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Development of a superconducting LINAC booster for the Pelletron at Mumbai

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Abstract. A superconducting linear accelerator (LINAC) to boost the energy of the heavy ion beams from the 14 UD pelletron accelerator at Mumbai is under development. The booster is based on quarter wave resonators (QWR) coated with lead which is superconducting at liquid helium temperature. The operating frequency is 150 MHz. Four resonators each are mounted in a cryostat module built indigenously. A total of seven such modules arranged in two arms with an isochronous and achromatic beam bend in the middle comprises the full LINAC. The transverse focusing of the beam through the LINAC is carried out using periodic quadrupole doublet magnets operating at room temperature. The present status of the project is described.

Keywords. Superconducting cavity resonator; cryogenic distribution system; pelletron accelerator; beam buncher; amplitude and phase feedback.

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1. Introduction

A 14 UD pelletron accelerator at the Tata Institute of Fundamental Research, Mumbai has been providing beams of accelerated heavy ions for various experiments in nuclear and atomic physics during the past decade. Beams of energy more than 1 MeV per nucleon in the entire mass range and above 5 MeV per nucleon for $A \leq 20$ are routinely available for experiments. To extend the scope of studies to projectile masses in the heavier range of $A \sim 100$, an energy booster to the pelletron accelerator is under construction [1]. The booster is based on independently phased superconducting quarter wave resonators (QWR). Since ohmic losses in such resonators are reduced by $\geq 10^4$ relative to normal room temperature cavities, a substantial reduction in electrical power to sustain large accelerating fields in these devices can be achieved. This allows the construction of compact accelerators operating in the continuous wave mode. Since the indigenous development was the prime consideration for the project, the technology of electroplated lead on copper was thought more amenable as compared to the more complex niobium fabrication. Further, the lead-plated QWRs are robust structures with considerable insensitivity to ambient mechanical vibrations and liquid helium pressure changes. This feature makes the resonator control easier and the operation more reliable. Hence, a LINAC is being constructed with lead-plated QWRs to serve as an energy booster to the Mumbai pelletron. The layout of the accelerator facility comprising of the pelletron, the

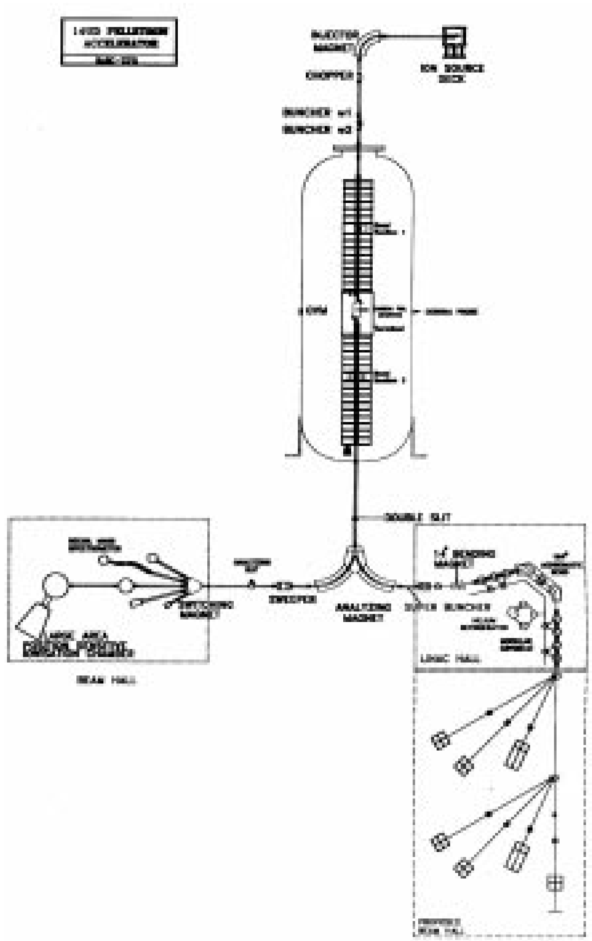

Figure 1. A schematic drawing of the Pelletron – LINAC Accelerator facility at Mumbai. The Pelletron is operational while the LINAC is under development. The construction of the new beam hall is to begin soon.

