PRAMANA — journal of physics
Vol. 57, Nos 2 & 3
Aug. & Sept. 2001
pp. 651–658

Superconducting LINAC booster for the Mumbai pelletron

B SRINIVASAN*, S K SINGH*, R G PILLAY†, M B KURUP† and M K PANDEY†
*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
†Tata Institute of Fundamental Research, Colaba, Mumbai 400 005, India

Abstract. We are in the process of constructing a superconducting linear accelerator (LINAC), to boost the energy of heavy ion beams from the 14UD Pelletron accelerator, at Tata Institute of Fundamental Research, Mumbai. The accelerating structures in the LINAC are quarter wave resonators (QWR) coated with lead which is superconducting at liquid helium temperature. With feasibility studies having been completed during the course of the 4th and 5th five-year plan periods, culminating with the demonstration of beam acceleration using one accelerating module, the construction of the LINAC is now under way.

Keywords. Superconducting linear accelerator; quarter wave resonator; lead plating; quality factor; RF electronics.

PACS No. 29.17. + w

1. Introduction

A 14UD pelletron accelerator has been installed at TIFR, Mumbai. 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 nuclear physics experiments. It is clear that with the heavy ion beams available from the pelletron, nuclear physics studies are possible only in a limited range of target-projectile combinations. It would, therefore, be desirable to extend the scope of studies by a further increase of the energy of the heavy ion beams from the pelletron.

It was realized more than two decades ago that significant benefits could be derived from the use of superconducting RF resonators for the acceleration of heavy ion beams for nuclear physics experiments. Since ohmic losses in such resonators are reduced by $\geq 10^4$ relative to normal ones, a substantial reduction in electric power to maintain large electric fields can be obtained, making it possible to build very compact accelerators operating in continuous-wave (CW) mode. Hence, a superconducting linear accelerator (LINAC) is being constructed to serve as a booster to the Mumbai pelletron.

The LINAC has been designed to provide heavy ion beams with energy >5 MeV per nucleon up to mass $A = 80$. At present, such superconducting LINAC boosters for heavy ion beams are in operation at the State University of New York, Stony Brook, USA, Argonne National Laboratory, Chicago, USA, University of Washington, Seattle, USA, Legnaro National Laboratory, Italy and at the Japan Atomic Energy Research Centre, Japan, etc. [1].

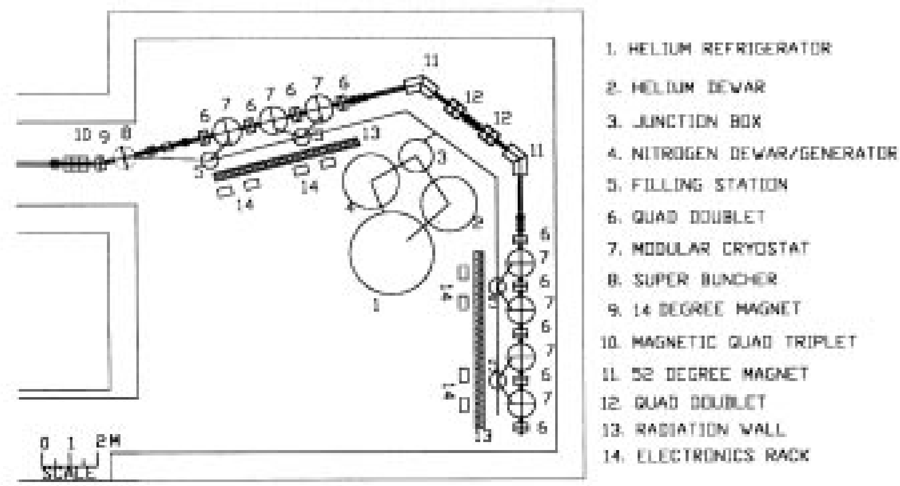

Figure 1. LINAC layout.

The main advantage of the LINAC lies in its modular structure. Each accelerating module houses four resonator cavities. Therefore, depending on the energy gain required, more accelerating modules can be added (figure 1). This also means that a major part of the R&D effort is actually centered on achieving beam acceleration using one accelerating module.

