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Superconducting linear accelerator system for NSC

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Abstract. This paper reports the construction of a superconducting linear accelerator as a booster to the 15 UD Pelletron accelerator at Nuclear Science Centre, New Delhi. The LINAC will use superconducting niobium quarter wave resonators as the accelerating element. Construction of the linear accelerator has progressed sufficiently. Details of the entire accelerator system including the cryogenics facility, RF electronics development, facilities for fabricating niobium resonators indigenously, and present status of the project are presented.

Keywords. Superconducting LINAC; cryogenics; RF electronics.

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1. Introduction

The 15 UD Pelletron accelerator at Nuclear Science Centre (NSC) [1] is capable of accelerating heavy ions up to mass 40 above the Coulomb barrier. In order to increase this mass range up to 100, a superconducting linear accelerator as a booster is presently under construction [2]. The LINAC would use superconducting niobium quarter wave resonators (QWR) as the accelerating element. The LINAC will consist of one superbuncher cryostat containing one QWR, three LINAC modules, each consisting of a cryostat holding eight QWRs and one superconducting solenoid magnet, and one rebuncher cryostat containing two QWRs. Figure 1 shows a schematic of the linear accelerator. The expected energy gain from the Pelletron LINAC combination is shown in figure 2. We describe here the various sub-systems and the present status of the project.

2. Linear accelerator

2.1 *Superconducting resonators*

The accelerating structure in the LINAC would be a superconducting niobium quarter wave resonator, which was chosen for its excellent mechanical stability and broad velocity acceptance. One single structure operating at 97 MHz and optimized for synchronous

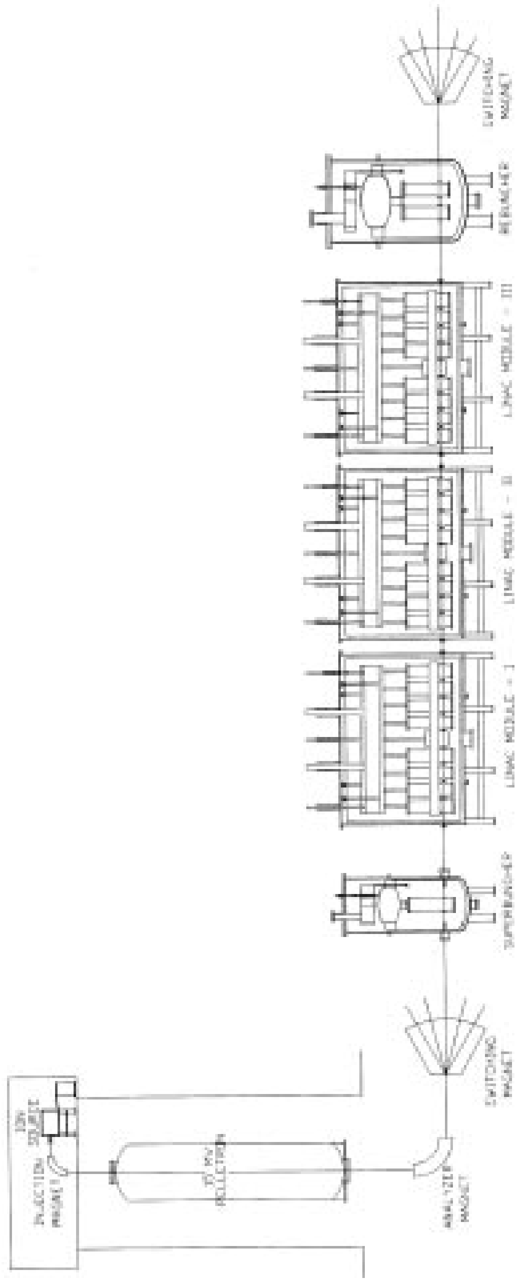

Figure 1. Schematic diagram of the NSC superconducting linear accelerator.