LINAC booster and the beam halls are shown in figure 1. The LINAC has been designed to optimally fit into the already constructed LINAC beam hall. The shown layout, to a large extent, preserves the excellent phase space properties of the beam from the pelletron.

A 14° dipole magnet shoots the beam from the pelletron to the first half of the LINAC where it gets accelerated in three accelerating modules. The beam then undergoes a 104° isochronous bend and goes into the second half of the LINAC where there are four more accelerating modules. The accelerated beam then enters the new beam hall where the beam will be switched to different experimental caves.

Several years of sustained developmental efforts in different aspects of the technology towards the development of the booster has resulted in the testing of a prototype accelerating module for beam acceleration [2]. Further, three accelerating modules for installation

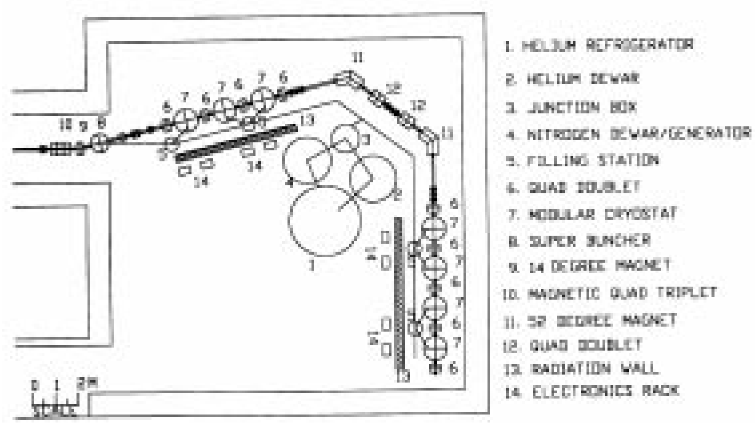

Figure 2. A blow up of the various subsystems of the LINAC. The cryogenic plant and the distribution system are also seen in this figure.

on the LINAC beam line are ready along with the necessary cryogenic installation. Another major development has been the design, fabrication and commissioning of the rf and control electronics for the LINAC.

The LINAC booster has the novel design concept of a modular structure which is very useful during the commissioning phase as well as at the time of maintenance. Each LINAC module consists of a liquid helium cryostat housing four 150 MHz lead-plated quarter wave resonators. The beam quality through the LINAC is preserved by periodic focusing of the beam by magnetic quardrupole doublets positioned periodically between the accelerating modules. The cryostats will be cooled to 4.5 K by pool boiled liquid helium provided by a closed cycle liquid helium facility attached to the LINAC as shown schematically in figure 2.

2. Superconducting cavity resonators

The rf resonators with appropriately incorporated drift tubes constitute the accelerating structure of a heavy ion LINAC. Of the several accelerating structures available for a heavy ion LINAC, we adopted the quarter wave resonator for our LINAC because of the stability and the broad velocity acceptance of these resonators [3]. Even though many of the laboratories use niobium as the superconducting material for the cavity, we chose to use lead as the superconducting material, primarily because of the simpler technology of preparation [4]. The 150 MHz $\beta(v/c) = 0.1$ QWR made of OFHC copper is shown in figure 3. The vertical tapered inner conductor is made hollow for filling with liquid helium while the outer surface is cooled by conduction. The outer can is connected to the base plate of the cavity through a deep penetration electron beam weld W_1 shown in figure 3. W_2 is a cosmetic electron beam weld done on the inner surface to make a smooth and continuous surface for facilitating the growth of good superconducting lead film. This cosmetic electron beam weld has been very critical in our fabrication cycle and has resulted in many failures. Improper W_2 often results in poor quality lead film leading to low quality factors in the superconducting state.