The scope of the project as envisaged in the original proposal includes:

- Design and fabrication of quarter wave RF resonators.
- Development of a facility for the lead-plating of the resonators.
- Design and construction of a suitable cryogenic system.
- Fabrication of appropriate beam transport components, to be used in the LINAC beam line for optimum beam transport.
- Development of RF electronic circuitry for resonator control.
- Monitoring and control of all LINAC parameters by a dedicated computer.

In what follows, the R&D effort and the present status in each of these subsystems is described.

2. The accelerating structure

A heavy ion LINAC consists of a series of RF resonators each individually phase-locked so as to have appropriate accelerating voltages across the gaps at the instant the ion beam passes through it. Two important parameters of the resonator are its resonant frequency and the $\beta(= v/c)$ value. A typical LINAC would have several such identical structures serving to accelerate a variety of charged particle beams from the pelletron. One of the widely used accelerating structure is the quarter wave resonator (QWR).

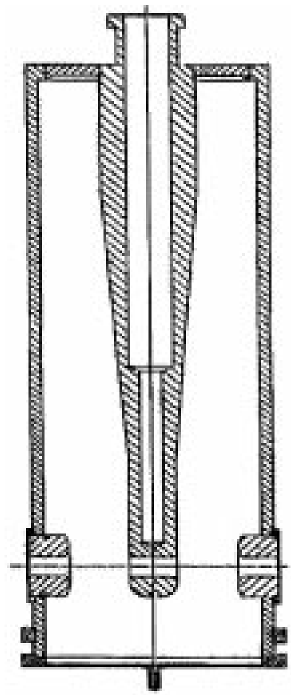

Figure 2. QWR schematic.

The QWR is essentially an open-ended λ/4 coaxial transmission line capable of supporting high accelerating voltages at its open end. This resonator is shown schematically in figure 2.

The QWR is made out of OFHC copper, has a resonant frequency of 150 MHz and its $\beta = 0.1$. The vertical, tapered, inner conductor is made hollow for filling with liquid helium, while the outer can is cooled by conduction. This resonator has a rigid mechanical structure. Consequently, resonant frequency excursions due to mechanical vibrations are relatively small. Being a two gap accelerating structure, it has a wide velocity acceptance, permitting effective acceleration over a wide range of heavy ions. On account of these attractive features it was decided to use the QWR as the accelerating structure in the LINAC [2].

The QWRs are being fabricated at Central Workshops (CWS), BARC. The machining of the resonator components is carried out at CWS, and at the premises of a private vendor in Mumbai who has the requiste capacity for the machinning of such precise structures. The joining of the central conductor/flange assembly is done using electron-beam welding at CWS. The inner conductor/flange assembly has been procurred as a forged piece, which reduces the number of electron beam welds to two per resonator instead of the four originally required. Considering that all welds occur in the region of high currents, this simplification is expected to improve the performance of the resonators.

The fabrication of 14 resonators is complete in all respects, and 21 more are expected to be completed shortly.

3. Lead plating

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 [2]. A lead plating laboratory has been set up at TIFR and the plating parameters have been optimized for two different plating baths – a fluoboric acid based plating bath and more recently, a methane sulphamic acid (MSA) based plating bath. A resonator (Seattle resonator) imported from the University of Washington, Seattle, USA, has served as the model for the standardization of the plating parameters.

An essential ingredient of the fluoborate bath is ‘shinol’ which is used to increase the throwing power of the solution. This is a proprietary item manufactured by M/s Harstan Chemicals, USA. The additive is known to have a shelf life and is now no longer available since its production has been discontinued. Also, since fluoboric acid is an essential ingredient of the bath, extreme care has to be exercised in using it. Further, disposal of used solutions is difficult because of the high lead content.

