Heavy ion superconducting injector for TIFR-BARC accelerator facility

DNAP, TIFR & NPD , ED, BARC

Scientific Objectives:

We plan to develop a low energy, injector system for the existing superconducting LINAC. At present the beam species and intensities delivered by the LINAC is limited by the available beams from the Pelletron which serves as the injector. For example, ion beams from the Pelletron, much heavier than nickel, are far below the velocity acceptance of the LINAC and hence cannot be boosted by the LINAC. To overcome this and utilize the full capabilities of LINAC, we propose to set up a 400 kV ion source deck using a high frequency ECR source of a commercially proven design. The ions from the ECR source need to be accelerated in ultra-low beta (β~0.01-0.03) and low-beta (β~0.05-0.07) sections to an equivalent of 12-14 MV/q prior to injection into the LINAC. We plan to develop a normal conducting pre-accelerator employing a Radio Frequency Quadrupole (RFQ) followed by superconducting accelerating stage based on Niobium based low-beta cavities. The proposed injector system would vastly extend the capability of the LINAC as a research tool for nuclear physics. This project, to be taken up after the completion of LINAC, was proposed in the previous plan and was approved (10P1802) to initiate R&D on the ECR ion source, RFQs and Noibium cavities.

The Pelletron accelerator facility at TIFR, set up as a collaborative project between BARC and TIFR, has been a major centre for heavy ion accelerator based research in India since its commissioning in 1989. Several major experimental facilities have been established at this centre to pursue research in nuclear physics, atomic physics and interdisciplinary areas. While majority of users of this facility have been from BARC and TIFR, it has also been available to scientists from all over the country and laboratories abroad. This facility has been extremely productive resulting in more than 50 Ph.D. theses and 350 publications in refereed international journals, including 12 publications in Physical Review Letters. The Pelletron accelerator serves as both a stand-alone accelerator and as an injector to the superconducting LINAC booster. The LINAC comprising seven modules, delivers beam in the energy range of ~5-10 MeV/A upto A~80. This will facilitate the investigations of reactions above the Coulomb barrier for beams around Ni impinging on heavy targets like U.

The main focus in nuclear physics research is to explore nuclear properties at the limits of stability with respect to deformation, isospin and angular momentum. The evolution of properties of nuclei having large excess/deficiency of neutrons is of great interest. These nuclei at the limit of binding will help us understand how the effective interaction depends on neutron to proton ratio. In other words, exploring the "isospin" degree of freedom, is fundamental to understanding nuclear structure and nuclear processes. This has a wide implication ranging from nuclear astrophysics, exotic nuclei, nuclei close to the line of stability, super heavy elements, etc. The existence of Super Heavy Elements (SHE) illustrates the delicate stabilization by the quantum mechanical shell correction on the classical liquid drop properties which result in arresting the immediate fission of these SHE nuclei. To study the nuclei under extreme conditions of excitation energy and angular momentum, energetic heavy ion beams, namely, beams in A~10-250 region with a few

MeV/nucleon energy are needed. With the proposed injector system and the available physics expertise in the BARC & TIFR, we will be able to address very relevant and pertinent questions about *the nucleus: an unique many body quantal system*. A few of the research problems of interest that can be pursued using the upgraded accelerator facility are briefly outlined below.

The proposed injector facility will enable the study of reactions above the Coulomb barrier even for very heavy systems like U + U. The reaction mechanism of the fusion, quasi-elastic and deep inelastic collisions (DIC) is not fully understood. Understanding these reactions is crucial for production of nuclei far from stability. For example, deep inelastic transfer represents a very powerful tool to explore neutron rich nuclei. The spectroscopy of both collective and single particle states in nuclei far from stability is an important aspect of nuclear structure. These studies will help in addressing the holy grail of nuclear physics − how can one derive the properties of composite objects from those of their building blocks. In nuclear structure studies, one of the interesting problems is the identification and study of multiple phonon excitation in deformed nuclei. This will give important information regarding phonon description of vibrational degrees of freedom in nuclear physics. The study of nuclear shapes and its underlying structure probed via electromagnetic decays has been a very active field of research. One of the major goals is to search for hyperdeformed shapes of nuclei at high angular momentum (major to minor axis ratio with 3:1). One of the exotic shapes exhibited by nuclei is the reflection assymetric shapes resulting from octupole correlations as in the case of Pb. Since these shapes are relatively less frequent, these studies will provide a new insight into shape generation mechanism in nuclei.