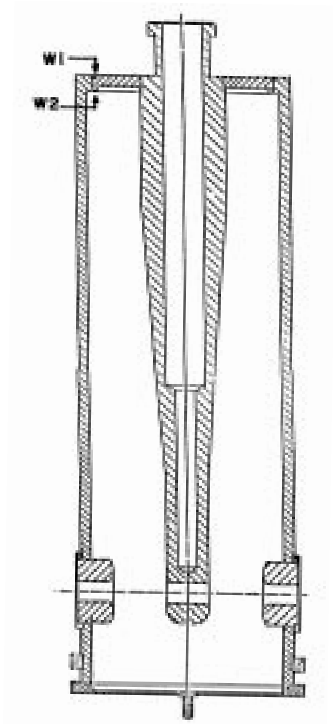

Figure 3. The 150 MHz quarter wave resonator.

Figure 4. Photograph of an indigenously fabricated QWR and its end plate.

Since QWR is a structure with only two accelerating gaps, its efficiency for accelerating ions in the range of $\beta = 0.06$ to 0.15, available from the pelletron accelerator, is reasonable. This enables us to have the entire LINAC with a single cavity structure. Figure 4 shows the photograph of an indigenously fabricated QWR and its end plate.

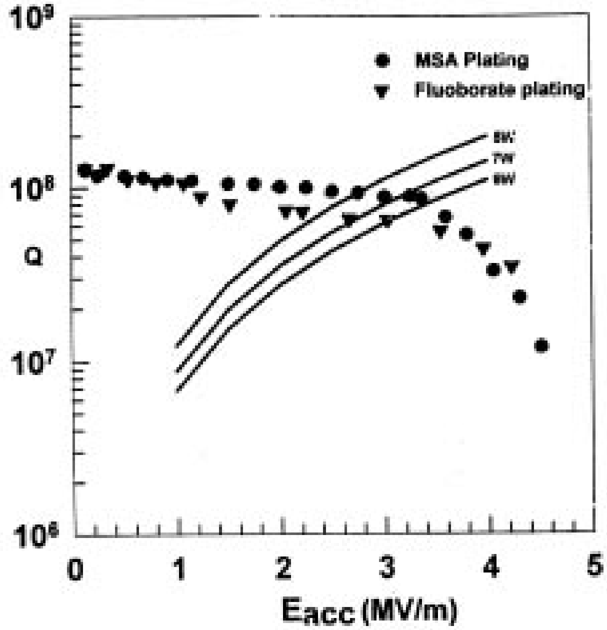

Figure 5. The quality factor Q plotted as a function of the accelerating field in the cavity for lead films prepared using different electrochemical baths.

The lead plating of the QWRs is done at TIFR using a pulsed electroplating technique. The plating parameters for two different plating baths ((i) fluoboric acid-based and (ii) a stannostar acid-based) have been optimized by us. From the measurement of the quality factors of the cavities plated with lead films produced using these two techniques, it was established that the stannostar plating technique is better and more robust. As can be seen from the Q vs. electric field in the cavity plotted in figure 5, the stannostar-based lead film results in the improved performance of the cavity. All the cavities for our LINAC are now being prepared using stannostar bath.

All the inside surfaces of the QWR are plated with a 2 μm-thick layer of lead which is superconducting at temperatures below 7.2 K. Electroplating of lead, in order to achieve acceptable cavity Q-values, places stringent requirements on the surface finish and cleanliness of the resonator's surface. Extensive trials have been made in order to develop the technique of achieving a clean copper surface with sub-micron finish prior to lead plating. The surface preparation technique essentially involves mechanical polishing using abrasives of various grades, surface buffing using walnut shells and a final electropolishing of the copper surface.

