Accelerator development at the Nuclear Science Centre

A. Roy

The Nuclear Science Centre has embarked upon a plan of augmenting the accelerator facility by constructing a superconducting Linac booster based on niobium cavity resonators. The plan has been evolved to fulfil major requirements of the user community to continue internationally competitive research in some focused areas. Most of the necessary technical developments connected with fabrication of different subsystems have been completed. Emphasis has been laid on technology development and indigenous fabrication as far as possible and on human resource development.

THE Nuclear Science Centre (NSC) was established under the aegis of the University Grants Commission of India as the first Inter-University Centre. The objective of the Centre is to provide front ranking accelerator-based research in some focused areas within the university system. The activities of the NSC, in terms of creating various infrastructure facilities were planned in a phased manner keeping the overall financial implications in view. In the first phase the thrust was to procure and commission a 15 UD tandem accelerator, capable of delivering energetic ion beams of almost all elements of the periodic table with energies up to about 200 MeV as well as to develop the necessary experimental facilities. Concurrent steps were also taken to establish different kinds of workshops and laboratories, like electronics laboratory, high vacuum laboratory, mechanical workshop, etc. as required for upkeep and maintenance of the accelerator as well as for fabrication of new experimental facilities. Due weightage was also given to human resource development in diversified areas of accelerator-related technologies by recruiting fresh M Sc graduates as scientist trainees and exposing them to current technology environment laboratories both within and outside the country.

With the human resource development and experience gained in phase I, a dedicated team of scientists and technologists are now planning phase II augmentation of the accelerator indigenously, to the maximum extent possible[1]. Their major target is to boost the energy of ion beams over a wider mass range by using superconducting linear accelerator (Linac) booster. The augmented energy of the Pelletron–Linac system makes certain regions that could not be investigated earlier accessible now. It would now be possible to accelerate nuclei up to mass 60 well above the Coulomb barrier. It would also be possible to obtain lighter ion beams up to 10–15 MeV per nucleon (E/A). Further, as a by-product, pulsed beam of ultra short width (~ 100 ps) would be available leading to experiments of a certain class involving time-of-flight measurements. Experiments in materials science concentrate on the use of heavy ions from the Linac to modify solid structure. With the higher energies of the ions from the Linac, the thresholds in the value of electronic energy loss beyond which properties of materials are modified significantly, would be crossed. It would also be possible to generate very high charge states of heavy ions and study their spectroscopy and their collisions of interest to plasma and astrophysics. Heavy Ion Pulse Radiolysis studies on biological and chemical systems would get a boost by using the accelerated heavy ions from the Linac as the beam would be naturally pulsed.

For the superconducting Linac booster, the associated sub-systems like cryostats, cryogenic distribution, RF instrumentation, beam transport and diagnostic devices have already been developed indigenously. The lack of expertise in the area of RF superconductivity has been bridged by collaboration with the Argonne National Laboratory (ANL), USA, where the world's first Heavy Ion Linac Booster was installed and is still the only laboratory having the know-how of niobium-based RF technology for heavy ion acceleration. Work in this regard is continuing in full swing to achieve the goal of accelerating heavy ions up to mass $A = 60$, above the Coulomb barrier. Parallel efforts are in process for commissioning/fabricating various subsystems like basic accelerating structures, RF instrumentation and control, the cryogenic system and beam optics.

Superconducting cavity resonator

A cavity resonator is an electromagnetic device that contains a standing wave field and does not radiate.

A. Roy is in the Nuclear Science Centre, Aruna Asaf Ali Marg, P. O. Box 10502, New Delhi 110 067, India.

Consequently, a charged particle which comes from outside and enters the cavity would experience the field only inside the cavity and a net exchange of energy between the particle and cavity is possible. Cavity resonators of a wide variety of shapes have been used for the purpose of acceleration of charged particles. A Linac would employ several cavity resonators in series to accelerate charged particles. All the booster Linacs for heavy ions employ either a quarter wave coaxial line (QWCL) or a half wave cavity resonator (HWR). A QWCL cavity may be represented schematically as shown in Figure 1. The effective distance d between the two gaps in the resonator is adjusted to the particle velocity, $v = \beta c$, and the resonant frequency, ω_0, so that the RF electric field points in the same direction during the transit of the particle across both the gaps. This condition is met if $\omega_0 d = \pi\beta c$. The energy gain, ΔE, in such a cavity of length L and accelerating field E_a, by ion having charge q, is given by $\Delta E = qE_aLF\cos\phi$, where ϕ is the phase offset and F is the transit time factor (TTF) which takes into account the change in energy gain during the finite time of transit of the ion through the accelerating gap.