The MSA based plating bath is currently being used for plating the resonators. Since the acid is essentially organic in nature, handling of the plating solution is now considerably simplified. Various test platings have been carried out using this solution under conditions of pulse plating, continuous plating and changing of additive concentrations. The MSA plating bath contains (by volume percent) acid 7%, lead concentrate 2.4%, smoothing agent RTH 0.5%, brightening agent HMM 1.5% and water 89.1%. The plating current density used is $\sim$ 3.6 mA/cm^2. The plating is done in pulsed mode with 50% duty cycle. We have observed that the quality of the lead plating is superior and the plating is much more reproducible as compared to that obtained with the fluoborate bath.

A quantitative evaluation of the Pb surface requires a measurement of the resonator’s quality factor below the superconducting temperature. Under conditions of critical coupling, power is pulsed into the resonator and the decay of the stored energy is observed on an oscilloscope [2]. With the Seattle resonator plated using the fluoborate bath we have obtained an electric field of 2.6 MV/m with a power dissipation of 7 W (figure 3) while fields in excess of 3.2 MV/m have been obtained with MSA plating.

A comparison of the quality factor of the Seattle resonator and a resonator manufactured at CWS is shown in figure 4. Also shown in the figures are constant power lines, from which, for a given fixed power, the desired quality factor needed to achieve a given accelerating field can be inferred.

4. The cryogenic system

For the stable operation of the LINAC, an efficient cryogenic system comprising of a refrigerator to produce the required low temperatures, cryostats to house the accelerating structures and transfer tubes for transferring the cryogens (liquid helium and liquid nitrogen) to the cryostats, is required. The cryostat is a vertical cylinder with cryogen storage tanks suspended from the top flange [3]. The top flange also provides ports for cryogen filling, high vacuum feed throughs and access for control and monitoring of all parameters of the QWRs. The QWRs are suspended from the horizontally mounted cylindrical liquid helium storage tank, through which liquid helium is gravity-fed to the QWRs. The helium circuit is enclosed within a radiation shield maintained at liquid nitrogen temperature and the entire assembly is maintained under ultra high vacuum.

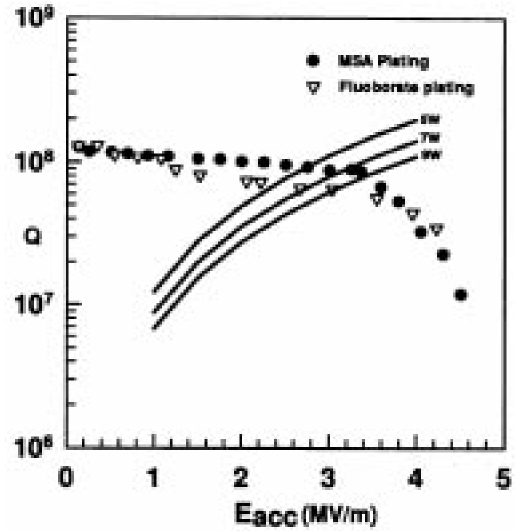

Figure 3. Quality factor vs average accelerating field in Seattle resonator for fluoborate and MSA plating.

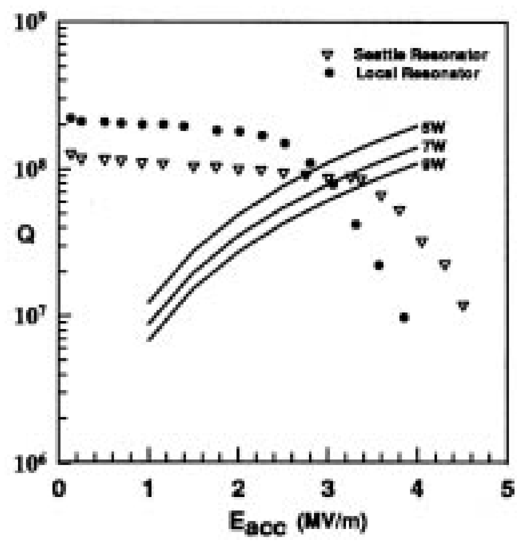

Figure 4. Comparison of Seattle resonator and local resonator for fluoborate and MSA plating.

