OPERATIONAL EXPERIENCE OF THE SUPERCONDUCTING LINAC BOOSTER AT MUMBAI

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Abstract

The superconducting LINAC booster, indigenously developed to boost the energy of the heavy ion beams from the 14 MV Pelletron accelerator at TIFR, Mumbai, has been fully operational since July 2007. The LINAC consists of seven modular cryostats, each housing four lead plated quarter wave resonators, designed for an optimum velocity β_0=0.1 at an operating frequency of 150 MHz. In order to maintain a stable phase and amplitude of the electric field in the cavity, the RF controller cards based on a self-excited loop (SEL) with phase and amplitude feedback have been developed indigenously. The cryogenic system for the LINAC has been designed for a typical power dissipation of 6 W in each resonator. Initial beam trials have yielded average energy gain of 0.4 MV/q per cavity corresponding to 80% of the design value. Operational experience of the LINAC, namely, empirically devised procedures for the acceleration of different beams and RF settings, and associated developments are presented.

INTRODUCTION

A superconducting linear accelerator, indigenously developed to boost the energy of heavy ion beams delivered by the Pelletron accelerator at Mumbai, has been operational since July, 2007 [1]. A schematic layout of the LINAC booster is shown in Fig. 1.

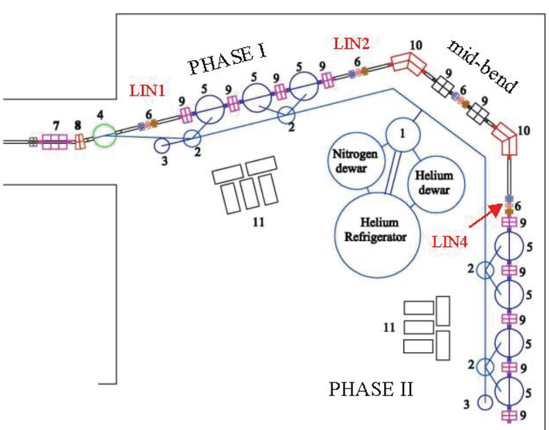

Figure1: A schematic layout of the LINAC.

The LINAC Phase I (superbuncher + 3 modules) and Phase II (4 modules) are connected by an achromatic, isochronous mid-bend magnet system (QD-MD-QD-QD-MD-QD). A compact longitudinal phase space is essential for acceptance in Phase II after the mid-bend and for optimization of the beam quality at target position. During the acceleration and beam transport, it is also important to preserve the longitudinal phase space over the length of the LINAC. The empirically devised procedures for the acceleration of different beams and RF settings are described in this paper. Different subsystems and associated developments are also presented.

QUARTER WAVE RESONATOR

The LINAC consists of seven modular cryostats, each housing four accelerating cavities. The RF cavity is a Quarter Wave Resonator (QWR), an open-ended $\lambda/4$ coaxial transmission line. The resonator is made out of OFHC copper (outer diameter 200 mm, 640 mm long) and is designed for an optimum velocity β_0=0.1, at an operating frequency of 150 MHz (Fig. 2) [2,3]. Typically, Q~1-2 x 10^8 is obtained at an average accelerating field of 2-2.5 MV/m.

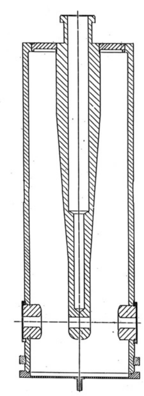

Figure 2: The Quarter Wave Resonator.

The fabrication and the e-beam welding of the QWR were carried out by the Centre for Design & Manufacture (CDM), BARC. The brazing of the two side beam ports to the outer conductor was carried out in a hydrogen furnace at SAMEER, Mumbai. The porosity present in the e-beam welded joint on the inner surface, at the junction of the shorting plate and the outer can, has been the single major manufacturing hurdle. We have designed a burnishing tool to repair some of the minor defects at this welding zone and have successfully refurbished several resonators. The QWRs were plated with Lead, approximately 2 µm thick, using a commercially available

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MSA (Methyl Sulfamic Acid) plating bath in a laboratory specially set up for this purpose at TIFR.