The transition from direct reactions like single nucleon, multi nucleon transfer to more dissipative processes can be addressed in the collisions of symmetric systems. Unification of these seemingly different processes would go a long way in our understanding of the heavy ion collisions. The large excitation energy and angular momentum would restrict the formation of a totally equilibrated system and would enhance other modes of decay like fast and quasi fission. The measurements of the mass and total kinetic energies in these processes will improve our understanding of fission dynamics. In particular, the temperature dependence of the nuclear viscosity is crucial to the survival probability of a high Z nucleus against fission decay. These have important implications for the production of super heavy elements. It will be possible to populate nuclei and investigate their properties over a wide range of the temperature upto 4 MeV. For example, in the study of giant resonances of hot nuclei two basic issues yet to be fully understood are the temperature dependence of the damping of the fundamental collective modes and the gradual vanishing of the collectivity with increasing temperature. These issues can be addressed by a simultaneous measurement of the high energy gamma-ray spectra and the temperature of nuclei emitting the gamma rays together with a proper characterization of the reaction mechanism. The entrance channel dependence of the nuclear reactions can be studied over a wide range of projectile-target combinations populating similar final nuclear complexes. Another interesting problem is the gamma ray production during the pre-equilibrium stages. It is possible that depending on the charge to mass ratio difference in the projectile and the target, dipole photons can be emitted before the nuclei fuse or after they separate into projectile and target like partners, both of which may be highly excited. The reaction mechanism can be studied using the characteristic energy spectra of photons emitted at different stages. The evolution of the nuclear level density parameter as a function of temperature is another basic question that can be investigated by studying the evaporated particle spectra.

One of the main advantages of the injector facility is that it will facilitate experiments in inverse kinematics, i.e. heavy beams on light targets. These reactions generate forward focused products in laboratory frame, thereby making complete kinematical coincidence measurements feasible. One of the objectives would be to use these intense heavy energetic beams to excite and study radioactive targets. The radioactive targets can be obtained using carrier free, long lived radioactive fission products from reactors at BARC. Using intense primary beams available from the ECR source in conjunction with suitable magnetic and electrostatic analyzers, we can extract projectile-like secondary ion beams (~few MeV/nucleon) from the products of the heavy-ion induced reactions. Reactions with these secondary beams can then be used to probe their properties through a variety of physical processes. In addition to the nuclear physics interest, such beams would also enable the investigation of some of the nuclear process that determine the fate of the stars and control the synthesis of elements.

In addition to the nuclear physics interests, high charge state ion beams will open up new windows in interdisciplinary areas. The high energy heavy ion accelerators are probably the most important tools to study the ionization, excitation and transfer mechanisms for strongly bound inner shell electrons. This provides understanding of fundamental atomic collision physics. The thrust of atomic physics research will be to understand the mechanism of various inelastic ion-atom collision processes in the case of strongly perturbative collision systems as well as to explore the multi-electron processes in heavy ion-atom, ion-solid and ion-cluster collisions. Investigation of the two center effect, post collision interaction and solid state effects on atomic collisions will be pursued using low energy electron and X-ray spectroscopic techniques. The subshell resolved electron transfer and ionization can be studied for deeply bound inner shell electrons in high Z target atoms. Nuclear techniques like perturbed angular correlations/distribution (TDPAC/TDPAD) have been applied to study electronic and magnetic properties of solids. It is possible to get information on spin dynamics over a wide range of physical variables like temperature and external magnetic field. Strongly correlated electron systems exhibiting heavy fermion behaviour, Kondo spin fluctuation, giant magneto-resistance and colossal magneto-resistance can be studied by recoil implanting specific activity produced in the heavy ion induced reactions. Effects of radiation damage in different materials, biologically relevant molecules & systems and production of medically useful radioisotopes can also be investigated.

In conclusion, a wide variety of beams with very large intensities will let us probe the nucleus at its extremes and address questions of contemporary interest. It should be noted that the research proposals outlined above will require a substantial augmentation of the existing detection facilities like large particle-gamma-ray arrays, gas filled magnetic separators and ion traps.

Current National and International perspective:

National: An indigenously developed 6 GHz and commercially available 14 GHz ECR sources has been installed at VECC (Kolkata) for use with the present cyclotron as well as with the superconducting cyclotron (SCC) under construction. Two commercially available

10 GHz and 18 GHz ECR sources have been procured by IUAC (New Delhi) for low energy atomic physics and high current accelerator development. The IUAC is also engaged in developing Niobium based superconducting cavities. High current proton RFQ has been developed at BARC for the ADSS project. A 14 GHz ECR source has been procured by DNAP, TIFR for atomic physics. This source would also serve as a test bench for the ultra-low beta accelerating sections. The proposed upgradation will cover the energy range intermediate to Pelletron + LINAC and the superconducting cyclotron being built at VECC.