The heat load per module on the helium circuit is typically about 30 Watts and with 7 accelerating modules and one superbuncher the total heat load is around 240 Watts. Since these modules would have to be physically spread out, such a system would entail a complex distribution network of the main trunk line, junction boxes and transfer lines to transfer the cryogens to the cryostats. Considering the standing heat load on the cryogen distribution network, a helium refrigerator with a cooling capacity of 300 Watts (without liquid nitrogen precool) and operating in a closed-cycle mode would be required.

Four large liquid helium cryostats with a number of high vacuum feed throughs and manipulators were designed and fabricated for use in the LINAC. The first one was a cryostat with 35 ltrs capacity for liquid helium used for mounting the superconducting buncher cavity (lead plated split-loop resonator) on the beamline. This cryostat was fabricated mostly in the TIFR central workshop. The outer vacuum shell of the cryostat, because of its large size, was fabricated by a private firm in Mumbai. This cryostat was the first big sized cryogenic container fabricated indigenously and provided us the basic inputs for the design and fabrication of the more complicated accelerator module cryostats. For the first modular cryostat, the engineering drawings were made at the central workshops, BARC. The fabrication was done at the IBP Co. Ltd., Nasik. Since this was the first liquid helium cryostat fabricated, significant R&D was involved in design and fabrication process. The second and third modular cryostats were fabricated by M/s Vacuum Techniques Pvt. Ltd., Bangalore and was based on our earlier design which was, however, somewhat modified in view of our experience gained during the commissioning of the first cryostat. All the internal components of the cryostats have been assembled and are ready for the mounting of the resonators.

A helium refrigerator, model TCF50S and a 1000 lts helium dewar was purchased from Linde, Switzerland. The installation and commissioning of the helium refrigerator has been completed. A cooling power of 372 Watts (without liquid nitrogen precooling of the cold box heat exchangers) and liquefaction rate of 82 l/hr has been obtained against the indented specifications of 300 Watts refrigeration and 50 l/hr liquefaction. Prior to the installation of the refrigerator, civil modifications were carried out in the LINAC hall in order to lay the gas and chilled water lines essential for the operation of the helium refrigerator and other beam line components. Two X-Y cranes of capacity 2 tons each necessary for the servicing of LINAC beam line components have been installed and commissioned.

Two junction boxes, each catering to two cryostats and one main junction box for feeding the main trunk line and transferring the return gas back to the refrigerator have been fabricated. Triaxial transfer lines and the main trunk line are currently under fabrication.

5. Beam transport

In order to preserve the beam quality in both the longitudinal and the transverse phase space, it is necessary to maintain a tight focusing of the beam throughout the LINAC. This is achieved by a magnetic quadrupole triplet situated in the injection path and a periodic array of magnetic quadrupole doublets interspersed between the accelerating modules. The triplet was fabricated by a local firm whereas the doublets have been fabricated by M/s. Danfysik, Denmark.

On account of the constraint on the available space, the LINAC is being constructed in two sections. An isochronous, achromatic and mirror symmetric bending magnet system has been designed to facilitate waist-to-waist transport with unit magnification in both the bending (x-z) plane and in the vertical (y-z) plane from the object point (exit of first half of LINAC) to the image point (entrance of second half of LINAC). Each symmetric half consists of a magnetic quadrupole doublet on either side of a 52 degree dipole magnet.

A beam profile monitor, X-Y slits and Faraday cup will be located in the object space of the magnet, in the image space of the mirror magnet and at the symmetry plane for beam diagnostic purposes.

The entire bending magnet system has been fabricated and delivered by M/s. Danfysik, Denmark. Beam diagnostic elements, similar to those mentioned above, to be used in the LINAC injection and exit paths have been procurred from M/s. Danfysik, Denmark. Timming chambers to monitor the beam pulse-width (100–200 psec) at various points in the LINAC are being designed.

