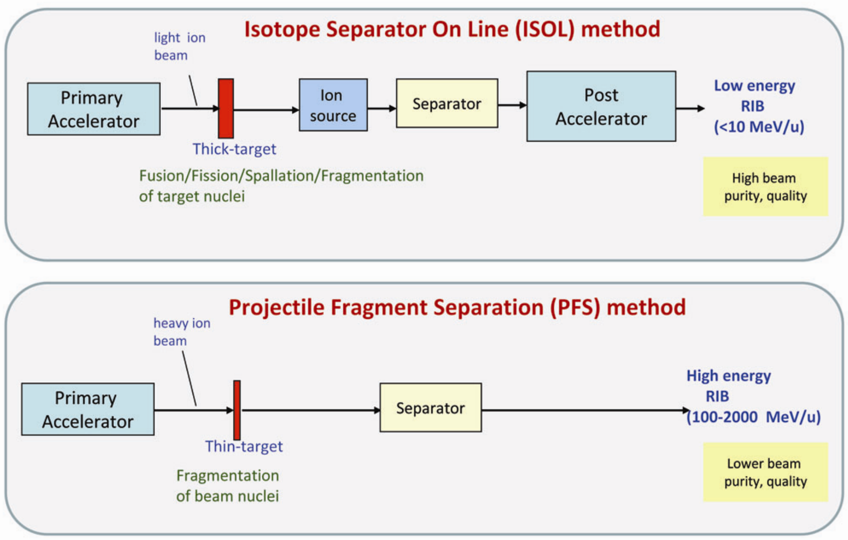

Figure 2. The two methods of producing rare isotope beams.

In many cases, intensities of one particle per second (pps) at the final focal plane, where the experiments are carried out, may be just adequate to allow identification of a new isotope and for measuring properties like mass, half-life, etc. But for detailed decay spectroscopy, production of super heavy elements (SHEs) and measurement of reaction cross-sections of astrophysical interest, one needs much higher intensities. Estimates show that RIB intensities of up to 10^9 pps will cover almost the entire phase-space of possible experiments.

The low intensity of RIBs poses a stiff challenge to experimenters to develop detectors with larger solid angle coverage[11,12], precision atomic traps[13,14] and novel detection techniques[15], storage rings[16,17], very high resolving power separators, including projectile fragment separators of large angular and momentum acceptance[18–20], and new detection techniques aiming at reducing the signal-to-noise ratio[21].

As mentioned earlier, the challenge for the facility builders is manifold. It starts with the primary accelerator that should produce high-intensity light/heavy ion beams of high enough energy. The next hurdle is the production target. In the PFS method, one aims to use high intensity (1E12 pps) beams of high energy (>100 MeV/u) heavy-ions and the beam loses only a part of its energy in the target. So, cooling of the target becomes a comparatively easier task and the target is often rotated to avoid degradation of the same spot by the beam. But cooling of the beam dump where most of the beam power is deposited becomes non-trivial, in fact, an extremely challenging problem. In the ISOL method, the production target itself poses a difficult technological hurdle, since a major fraction of the beam power gets deposited in the target. The requirement of efficient diffusion of radioactive atoms out of the target makes the target design even more complicated.

In ISOL-type RIB facilities, one needs to design a production target with the power handling capacity of 50 kW or more, which should allow simultaneously fast and efficient diffusion of rare isotopes from inside the target where they are produced to the outside, so that the atoms can reach an ion source closeby for ionization. The ion source is no less a hurdle. An ion source that can ionize all the elements of the periodic table with reasonable efficiency and satisfy all other requirements for post-acceleration of a ‘pure’ beam does not exist in practice. The next step is post-acceleration of RIBs. The design of highly efficient post accelerators maintaining the necessary beam quality of low energy and pulse width is not trivial and requires state-of-the-art accelerator development. In short, RIB development needs an intense R&D effort in all the areas of accelerator design and technology (such as development of highly specialized superconducting magnets, ion sources, superconducting cavities, superconducting radio frequency (SRF) technology, high-power radiofrequency sources and large high vacuum systems) and in high-power target technology.

International scenario

Several RIB facilities are operational worldwide and next-generation facilities are being planned[22]. This is testimony to the fact that RIB has been recognized internationally as one of the research frontiers for the future. The leading ISOL-type facilities are: ISOLDE at CERN; Louvain-la-Neuve facility at Université catholique de Louvain, Belgium; ISAC (TRIUMF) in Canada and SPIRAL (GANIL) in France. The PFS facilities are at GSI, Germany; GANIL, France; RI Beam Factory at RIKEN, Japan, and NSCL at Michigan State University (MSU), USA. Many facilities are under construction or in planning stage, such as FAIR facility at GSI, Germany; FRIB at MSU; SPIRAL-2 at GANIL; ARIEL at TRIUMF and the EURISOL project in Europe.