CRYOGENICS

The heart of the cryogenic system for the heavy ion superconducting LINAC booster is a custom-built liquid helium refrigerator Linde TCF50S. The Refrigerator is rated for 300 Watts at 4.5 K with a dual JT (Joule-Thomson valve) at the final cooling stage, which allows simultaneous connections to the cryogenic loads (the LINAC module cryostats) and to a liquid helium storage dewar (1000 l). The two-phase helium at 4.5 K produced at the JT stage in the refrigerator is delivered to the cryostats through a cryogenic distribution system. The phase separation is achieved in the individual cryostats and the cold (4.5 K) helium gas is returned, by the distribution system, back to the helium refrigerator. The four quarter wave cavities inside each cryostat are gravity-fed from a horizontally mounted liquid helium vessel. The total mass at 4.5 K in each of the modules is close to 250 kg.

The cryogenic distribution system for the LINAC is designed to deliver both liquid helium and liquid nitrogen to the cryostats [4]. The system consists of a main junction box, distribution trunk lines, remote filling stations, triaxial transfer tubes and loop back end boxes.

A 300 l dewar is used as a source of the liquid nitrogen to the main junction box. The boiled off nitrogen gas returned from the cryostats is used for thermal shielding of the distribution line and let out to the atmosphere at the main box.

The cryostat has a helium vessel of 40 l capacity connected to the recovery system via a manual valve and a relief valve (set at 0.7 bar), and two blow off valves set at 1.7 bar for over-pressure safety. In addition, the He vessel has a pressure transducer and a liquid He level sensor. Silicon diodes are mounted on the relief valve ports and are used for remote monitoring of the temperature in the neck zone to trigger an audio-visual alarm in the control room. This over-pressure warning has resulted in a failsafe and efficient operation of the cryogenic system.

The cold gas after the JT stage in the cold box is used for the cool down of the modules starting from ambient temperature. An empirical procedure has been evolved to make a smooth switchover on different return paths in the cold box. The entire LINAC comprising all 8 cryostats is cooled simultaneously and a complete cool down is typically achieved in 3-4 days. The plant is designed to work automatically and the control is based on a Siemens SIMATIC S7-400 PLC system. We have developed a control system for the remote operation of the plant from the accelerator control room using the Siemens visualization software platform, WINCC.

Table 1 gives details of estimated and measured heat load. Actual total heat load of 180 W was observed for the whole system without RF power. Therefore, the available cooling power for RF load is only 120 W, which is not adequate. Hence during the user cycle, the refrigerator was operated with liquid nitrogen precooling. The refrigeration power can be enhanced by a maximum of 150 W with a full precool.

Table 1: Estimated and Actual Heat Load

	Estimated Heat load		**Actual Heat load**
	Phase I	**Phase II**	
Distribution box, main box, and Trunk line	16W	16W	50W
Transfer tube and cryostat	4x12W=48W	4x12W=48W	130W
RF power load (SB + Modules)	12x6W=72W 1 x 4W =4W	16x6W=96W	172W
Total (Phase I+II)	300W		352W

RF POWER AND PHASE SETTINGS

In order to maintain a stable phase and amplitude of the electric field in the cavity, Electronics Division, BARC has developed the RF controller cards based on a self-excited loop (SEL) with phase and amplitude feedback [5]. The RF power is fed to each resonator using this controller card with a solid state 150 MHz, 150 W RF power amplifier. It is essential to calibrate the RF output power as a function of the controller card settings. Fig. 3 gives a schematic representation of the calibration procedure. A reference signal at 0 dBm is given to the input of the controller card and by varying the RF level from the controller, the output power of the amplifier is measured at the resonator end terminated with a 50 Ω load. The output power is measured by an in-line power meter and at the side port of a calibrated directional coupler.

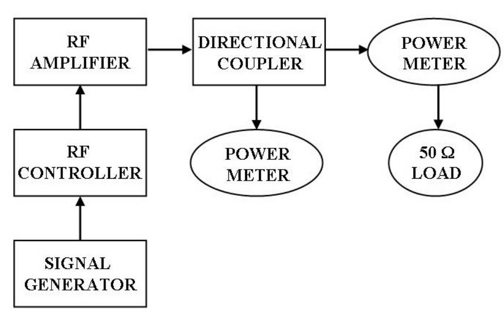

Figure 3: Power setting procedure for the QWR.

The voltage pickup for each resonator at the desired power setting (6 W) is recorded under critical coupling condition. These pickup values are monitored during the accelerator operation. The quiescent power from the amplifier is set to 50 W and the variable power coupler is adjusted to achieve the necessary over-coupling and the field amplitude in the cavity as measured for the critical coupling at 6 W setting.