6. RF electronics

One of the main advantages in the LINAC is the independent phase control of each of the resonators. This permits, depending on the accelerating structure, acceleration of beams over a wide range of velocity. However, in order to achieve coherent acceleration of the beam, it is essential to maintain the phase and amplitude of the field in each resonator to a stability better than 0.1%. This is achieved using an RF controller, which is essentially a feedback control system where the output phase and amplitude of the electric field in the resonator is compared with a reference phase and amplitude. The resulting error signals are used to generate in-phase and quadrature power components which lock the resonator's field amplitude and phase to set values [4].

A crucial component in the RF controller is the complex-phasor modulator (CPM), which has to be imported. We have experienced considerable difficulties in procuring this sensitive item and moreover have managed to procure only a few of them. Consequently, a new design of the RF controller has been developed, at Electronics Division, BARC, wherein the CPM's have been simulated using discrete components. These RF controller cards have been extensively tested for their phase and amplitude locking characteristics and at present 10 such cards are being wired.

These controller cards have also been tested on resonators at Nuclear Science Centre (NSC), New Delhi and Australian National University, Canberra, Australia.

Electronic circuits for the control of the various components in the injection path of the LINAC have also been designed and fabricated at Electronics Division, BARC.

Prototype RF power amplifiers of 150 Watts power output and central frequency of 150 MHz have been developed with the collaborative effort of NSC, Electronics Division, BARC, and Bharat Electronics Limited (BEL), Bangalore, for this project. Two prototypes fabricated at BEL have been successfully tested, and the entire requirement of RF amplifiers will be met by BEL.

7. The accelerator control system

The accelerator control system uses CAMAC front end [5]. A combination of CAMAC crates with functional modules, RF control and other electronics for monitoring cryostat parameters, and a PC forms a local control station (LCS). Each LCS will control two cryostats. Several such LCS's will be interconnected through fast ethernet to the main control station (MCS) located in the control room. The various LCS's will help in the simultaneous setting up of parameters for the various LINAC modules with the MCS being used for overall control when the LINAC is accelerating the beam. All CAMAC modules and software for accelerator control have been developed at Electronics Division, BARC. The software for the LCS/MCS system has been developed under Linux OS.

8. Conclusions

The culmination of the R & D efforts in the various subsystems of the LINAC was the demonstration of bunching of heavy ion beams to picosecond widths [6] and the acceleration of heavy ion beams using one accelerating module [7]. The construction of the LINAC is now in progress, with the immediate goal being the setting up of the first half of the LINAC, comprising of the LINAC injection system, three accelerating modules and the bending magnet system. Almost all hardware required to accomplish this has been procured.

Acknowledgements

The authors gratefully acknowledge the guidance and support of Dr. S S Kapoor, Homi Bhabha Fellow, BARC and Prof. S S Jha, Director, TIFR.

References

[1] L N Bollinger, *Ann. Rev. Nucl. Part. Sci.* **36**, 475 (1986)

[2] R G Pillay, M B Kurup, A Jain, D Biswas, S A Kori and B Srinivasan, *Ind. J. Pure Appl. Phys.* **27**, 671 (1989)

[3] B Srinivasan, *Proc. DAE Nucl. Phys. Symp.* Invited talks, **A36**, 157 (1993)

[4] G Joshi, C I Sujo and J Karande, *Proc. Symp. Intelligent Nucl. Instrum.* **2001**, 105 (2001)

[5] G Joshi, S K Singh, R S Kapartal, K Jha, N C Rathod, C I Sujo, T S Ananthakrishnan, A Narsaiah, M D Ghodgaonkar and S K Kataria, *Proc. Symp. Intelligent Nucl. Instr.* **2001**, 100 (2001)

[6] R G Pillay, M B Kurup, M K Pandey, B Srinivasan, M N Thakur, M G Betigeri, M Y Vaze, P J Bhalerao, S K Gupta and P V Bhagwat, *Proc. DAE Symp. Nucl. Phys.* **B37**, 497 (1994)

[7] R G Pillay, M B Kurup, M K Pandey, B Srinivasan and M G Betigeri, *Proc. DAE. Symp. Nucl. Phys.* **B39**, 368 (1996)