A number of projects are also underway in Asia. The upcoming facilities – CARIF in China and the Korean KARIA facility, both have over one billion dollar funding. The VEC-RIB facility at the Variable Energy Cyclotron Centre (VECC), Kolkata is close to commissioning and approval is awaited for the proposed ANURIB facility. Collaboration with various international laboratories is a common feature of all these facilities.

RIB efforts at VECC

It was in the late nineties that the proposal to develop a RIB facility took shape at VECC, prompted by the exciting physics that emerged from the study of exotic nuclei that led to enormous activity worldwide in the construction of RIB facilities. Given the R&D and highly challenging nature of the task involving design and development of advanced ion-sources, accelerators and detector systems, it was decided to proceed in steps and in a R&D mode, aiming at developing capabilities (and blueprints) for the ultimate construction of an internationally competitive RIB facility in the country. The capacity-building exercise should also include in a significant way experiments with stable and radioactive ion beams and facility development for the same. To meet these objectives, it was decided to construct an ISOL-type RIB facility around the VEC cyclotron as the driver or the primary accelerator[23]. The project received some seed money in 1998 and then adequate funding for construction of accelerators was made available in 2003 and again in 2007.

So far a number of linear accelerators, ion-sources, and facilities for ion beam-induced materials science and laser spectroscopy studies of exotic nuclei have been built. Also, proton and alpha particle beams from the cyclotron have been used to produce rare isotopes with suitable targets that include actinide targets. Using an innovative gas-jet recoil transport coupled ECR technique[24,25], radioactive ion beams of ^{14}O ($t_{1/2}$ = 71 s), ^{42}K ($t_{1/2}$ = 12.4 h), ^{43}K ($t_{1/2}$ = 22.2 h), ^{41}Ar ($t_{1/2}$ = 109 min), and ^{111}In ($t_{1/2}$ = 2.8 days) have been produced.

A schematic layout of the facility is shown in Figure 3. The scheme is to produce rare isotopes using a suitable target in alpha/proton-induced nuclear reactions, ionize the reaction products in an ion source, mass separate the reaction products to choose the rare isotope of interest and then accelerate the same in a series of linear accelerators. The ECR ion-source operating at 6.4 GHz was developed in-house at VECC. The first accelerator is a radio frequency quadrupole (RFQ) linac, followed by a number of heavy-ion linear accelator modules to boost the energy to about 1 MeV/u.

The RFQ linac is a unique accelerator that can bunch, focus and accelerate ion beams in a single structure with high transmission efficiency, especially for low-velocity beams. A state-of-the-art machine, the RFQ has been indigenously developed at VECC in various steps starting from physics design, prototype development and final construction. First a 1.7 m long RFQ[26,27] was constructed with the aim to study the machining and fabrication aspects as well as to 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. Argon, oxygen, nitrogen and iron ion beams have been accelerated through RFQ with transmission efficiency of 85%. Operating in CW mode at 33.7 MHz, the RFQ accelerates ion beams from energy 1.38 to 29 keV/u. The most critical components of RFQ are the copper electrodes and supporting posts. These have been machined at the CSIR-Central Mechanical Engineering Research Institute, Durgapur. Other components have been made in Indian industry. A second RFQ (Figure 4) has been commissioned in 2008 (refs 28, 29). This 3.4 m long RFQ is the first accelerator in the RIB facility and accelerates beam with $A/q = 14$ to an energy of 100 keV/u. The high-power RF sources for RFQ and linac were developed indigenously at SAMEER, Mumbai.

After the initial acceleration in RFQ, the beams are accelerated further using a number of IH-type linear accelerator modules to higher energy. Three linac modules have been indigenously designed and built so far. In these modules the 100 keV/u beam from RFQ is accelerated to about 415 keV/u. The first two linac modules operate at 37.8 MHz and the third one operates at 75.6 MHz (Figure 5)[30]. The three modules have been built in Indian industry and the commissioning with ion beam was successfully done in 2010 by accelerating 400 nA $^{14}N^{4+}$ beam to 414 keV/u (5.8 MeV). Two more linac modules (4 and 5) are being added to take the beam energy to 1.0 MeV/u and thereafter the beam will be accelerated to about 2 MeV/u in two super-conducting heavy-ion linac modules. The physics design of the ECR ion source, RFQ, and IH linac have been done in collaboration with RIKEN, Japan.