The lead-plated QWRs are subsequently tested for their individual performance at liquid helium temperature using a rf test set up coupled to a Koch 1410 helium liquifier operating in a closed cycle mode. Using this set up, the decay time τ of the cavities at 4.5 K is measured under conditions of critical coupling for the input rf power, employing the relation $U = U_0 e^{-(t/\tau)}$ where U_0 is the stored energy in the cavity. From the measured τ the low field $Q = \omega\tau$ is calculated. At high fields, Q is measured from the dissipated rf power using the relation $Q = \omega U/P$ where P is the measured input rf power and U is the stored

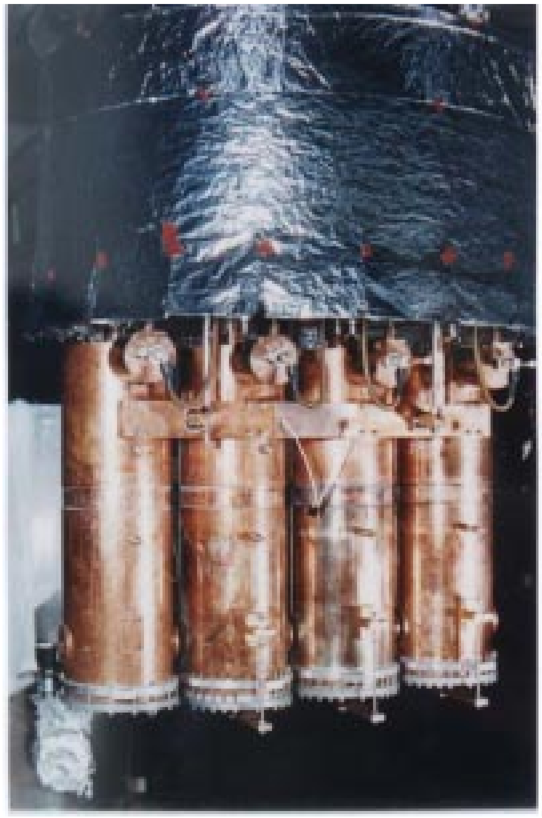

Figure 6. Photograph of the four QWRs mounted to the helium bath of the cryostat.

energy. A typical *Q* curve vs. the accelerating field is shown in figure 5. The results for the stannostar-based plating are shown along with those for the fluoborate-based plating. A field level in excess of 3 MV/m in the cavity can be generated with a power dissipation of about 7 W at 4.5 K.

3. Cryostat modules

For running the resonators in the superconducting state, they must be maintained at temperatures below their T_c (7.2 K). Usually the resonators are operated around a temperature of 4.5 K and this temperature is obtained by using liquid helium as the cryogen. The entire cryogenic system for the LINAC can be divided into three parts, viz., (i) the cryostat modules to house the resonators, (ii) the closed cycle helium refrigeration system to produce the cryogen and (iii) the liquid helium and liquid nitrogen distribution system. All these features can be seen in figure 2. An efficient cryogenic distribution system is essential for the successful operation of the LINAC. To take advantage of the modular structure of a LINAC, the cryostat modules are designed to hold four resonators each. These resonators are connected to the liquid helium tank of the cryostat as can be seen from figure 6. The figure also shows the power coupler and frequency tuner attached to each of the resonators. The

Figure 7. TCF50S with its 1000 l dewar.

predominant heat load at the 4.5 K stage is from thermal radiation. To minimize this heat load on the helium circuit, the liquid helium storage tank and the resonators are shielded by surfaces cooled to liquid nitrogen temperature. The radiative heat load on liquid nitrogen is minimized by superinsulating the outer surface of the liquid nitrogen shield with several layers of aluminized mylar of very high quality. The entire assembly is enclosed in a 1 m diameter vacuum vessel with beam in and out ports.

In addition to cooling the resonators, the cryostats also provide, through its top flange, access for various control and monitoring functions necessary for the running of the resonators. There are four penetrations each for rf power couplers and tuners. Through these penetrations, the drive shaft of the stepper motors are connected to the drive mechanisms of the couplers and tuners. The torque is transferred through high vacuum compatible rotary motion feed throughs. There are also penetrations for rf power pick up and for various diagnostic and control elements connected with vacuum and cryogenics.