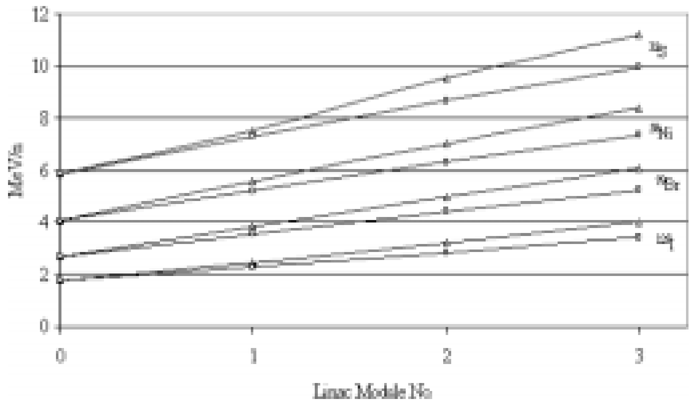

Figure 2. Resultant energy per mass unit for different ions from the Pelletron LINAC combination. Triangles are for average accelerating electric field of 4 MV/m and squares are for 3 MV/m in the resonators.

velocity $\beta(= v/c) = 0.08$, would be used in the entire LINAC. Prototype resonator was designed, fabricated and tested in collaboration with Argonne National Laboratory (ANL), USA [3]. A schematic diagram of the quarter wave resonator is shown in figure 3. Several new features have been incorporated in the design, details of which are already presented elsewhere [4]. Resonators for the first LINAC module have also been fabricated in collaboration with ANL [5]. Performance of two resonators from this production is shown in figure 4. Resonators for the remaining two modules, and for future projects, will be fabricated in-house and facilities for the same are being set up at NSC, which will be described later.

2.2 *Cryogenic system*

The cryogenic system for the superconducting linear accelerator consists of helium and nitrogen refrigerators, cryogen distribution network, and cryostats. The estimated total heat load at 4.5 K in the LINAC would be about 280 W [6]. This includes the static heat load of the cryostats and the helium distribution line, and dynamic heat load from the resonators (6 W per resonator). Considering future expansion needs and uncertainty in the continuous performance of the refrigerator at peak capacity, a helium refrigerator of design capacity 600 W at 4.5 K has been installed and is being operated regularly in both closed and open loop modes. This plant is nominally delivering about 450 W of refrigeration power at 4.5 K. The requirement of liquid nitrogen for shield cooling of cryostats, distribution line, and for precooling of helium refrigerator is met by a plant of capacity 5000 W at 80 K. An external LN_2 tank of 5000 l capacity with its distribution system has also been installed to take care of shortfall in the LN_2 requirement arising out of other needs, or due to any failure of the LN_2 plant.

At present the superbuncher cryostat and the first of the three LINAC cryostats are installed in the beam line and integrated with the refrigerators through the cryogen distribution network. During the first DC beam test and the subsequent pulsed beam test [7], the superbuncher cryostat was successfully cooled using the integrated cryogenic network.

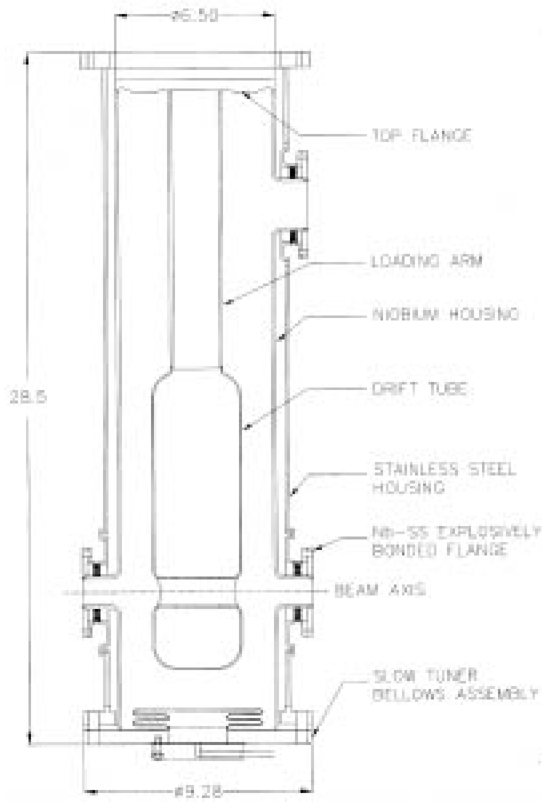

Figure 3. Schematic diagram of the quarter wave resonator. Dimensions are in inches.

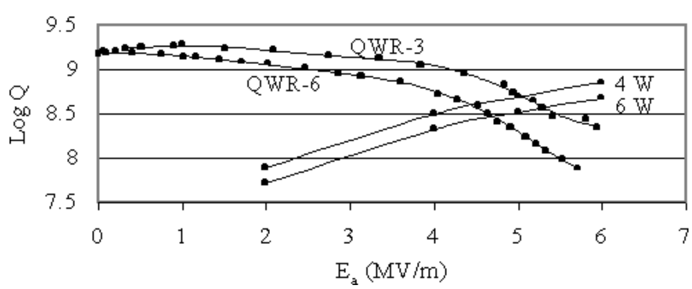

Figure 4. Measured values of resonator Q as a function of accelerating electric field E_a at 4.5 K.