Synchronous Phase Settings

As the phase of the electric field in each of the cavities can be set independently, it is possible to accelerate a variety of ions (Q, M) over a wide range of velocities (β). Furthermore, to maintain a periodic time focusing of the bunched beam over the length of the LINAC, the accelerating cavities need to be set at synchronous phase angles (Φ_{res}) corresponding to time focusing or de-focusing.

The reference phase setting of the controller (Φ_{ref}) for each individual resonator needs to be determined as a function of Q, M and β of incident ions. In order to set these phases, it is necessary to measure the phase offsets (Φ_0) for each resonator. The phase offset for each resonator control circuit is independent of the beam and depends only on the hardware. The phase of the RF field in each resonator can be expressed as:

$$\Phi_{res} = \omega t + \Phi_{ref} - \Phi_0 \quad (1)$$

where ω is the RF frequency and $t = l/\beta$ is the arrival time of the beam after the drift length l from the preceding cavity. The Φ_0 can be extracted from Φ_{ref} values corresponding to zero energy gain, namely at $\Phi_{res} = 0$,

$$\Phi_{ref} = \Phi_0 - \omega t \qquad (2)$$

Both the $\Phi_{res}=0$ (time focusing) and $\Phi_{res}=\pi$ (time de-focusing) correspond to zero energy gain and were measured for different beams (C, O and Si) over a wide range of velocities ($\beta \sim$ 0.05 to 0.12) to extract the phase offsets for all cavities.

We have developed a program to optimize the longitudinal phase space (ΔE-Δt) at the target position based on a complete non-linear algebra using the measured resonator field values. The program tracks the evolution of the longitudinal phase space for all 2^N configurations corresponding to both time focusing (-20°) and time defocusing (+20°) of N resonators. The LINAC Phase I (Superbuncher and M1 to M3) and Phase II (M4 to M7) are computed sequentially. For the Phase I, the starting 2D Gaussian distribution with $\sigma_t \sim 0.375$ ns, $\sigma_e \sim 0.05$ MeV, is taken from longitudinal phase space measurements of the bunched beam at the injection of the LINAC. For the Phase II, the starting phase space is taken as a bounding 2D Gaussian distribution describing the output of the Phase I. Fig. 4 shows the calculated phase space for a distribution of 1024 rays at various points during the acceleration in the Phase I.

From the outputs corresponding to all 2^N configurations, a subset of solutions satisfying criteria of a compact phase space throughout the accelerating length (minimum ΔE and ΔT) is chosen. For any of these configurations, the given set of Φ_{res} is used to calculate the reference phase settings (Φ_{ref}) for all resonators using Eq. 1. A final configuration corresponding to an optimal phase space at target (determined by measurement of the transmission and the time structure) is then selected from this subset.

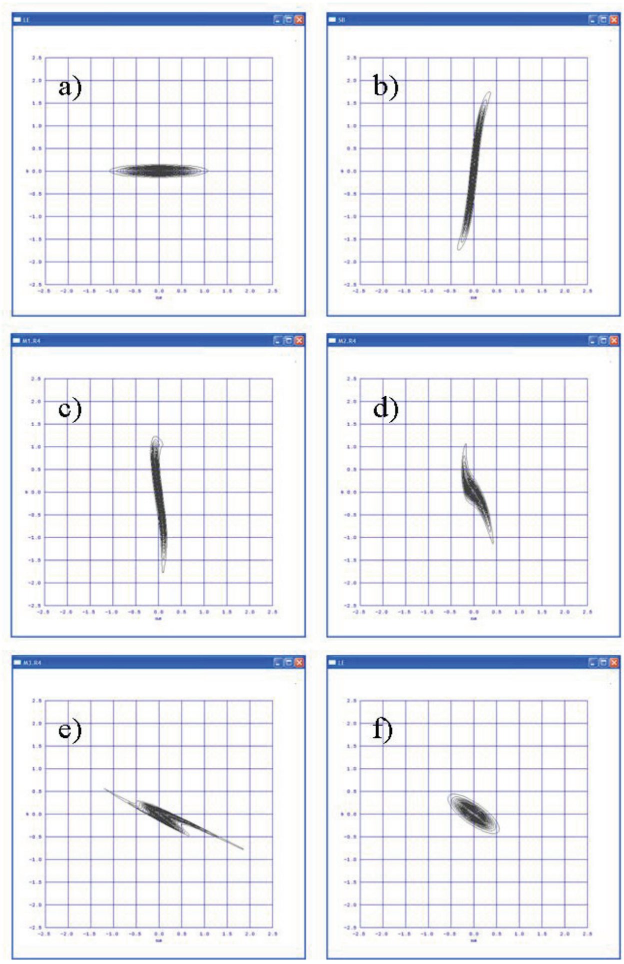

Figure 4: Longitudinal phase space (see text for details): a) at LINAC injection, b) after Superbuncher, at the entry of M1, c) after M1, at the entry of M2, d) after M2, at the entry of M3, e) after mid-bend, at the Phase II entry, f) equivalent distribution for the Phase II corresponding to (e).