VECC has also taken up the task of designing and developing a high-power state-of-the-art superconducting electron accelerator[31] (Figure 6), which will be the main driver accelerator for the production of exotic neutron-rich isotopes in VECC's future RIB project. This activity is being pursued in collaboration with TRIUMF, Canada.

The design and development of production targets, new ion sources, RIB production, ionization and acceleration are by themselves highly R&D-intensive activities requiring innovation. Apart from these studies, the stable ion beams from the facility have been used for materials science research, especially in the fields of ion beam-induced nano-structure formation[32,33] and studies on room-temperature ferro-magnetism in ZnO and other oxides[34–36]. Also, a laser spectroscopy hut has been set up for pursuing quantum optics studies[37] relevant to photo-ionization and for measurements of atomic hyperfine splitting and isotopic shift of exotic nuclei using collinear laser spectroscopy. Together, these efforts have so far led to about 55 publications in international journals and 7 Ph D theses.

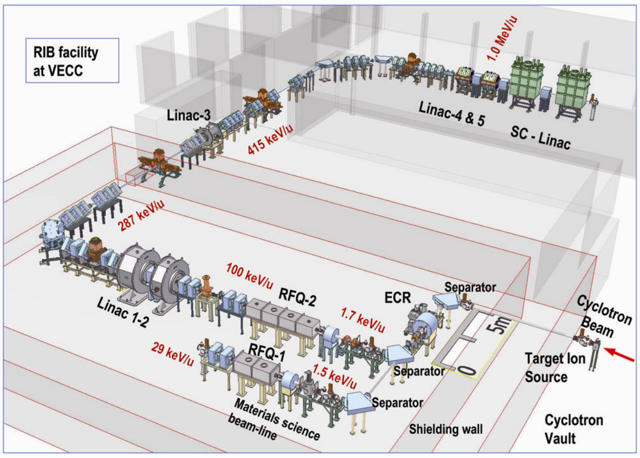

Figure 3. Layout of the RIB facility at VECC, Kolkata.

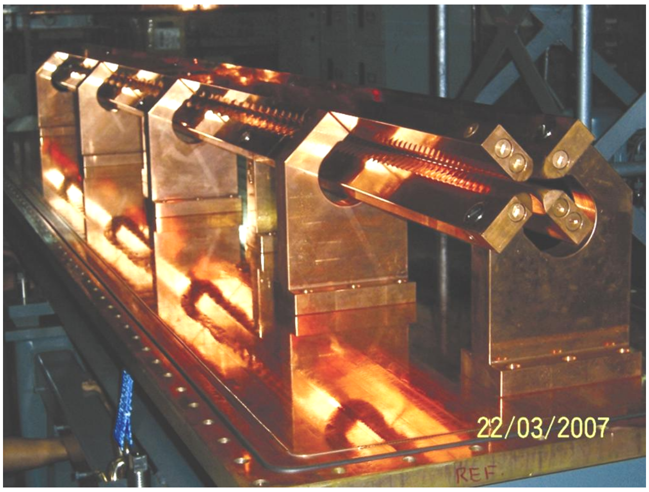

Figure 4. Photograph of the 3.4 m long RFQ linac taken during installation at VECC.

In nuclear physics, the beta, gamma and particle decay spectroscopy and laser spectroscopy studies of neutron-rich and proton-rich isotopes would be the first programme to be taken up with the VEC facility. Experiments of interest to nuclear astrophysics would be taken up after completion of the new annexe building in which the linacs to boost the energy to 1 MeV/u and more, and the experimental beam-lines are to be housed.

ANURIB – VECC's upcoming flagship project

In the 12th Plan and beyond, VECC has decided to take up the development of an internationally competitive RIB facility as the flagship project of the Centre. The experience gained in the last decade in the areas of advanced accelerator and detector development has generated enough expertise and a competent young brigade, which is a necessary prerequisite to taking up such an ambitious project. The project named ANURIB (Advanced National facility for Unstable and Rare Isotope Beams) will be a green-field project built at VECC's new 25 acre campus in New Town, Kolkata. An International Advisory Committee (IAC) comprising world experts in the field of accelerators and nuclear physics has been constituted by DAE to review the ANURIB project proposal. The committee has given a favourable recommendation and suggested the formation of working groups, use of modern project management techniques and building up of institutional and industry linkages for speedy and successful implementation of the project. The RIB production and acceleration scheme for ANURIB[38] is shown in Figure 7.