Each major test continued uninterrupted for more than a week without the need for any changes in the settings of the refrigerator or the distribution system. The resonator in the superbuncher cryostat was cooled from 300 K to 220 K by inverse radiation of LN_2 shield and then precooled up to 130 K using liquid nitrogen. Cooling from 130 K to 4.5 K and subsequent filling of liquid helium was carried out in closed loop mode. The two-phase

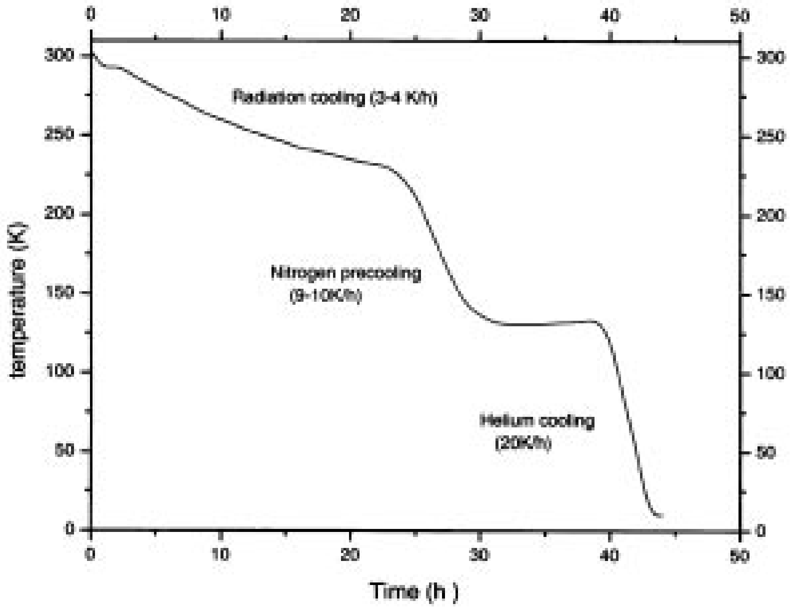

Figure 5. Temperature profile of the resonator cool down in the superbuncher cryostat.

liquid helium, after JT expansion, is first converted into 100% liquid in a 1000 l Dewar and then passes through the valve boxes and distribution line to cool the resonators and cryostat. The entire operation to bring the temperature down from 130 K to 4.5 K took about 5 to 6 h at a liquid helium flow rate of 30 l/h. Figure 5 shows a typical cool down profile of the resonator. The return helium gas initially joins at compressor suction, and later at the helium Dewar when the return temperature is less than 15 K. Depending on the heat load, the refrigerator capacity was optimized by adjusting compressor throughput and engine speed. Fine tuning of the heat load balance was done with the help of an immersion heater inside the l000 l master Dewar. A cryogenic data acquisition and control system (CRYO-DACS) is under development to control and monitor the cryogenic data from a remote control room. The hardware architecture of CRYO-DACS is VME bus with Vx works on a Windows2000 server host operating system. A brief description on helium distribution line and cryostats is given in the following sections.

2.2.1 *Helium distribution network*: The cryogen distribution network [8] has been designed in-house for parallel feeding of liquid helium to all cryostats by using four valve boxes. Long stem WEKA valves with minimum heat load (0.43 W) have been used for the supply, return and bypass line. Except for the field joint portion, the entire distribution line of approximately 40 m length is liquid nitrogen shielded, multilayer insulated, and enclosed in a vacuum-jacketed pipe of 8$''$ diameter. The integration between valve boxes and cryostats has been performed by vacuum break at both ends and a demountable joint without liquid nitrogen shielding. The total heat load of the distribution line was evaluated by measuring the rise of temperature for cold helium gas at a constant flow rate. The measured average heat load is less than 1 W/m length, of which 60% is contributed by the vacuum break, valves, and the unshielded portion of the line.

Figure 6. Inside view of LINAC cryostat (only six, of the eight, resonators are mounted).