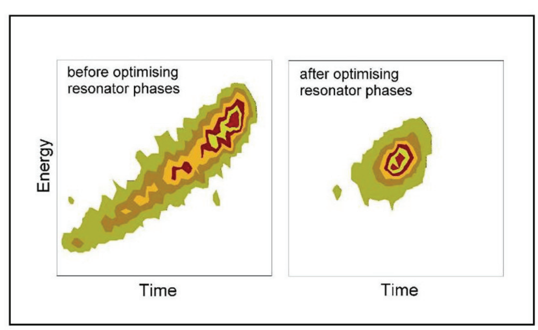

Figure 5: Longitudinal phase space across the mid-bend.

As a part of initial diagnostic tests, detailed measurements were carried out using microsphere plate, BaF_2 detector and Silicon detector. Fig. 5 shows the longitudinal phase space measured for scattered Si beam from a thin Au target at the entrance of the LINAC Phase II [6].

This procedure described above has been established with several beam trials and eases the setting up of beam acceleration for routine operation.

RF Stability

A stable operation over a period of several days is essential to deliver the beam for experiments. This necessitates very high stability for the RF control system. The control circuit is designed with a phase stability better than 0.1 and amplitude stability better than 0.1% [5]. At startup, typically 30 minutes are required for the stabilization of the controller circuits and the power amplifier. Detailed stability tests were carried out over the period of several days, where both amplitude and phase errors were recorded for each controller card and amplifier. The high power devices employed in the RF amplifier and the controller cards are prone to drift as a function of the ambient temperature. However, this does not adversely affect the acceleration as the phase and amplitude in the controller circuit is derived from a low power section of the circuit, which is fairly independent of the ambient temperature.

CONTROL SYSTEM

A CAMAC based accelerator control system based on a master-slave configuration has been developed [7]. A local control station (LCS) consisting of a PC interfaced to CAMAC crates with analog and digital modules and the RF electronics controls up to eight cavities (i.e. two modules). These LCS in the accelerator hall are interconnected via Ethernet to the main control station (MCS) located in the control room. This system allows simultaneous setting up of parameters for the different LINAC modules with the MCS enabling overall control during the beam tuning. The control software developed using JAVA operating on Linux OS, consists of two layers, namely, a scanner and a graphical user interface (GUI). The scanner acts as a TCP/IP server and directly accesses the CAMAC crates, while GUI connects to the scanner via TCP/IP.

INSTRUMENTATION

Interface and control electronics has been developed for various cryogenic parameters and beam line devices. The MCS in the control room communicates to different addressable local control stations (μC based) via Ethernet to serial link.

A local multi-channel, multiplexed cryo-control station, controls and monitors the cryogenic valves, level sensors for both LHe and LN_2, pressure and temperature of each cryostat. Two such cryo-control stations, catering to four cryostats each, have been installed.

A large number of locally developed Faraday Cups and beam profile monitors (BPM) have been installed in the beam lines. A 24 channel multiplexed, control and readout unit with a 12 bit ADC has been developed for Faraday cups as well as for BPMs.

A magnetic X-Y steerer designed using a standard motor stator with sin-cos windings to provide a uniform magnetic field over a ~50 mm diameter and length ~100 mm have been installed at several locations. All the power supplies for magnetic elements like steerers, quadrupoles and dipoles are individually controlled from the MCS via the ethernet to serial link.

ACCELERATOR OPERATION

Carbon, Oxygen and Silicon beams were accelerated and delivered at various experimental stations in user hall I (Table 2). Energy of the accelerated ions was measured by the magnetic field of the bending magnet. The number of resonators used for acceleration is varied as per the user requirement. The field in each resonator was also similarly measured using energy gain of the DC beam. Initial beam trials have yielded average energy gain of 0.4 MV/q per cavity corresponding to 80% of the design value. Beam transmission from entry to exit of LINAC was found to be 80%, without using any beam steerers. Timing detectors are provided at injection of the LINAC, at entry of the Phase II and after the switching magnet in user beamlines. Typically, beam transmission at target after collimation was found to be ~50% of that at the entry to the LINAC. The beam timing measured at target was found to be excellent σ ~ 250 ps (see Fig. 6).