4. Cryogenic distribution system

The cryogenic requirement at 4.5 K for the LINAC is met by a closed cycle helium refrigerator connected to the LINAC by appropriate vacuum insulated transfer lines. The layout of the refrigerator and the transfer system can be seen in figure 2. The refrigeration power at 4.5 K required to run the full LINAC is estimated to be 250 W. This requirement is met by a Linde TCF 50S helium refrigerator which can be seen in figure 7. This refrigerator operating with two turbines has already been installed and commissioned. The TCF 50S has delivered in excess of 300 W of cooling power at 4.5 K without liquid nitrogen precooling. With liquid nitrogen precooling, the cooling power can be increased to beyond 350 W.

The cryogen supply from the sources to the cryostat is done through a cryogenic distribution system. As can be seen from figure 2 it consists of the liquid helium storage tank, the vacuum insulated trunk line to carry the cryogens to the valve boxes and the interconnecting transfer lines between the valve boxes and the module cryostat. This interconnecting line is a multi co-axial one to carry liquid helium into the cryostat and take the return helium gas back to the refrigerator through the valve box. The inner most line carries liquid helium and the outside co-axial tube carries return helium gas and the outermost co-axial tube facilitates vacuum. The transfer of cryogens to the module cryostats are done by cryogenic control valves guided by cryogenic liquid level sensors installed in the cryostats. One control station will take care of two cryostat modules. The installation of the cryogenic distitution system is in progress.

5. Electronics

There are two layers of requirement of the electronic systems for the project. The first one is the rf electronics consisting of rf controllers and amplifiers required to run the cavity resonators. The second layer is the control and monitoring systems based on the CAMAC instrumentation scheme required to run the rf and cryogenic systems. Both the rf controllers and the CAMAC systems are developed by the electronics division of BARC while the rf amplifiers are being built by BEL, Bangalore based on a design provided by the Nuclear Science Centre, New Delhi.

The different resonators in the LINAC can add energy to the beam coherently only if each one of them is operated at the desired phase and amplitude with a stability better than 0.1%. This stringent stability condition of the superconducting resonators, with a $Q \sim 10^8$, is achieved by an electronic rf feedback system for each of the resonators. The resonator is run by a self excited loop, which contains a power amplifier, an amplitude feedback and a phase feedback. Both these feedback systems get signals from the resonator. The phase and amplitude of the electric field in the resonator at any instant is compared with predecided reference values and the error signals thus derived modulate the input rf power to the resonator to achieve the desired stability.

To effectively match the beam from the pelletron into the LINAC, various other rf devices, viz., the low energy double harmonic drift bunchers, the sweeper-corrector, the phase pickup cavity and the post-tandem superconducting buncher have to be stabilized and phase locked to the LINAC reference clock as shown schematically in figure 8.

The low energy double harmonic drift bunchers consist of high voltage drift tubes which are excited by tuned resonant circuits operating at the 16th and 8th subharmonics of the LINAC frequency (150 MHz). Approximately 66% of the DC beam are bunched into 1 ns pulse, with a repeat period of 106 ns, at the output of the pelletron. In order to remove the residual unbunched DC beam, a sweeper-corrector has to be installed at the LINAC injection path. The sweeper-corrector consists of two pairs of deflecting plates excited by resonant circuits operating at 32nd subharmonic of 150 MHz. The beam pulses pass through the sweeper when the plate voltage is near zero, while the background DC component is deflected by the high voltages present on the plates during the period between pulses. Because of the finite transit time of the beam through the deflecting plates, the sweeper introduces a coherent distortion on the beam pulses. In order to achieve optimum and efficient beam transmission through the LINAC the beam quality has to be restored and the corrector (operating at low voltages and 90° out of phase with respect to the sweeper) is used to correct these distortions. To detect the time of arrival of the beam pulses at the exit of the pelletron, a phase pickup cavity has to be located between the sweeper-corrector and