2.2.2 *Cryostats*: The first LINAC cryostat [9], superbuncher cryostat, and a simple test cryostat for testing resonators offline, have been designed and fabricated indigenously. Vacuum requirement is one of the stringent factors for all these cryostats, as the beam line vacuum and cryostat vacuum is common. To meet the requirement of clean environment around the resonators, multilayer insulation was avoided and liquid nitrogen cooled thermal shield has been used to reduce the radiation heat load contribution. Shield cooling of superbuncher cryostat is achieved by gravity flow whereas for the LINAC cryostats it is by forced flow of LN_2 through SS pipes clamped on the copper shield. With an optimized flow rate of 20 l/h the achieved shield temperature is around 95–99 K. The achieved vacuum in superbuncher and LINAC cryostat at 4.5 K is $<10^{-8}$ Torr and measured static heat load of the LINAC cryostat without resonators and solenoid magnet is 7 W. A mechanism has been developed to align each resonator and the magnet individually, as well as the entire assembly, with reference to the beam line. Figure 6 shows the inside view of the first LINAC cryostat.

2.3 *RF electronics*

The superconducting resonators will operate at 97 MHz frequency. The phase and amplitude of the rf fields in the resonators need to be stabilized with respect to a reference master oscillator. The resonant frequency variation of the resonator acts as the main disturbance to the stabilization process. The resonant frequency variation occurs on two time scales. The fast component is due to the vibration of central conductor of the resonator and the slow component is due to the pressure variation in the cryogenic system. A resonator control scheme has been developed for the resonator, which incorporates a fast and a slow tuner section. In the fast tuner section the resonator is made the frequency selective part of an

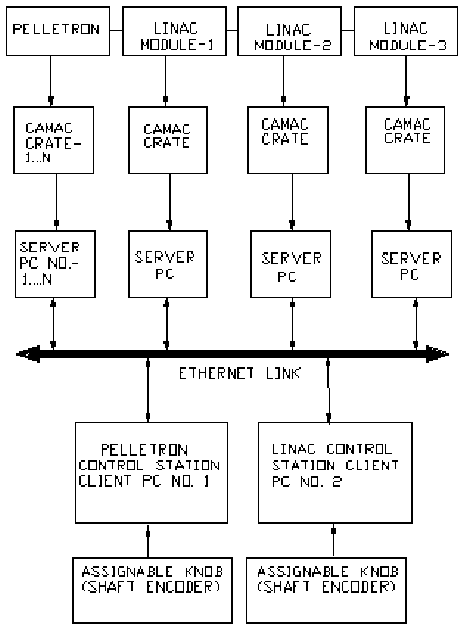

Figure 7. Schematic diagram of the Pelletron-LINAC control system.

oscillator. The phase of this oscillator is locked with the reference by dynamically inserting a phase shift in the oscillator by adding a quadrature signal in the oscillation loop [10]. The slow-tuner control mechanism has been incorporated to keep the average of the resonator frequency the same as the master clock. The inclusion of the slow tuner mechanism reduces the load on the fast tuner and results in reduced power requirement for control. This control scheme has been successfully tested with the resonator [11]. RF amplifiers for the control have been designed and developed. The amplifier consists of MOTOROLA power MOSFETs in a push pull design and can deliver 200 W RF power continuously and has full protection against the reflected power.

2.4 *Control system*

A distributed control system has been developed for the Pelletron-LINAC accelerator system (figure 7). It runs on a network of Pentium computers under the LINUX operating system. The devices of the accelerator are connected to several computers using CAMAC interface. The design is based on a client server model and the computers connected to CAMAC run the server code. Machines are provided on the same network for operator interface, by running the client program. The client computers use the X-window graphics and shaft encoder knobs interfaced to them to provide the operator interface. The system supports the monitoring and controlling of all the accelerator parameters including the beam profile monitors, from any of the clients. Client programs can be written for any specific application like automatic beam tuning through a particular section of the machine, conditioning of resonators etc. The system has been running the Pelletron accelerator for the past two years.

2.5 *Pre-tandem buncher and post accelerator sweeper*

A multi-harmonic pre-tandem buncher operating at 12.125 MHz has been fabricated and installed in the low energy section of the Pelletron [12]. The buncher is phase locked using a spiral cavity phase detector [13] installed in the post analyzer section of the tandem accelerator. The buncher is presently being used for producing pulsed beams for experiments. To remove the dark current in between pulses, a high energy sweeper, operating at 6.0625 MHz, has been designed, fabricated and installed recently in the post analyzer magnet section of the beam line [14]. The sweeper would be tested in the forthcoming beam tests for the LINAC.