Table 2: Beams accelerated through LINAC

Beam	E_{pell} (MeV)	E_{LINAC} (MeV)	E_{total} (MeV)
^{12}C	82.5	37.5	120.0
^{16}O	93.6	22.1	115.7
^{19}F	94.0	50.2	144.2
^{28}Si	90-100	48-109	138-209

With the procedure described in the preceding section, typically 6-8 hours are needed for tuning the beam to the experimental station.

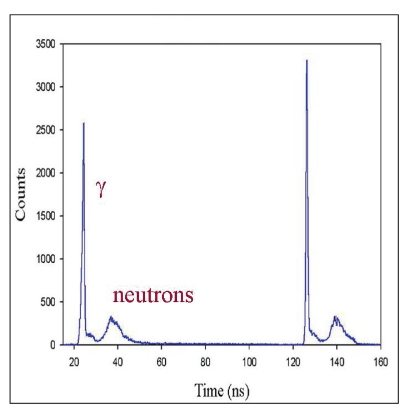

Figure 6: Time spectrum with BaF_2 detector at target position (σ_{beam} ~ 250 ps).

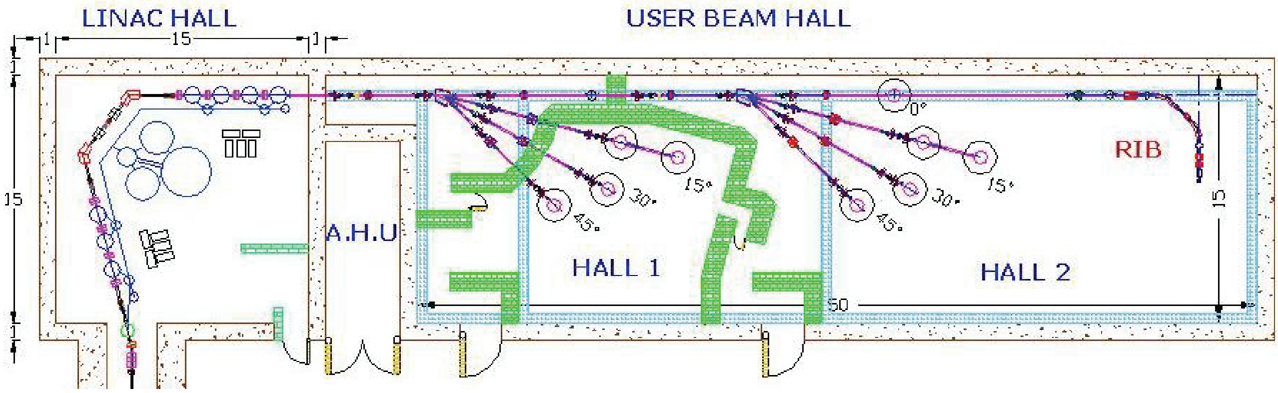

Figure 7: A Schematic layout of the experimental facilities.

EXPERIMENTAL FACILITIES

The complete layout of experiment halls together with LINAC is shown in Fig. 7. A total of 7 beam lines are planned in two separate user areas. The research programmes cover a wide span of disciplines like Nuclear Physics, Atomic, Molecular and Cluster Physics, and Condensed Matter Physics. Several new experimental facilities are planned. For example, BGO/NaI multiplictity filters, BaF_2 array for high energy gamma ray studies, 1 x 1 m^2 plastic scinitillator array for neutron spectroscopy have already been installed. The Indian National Gamma Array (INGA) a 24 element Clover array for high resolution in-beam gamma spectroscopy, will be commissioned at PLF, Mumbai in near future. A Momentum Achromat for light Radiaoactive Ion experiments (MARIE) and a large solid angle, modular, segmented array of 50 detectors (Si+CsI) are under development.

CONCLUSION

The superconducting LINAC booster at PLF, Mumbai is fully operational. For acceleration of different beams, an algorithm for RF power and phase settings of the individual resonators has been devised. We plan to extend routine operations to heavier beams (up to Ni). The development of digital RF controller cards and improvements to GUI are being planned for better performance. We also propose to upgrade the cryogenics system so that LINAC can be operated without LN_2 precool.

ACKNOWLEDGEMENT

We would like to thank Electronics Division and CDM, BARC, Central Workshop and Low Temperature Facility, TIFR, and the Pelletron-LINAC staff for their dedication, hard work and support.

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