International: The ATLAS accelerator operational at Argonne National Lab., USA has a configuration similar to what is being proposed. At INFN (Legnaro, Italy) a similar project PIAVE is being currently implemented.

The proposed upgradation will generate trained manpower in diverse technological areas like: accelerators, cryogenics, normal and super-conducting accelerating structures, high power RF systems, data processing and control systems, etc. This project involves the development of the heavy-ion Radio Frequency Quadrupole pre-accelerator and the superconducting Niobium based accelerating stages comprising of ultra-low and low-beta resonators. This would establish the technologies required to build a Radioactive Ion Beam (RIB) facility in the country. This will also help in the development of efficient, high current accelerators for Accelerator Driven Subcritical energy Systems (ADSS).

Major facilities to be created:

During the R&D and implementation of the superconducting LINAC project new infrastructure at TIFR and BARC were established and in addition several manufacturers/fabricators in Mumbai, Pune, Bangalore, etc were developed. This was essential to facilitate fabrication of the OFHC copper quarter wave cavities; fabrication of cryogenic & vacuum systems; fabrication of beam transport and diagnostic devices; design, testing and fabrication of RF systems; electronics for monitoring, measurement and control, etc.

For this project, in addition to the above infrastructure established at the TIFR, BARC and vendors, we need to develop facilities to undertake complex machining of the RFQ accelerating structure, high purity Niobium machining, welding, processing, etc.

It is envisaged that all the experiments done with beams from the Pelletron or the Pelletron+LINAC will utilize the experimental stations available in the new user hall. The current experimental hall using the beams directly from the Pelletron will be thus cleared of all experimental activities. This hall will refurbished to house the heavy ion injector comprising the ECR ion source, the RFQ pre-accelerator and the superconducting niobium cavity based low energy accelerator. The beams delivered by the injector will be further boosted by the LINAC and be made available for experiments in the LINAC user hall.

Work Methodology:

Commercially available ECR sources are capable of producing highly charged heavy ion beams of excellent quality and intensity. The ECR source also produces beams of group I, II and VIII elements, viz.: Na, K, Ca, Ar, etc., which cannot be produced in the negative ion source of the Pelletron. We propose to procure this source with a capability of producing heavy ions with A/q in the range 2.5-7 (that is, upto Au^{30+}, U^{34+}).

The injector will consist of two stages of RFQ and four modules of superconducting Quarter Wave Resonators (QWR). The RFQ's will be designed to accept ion beams with $\beta \cong 0.01$ (at 300 kV or lower deck voltage) and will be accelerated to $\beta \cong 0.035$. These beams will then go through two sets of superconducting cavities with $\beta \cong 0.05$ and $\beta \cong 0.07$, respectively. This pre-acceleration is expected to bring all ion beams from Oxygen to Uranium, in the velocity range $\beta \cong 0.08$-0.013 which is suitable for the main LINAC. After further acceleration in LINAC, ~12 MeV/A light ion beams or ~5 MeV/A heavy ion beams will be available at the target.

The tasks related to the various major subsystems of this injector will be undertaken at both TIFR and BARC and the work plan is given below:

a) Noibium Cavities ultra-low and low beta (TIFR)
b) Cryogenics (TIFR)
c) ECR ion source plus 400kV deck (NPD, BARC)
d) RFQ (TIFR, NPD)
e) RF control and RF power systems (ED, BARC)
f) Beam transport, diagnostics and vacuum systems (TIFR, NPD, ED)

In the Xth plan period design of the RFQ was started and procurement of a suitable ECR ion source was initiated. During the last year of the Xth plan and beginning of the XIth plan the detailed design of the accelerator components, beam transport, vacuum systems and diagnostics will be finalized. Commissioning of the ECR ion source and fabrication of the RFQ is proposed to be done in the beginning of the plan period. Simultaneously, R&D on the niobium cavities will be undertaken and the fabrication of the cavities is proposed to commence in during the middle of the plan period. The fabrication, installation and testing of the cryogenic systems, beam transport and diagnostics and the RF systems is proposed to commence in the later half of the plan period. It is envisaged that the complete injector can be commissioned in the beginning of the XIIth plan period.