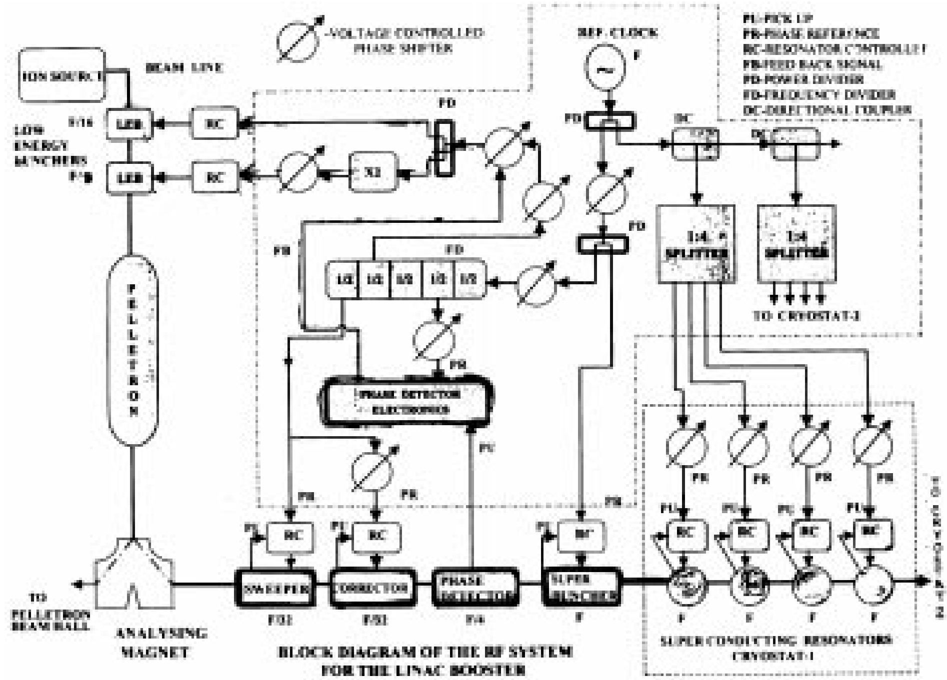

Figure 8. Schematic view of the Pelletron–LINAC beam stabilization scheme.

the superbuncher. The phase pickup cavity operates at the 4th subharmonic of the master 150 MHz clock. This cavity is excited by the periodic train of beam pulses and this phase detector signal is used in the phase feedback loop of the low energy bunchers to correct for transit time variations through the pelletron.

The superbuncher, comprising of a single superconducting cavity operating as a buncher, is used to further bunch the 1 ns beam pulses down to approximately 150 ps prior to injection into the accelerating modules. For phase stable beam transport and acceleration through the LINAC, the beam pulses have to be within 5–10° phase window of the 150 MHz rf field in the accelerating cavities. This bunching, at the injection stage, is done by the superbuncher situated 3–4 m before the first LINAC module. The subnanosecond bunches are then accelerated through the independently phase locked cavities located in the various modules. The superconducting cavities operate at the primary LINAC frequency of 150 MHz, while the phase detector, the two low energy bunchers and the sweeper-corrector operate at the 4th, 8th, 16th and 32nd subharmonic frequencies, respectively.

6. Current status

Three accelerator modules with four QWRs are assembled to be put on the first half of the LINAC beam line. The electronic controllers and the camac system for running these three modules are also under final stages of completion. The TCF 50S cryogenic plant is installed and tested. The cryogenic distribution system for running the first half of the

LINAC is under installation. This section of the LINAC booster is expected to start trial runs soon.

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References

[1] R G Pillay, M B Kurup, Anemesh Jain, D Biswas, S A Kori and B Srinivasan, *Indian J. Pure Appl. Phys.* **27**, 671 (1989)
[2] M B Kurup, *Proc. Int. Symp. on Nuclear Physics* edited by M A Eswaran and R K Choudhury, Mumbai (1995) p. 528
[3] D Storm, *Nucl. Instrum. Methods Phys. Res.* **A238**, 213 (1992)
[4] V Palmieri, *Particle accelerators* **53**, 217 (1996)