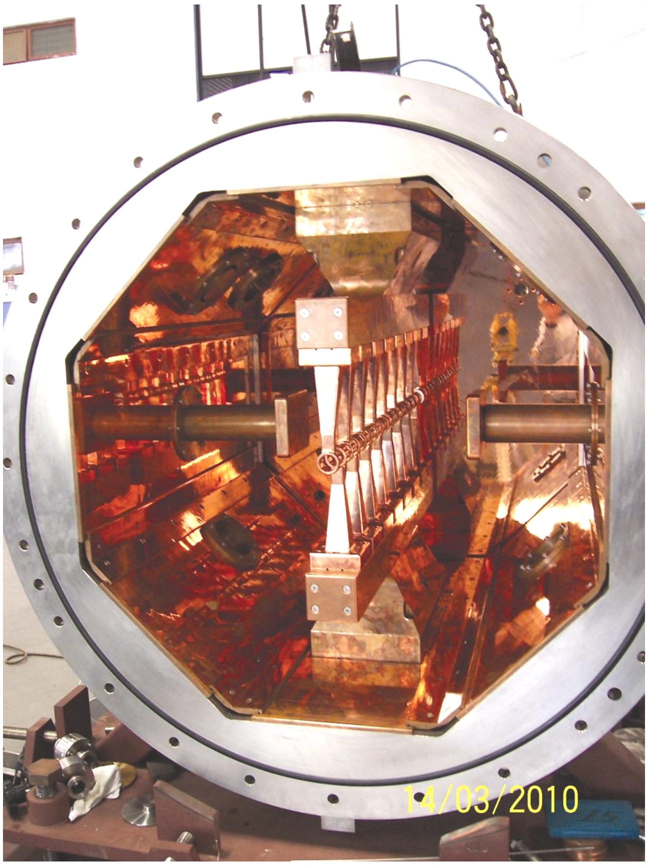

Figure 5. Photograph showing the third heavy-ion linac module with the front cover open. Designed at VECC this linac was fabricated in an industry at Bangalore.

The high-power (100 kW CW) superconducting electron accelerator, presently under development jointly with TRIUMF, will be the main driver accelerator for the ANURIB and one of the main driver accelerators for the ARIEL (Advanced Rare Isotope Laboratory) project at TRIUMF. The electron accelerator will produce neutron-rich rare isotopes through gamma-induced fission of actinides. The development of actinide target for optimum production is a very challenging task. This is also being pursued jointly with TRIUMF. A high-current 50 MeV proton cyclotron would be the second driver accelerator to be used for the production of proton-rich isotopes. A dedicated ECR ion-source and high-current injector will produce intense beams of beta-stable isotopes that will be mass-separated and accelerated using the same set of accelerators. Thus both RIB as well as stable isotope beams (SIB) will be available from ANURIB.

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 7. After initial acceleration in RFQ and room temperature linacs, superconducting linac boosters (SLBs) will be used to increase the beam energy to around 7 MeV/u, opening up the regime of Coulomb barrier physics and production of SHE using RIBs as well as SIBs. For ANURIB, a novel acceleration scheme[39] using asymmetric alternate phase focusing will be employed in the SLBs that would allow simultaneous acceleration of multiple charge states of heavy ions[40].

A sector-focused ring cyclotron will be designed and built to accelerate 7 MeV/u beams after the SLB to about 100 MeV/u. The fragmentation of these RIBs in a secondary target would produce highly exotic rare isotopes, which cannot be produced through fragmentation of stable ion beams. Also, 5–7 MeV/u beams of *p*-rich nuclei can produce exotic *p*-rich species using compound nuclear evaporation reaction. Compared to stable ion beams, reactions with secondary beams result in huge gain in signal-to-noise ratio, since with secondary beams the exotic nuclei of interest can be produced with much higher cross-sections than those closer to beta-stability, making a cleaner separation of exotic nuclei possible. This can compensate in many cases for the lower intensities of secondary beams[41] and make studies on new unstable nuclei possible.