The positive ion injector will enhance the capability of the Pelletron+LINAC accelerator facility at TIFR. This would widen the scope of accelerator based experimental programmes and would be complimentary to the physics done at higher energies with the Superconducting Cyclotron at Kolkata. The TIFR-BARC accelerator centre would also act as a breeding ground for new accelerator technologies and in particular contribute to the national RIB facility which is under active consideration.

For more details contact Prof. R. G. Pillay (DNAP, TIFR).

Appendix

The proposed injector layout (schematic)

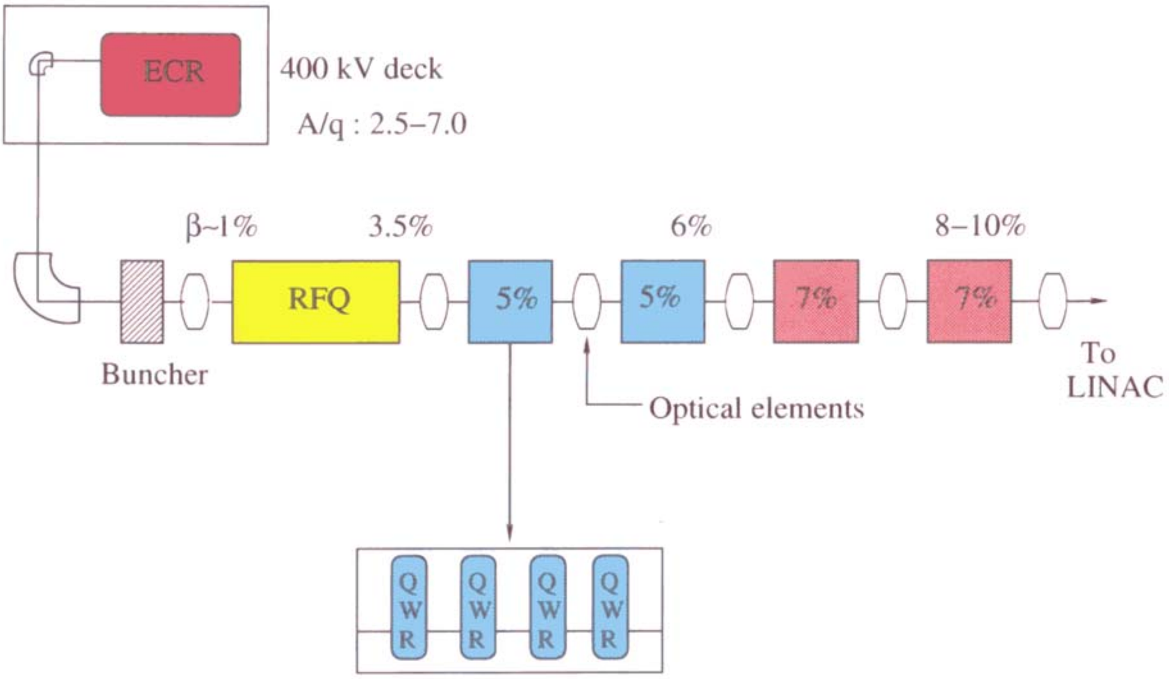

Table 1: A schematic of velocity profile in pre-acceleration stages of the proposed injector

	β_{in}	β_{out}
RFQ 1	0.010-0.012	0.022-0.028
RFQ 2	0.022-0.028	0.033-0.040
Two modules of β ~0.05	0.035-0.040	0.06-0.09
Two modules of β ~0.07	0.06-0.09	0.08-0.12

Table 2: An estimate of available and expected energies for various ions with approximate beam currents available at the target position at that energy. Pelletron energies are calculated for 13 MV terminal voltage. Typical beam currents on target for the present Pelletron+LINAC combination are in the range 1-10 pnA. ECR yields are estimated from yields of 14 GHz ECR at LBNL and Ssupernanogan of Pantechnik.

Ion	Pelletron		Pelletron+LINAC	Proposed Injector +LINAC		
	A/Q	E(MeV)	E(MeV)	A/Q	E(MeV)	I_{target}(pnA)
O	2.5	90	210	2.5	220	>1000
Cl	4.0	126	360	4.0	400	60
Ar	--	--	--	3.5	460	60
Co	6.0	145	470	4.5	600	100
Kr	--	--	--	4.5	800	70
Xe	--	--	--	5.0	1150	3
Au	16.0	180	--	7.0	1300	8
U	20.0	180	--	6.5	1600	5