2.6 *Beam transport system*

The beam transport system consists of beam diagnostic devices (Faraday cup, beam profile monitor etc.), quadrupole magnets, magnetic steerers, phase detectors (spiral cavity), vacuum components (valves, pumps, gauges etc.) and drift tubes. Several components of the beam transport system, such as the diagnostic box – which houses a Faraday cup, slits, target holder, and detector mounting arrangement – quadrupole magnets and power supplies, magnetic steerers and power supplies, phase detectors, have been designed and fabricated indigenously.

The ion optics calculations for the LINAC were performed using a ray tracing computer program developed at NSC [15,16], to optimize the position of the superbuncher, LINAC modules, and the rebuncher, in order to deliver either short time width or narrow energy width pulses on the experimental target. Detailed calculations have been performed to study variability of energy, simulation of realistic running conditions in a LINAC, and transportation of beams from Pelletron accelerator to the new beam hall. In addition, element misalignment calculations have also been done. In order to correct steering arising out of misaligned solenoid magnets, a bellows-steerer combined assembly has been designed [17], which will be installed between the LINAC modules.

3. Superconducting resonator fabrication facility (SuRFF)

To fabricate superconducting resonators in-house for the second and third LINAC modules, and resonators for future projects, three major facilities have been set up under the superconducting resonator fabrication facility (SuRFF) [18].

1. Electron beam welding facility.
2. Surface preparation laboratory.
3. High vacuum furnace.

3.1 *Electron beam welding machine*

The electron beam welding machine is a 3 axis CNC controlled, fully programmable, 15 kW, 60 kV machine with a vacuum chamber of size 2.5 m $\times$ 1.0 m $\times$ 1.0 m from M/s Techmeta, France. The run out table (1.4 m long) can travel 1.0 m and the electron gun can move $\pm$0.25 m. The machine is equipped with a rotary fixture having tilting facility, with matching tail stock. The vacuum chamber is pumped through two diffusion pumps of capacity 8000 l/s, which can pump the chamber to 2.0×10^{-5} Torr in less than 1 h. The operator interface consists of a computer and touch screen, and a CNC console for programming. The machine is very user friendly with online alarms and built-in fault manual. The machine has been commissioned at NSC and niobium welding parameter development is currently under progress.

3.2 *Surface preparation laboratory*

The surface preparation laboratory would be used to electropolish the niobium resonators. For this an acid fume hood and other accessories have been set up. A separate Class-100 clean room has been built which houses a high pressure water rinsing system (80 bar) for cleaning the resonators prior to final assembly. A high resistivity water system (18 MΩ-cm) supplies water to this facility. Except for the constant voltage high current power supply, all the other equipments such as water chiller, ultrasonic cleaner, large sink, safety systems, acid neutralizing tank etc. are in place. This lab is expected to be fully commissioned by July 2002.

3.3 *High vacuum furnace*

A high vacuum furnace supplied by M/s Hind High Vacuum Ltd., India, to anneal the niobium resonators up to 1200°C in vacuum ($\sim 10^{-6}$ T), has been commissioned at NSC. The double walled furnace chamber is water cooled and the hot zone size is ϕ600 mm × 1000 mm, which is pumped by a 5000 l/s turbomolecular pump. The heating elements are made of molybdenum. The furnace is bottom loading type, which is moved through a hydraulic system. The furnace can be programmed through a computer for ramp up and hold on time. The computer also logs the data and monitors the various interlocking systems.

4. Present status

Construction of the linear accelerator has currently reached an advanced stage with all the designing and prototyping aspects completed. The LINAC beam line has been laid up to the first LINAC cryostat, and the superbuncher and LINAC cryostats are installed in the beam line. Liquid helium and liquid nitrogen plants have been installed and are in regular operation. The cryogenic distribution system has been designed, fabricated, installed and operated for transferring liquid helium to the cryostats. A resonator control module, suitable for the NSC LINAC, has been designed and tested with the resonator. Several RF amplifiers and other electronic items for control have been designed and fabricated. A number of beam transport items have been fabricated indigenously. A multiharmonic buncher has been installed in the low energy section and a post accelerator sweeper has been installed in the high energy section of the Pelletron accelerator. The superbuncher has been tested with both DC and pulsed beams. Details of the tests are presented elsewhere in this conference [7].

We plan to commission the first LINAC module by the end of this year. It is planned to lay the beam line up to the second switching magnet so that beams can be delivered in the new beam hall. Indigenous fabrication of resonators will begin soon. In the first phase three resonators will be fabricated, and after assessing their performance production of the remaining resonators will be taken up.

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