ANURIB will be built in two phases. In phase-1 (2012–2017), the physics and engineering design of the entire facility comprising accelerators and experimental

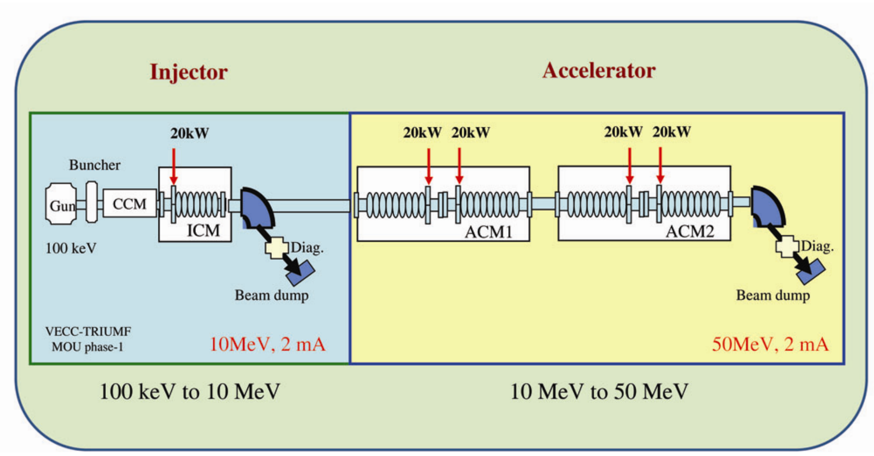

Figure 6. Layout of superconducting electron linac (e-linac) photo-fission driver that will be constructed in two phases at VECC. A MoU has been signed between VECC and TRIUMF, Canada for joint design and development of the e-linac.

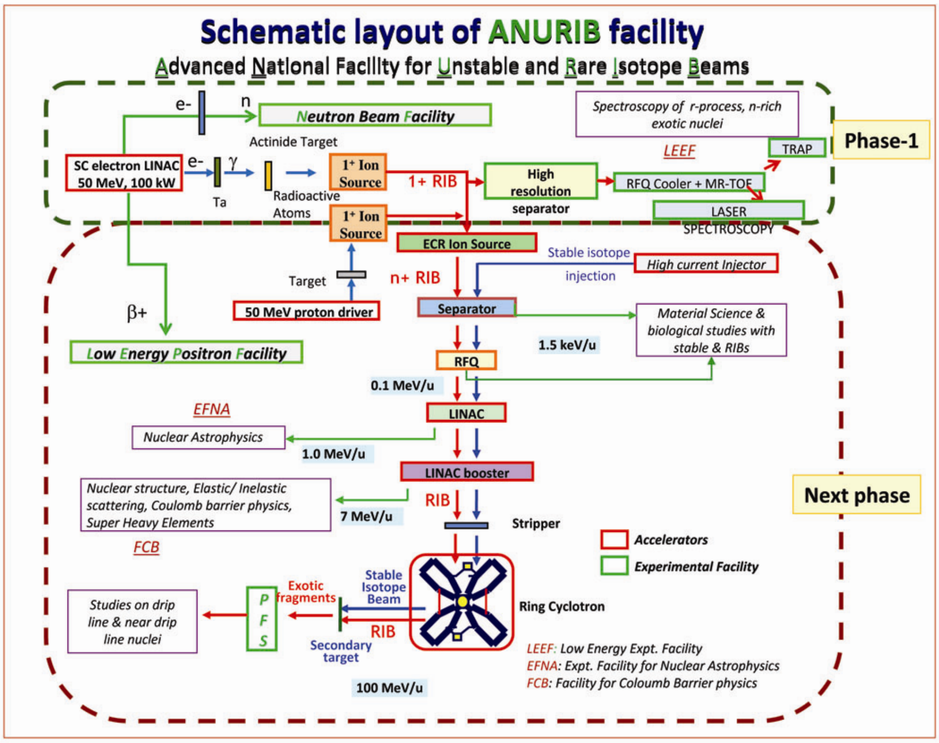

Figure 7. Schematic layout of the ANURIB facility.

facilities will be completed and a detailed technical design report (TDR) will be published. ANURIB would roughly need around Rs 900 crores and 12 years for completion. A more accurate estimate of the project cost as well as the time schedule will emerge after the TDR is completed. In phase-1, apart from the TDR, construction of a part of the accelerator complex that can house the electron linac, the target and the low-energy experimental facility will be completed. The beam energy in phase-1 will be 1.5 keV/u. The low-energy experimental facility would comprise state-of-the-art devices such as the RFQ cooler and buncher, multiple reflection time of flight (MR-TOF) spectrometer, Penning traps, and laser spectroscopy set-up. In phase-2, the RFQ, room temperature linear accelerators, SLB, and ring cyclotron would be constructed along with experimental facilities like projectile fragment separators, beam-line and detector facilities for nuclear astrophysics and nuclear physics. The use of electron driver for production of n-rich RIBs, combination of both ISOL and PFS methods, fragmentation and fusion reactions with RIBs, and availability of intense, stable, heavy-ion beams together would make ANURIB a unique and internationally competitive facility.

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Received 25 April 2014; revised accepted 16 October 2014