Superconducting accelerating cavities that have been used for acceleration of heavy ions, for β values between 0.008 and 0.20, have linear dimensions in the range 5–20 cm corresponding to the radio frequency range (RF) 50–150 MHz. For normal cavities made of Cu, the quality factor, $Q < 10^4$, and the power required to generate accelerating fields in the range of MV/m is ~ MW/m. For superconducting structures, Q is five orders of magnitude higher ~ 10^9. As the power required to generate the accelerating field is inversely proportional to the Q factor, the power required for generating MV/m fields in a superconducting cavity is only a few W/m. To be useful in a superconducting cavity the material should have a high T_c (critical temperature) and a high H_c (critical magnetic field) and H_{sh} (superheating critical field). Superconducting cavities allow these accelerators to run in essentially continuous wave mode due to the inherent low losses in the cavity. Also due to the high field gradients these cavities achieve, the length of these accelerators also are smaller than those operating at room temperature. Among important considerations for a superconducting cavity are the mechanical workability to form cavity shapes, good thermal conductivity and stability of the superconducting properties of the material used. For compound materials it is important that the desired phase be stable over a sufficiently broad composition range so that a single phase is achieved over a large surface area. At present these considerations have limited the use of materials to Pb and Nb in the accelerators. Nb is generally favoured over Pb because of its higher T_c and H_c values. Compounds like Nb_3Sn coatings have been tried on Nb to exploit the higher value of T_c, but this development is in its infancy at the moment. The new high T_c superconductors are very attractive with T_c value near 90 K. But uniform large areas with low surface resistance that are required, have not yet been achieved.

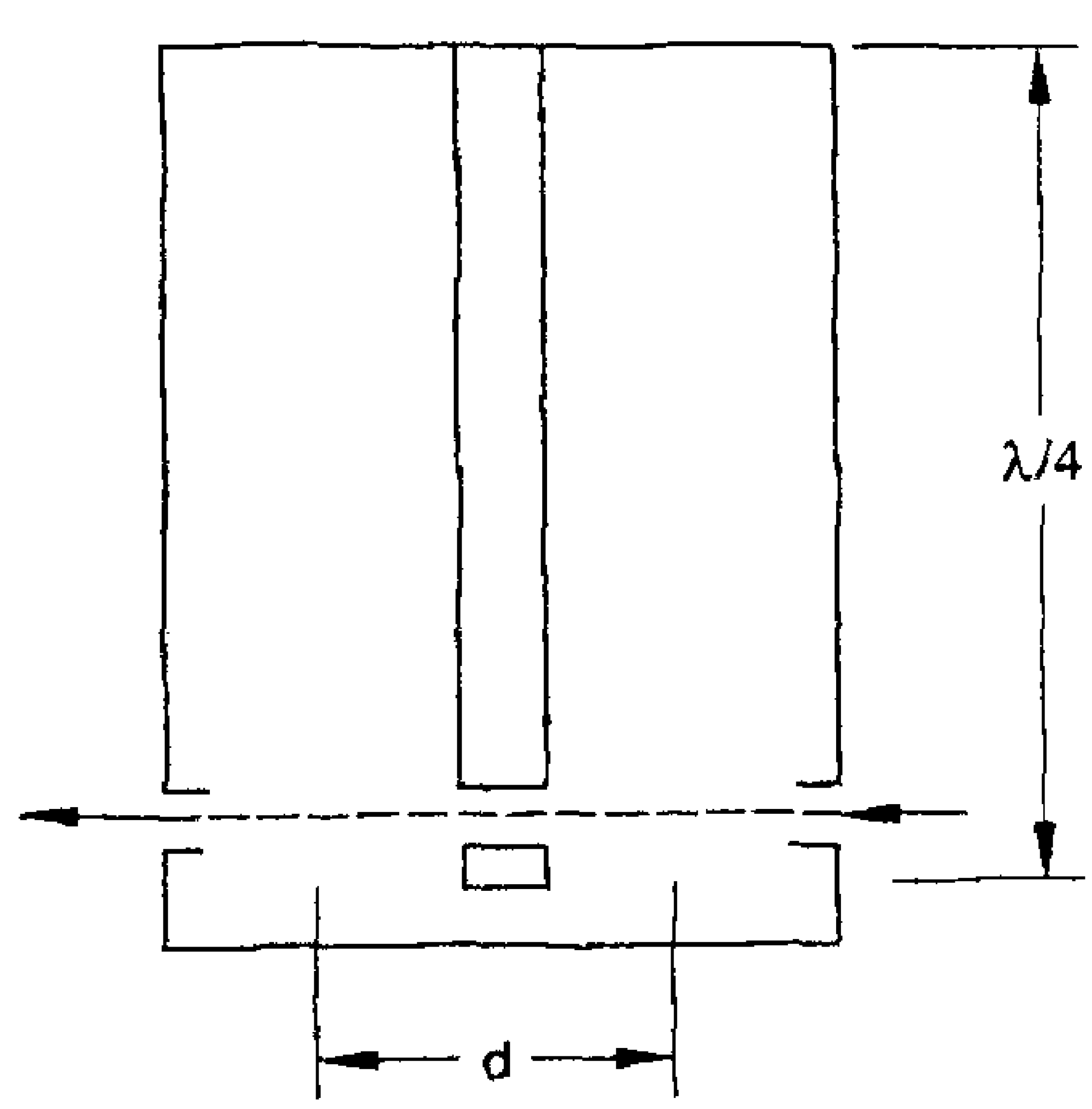

Figure 1. Schematic of a quarter wave resonator.

In the case of a heavy ion accelerator, a wide variety of beams (practically from H to U) are accelerated and these beams have a broad velocity spectrum. The QWCL geometry is characterized by excellent mechanical stability and a broad velocity acceptance. Thus a single resonator geometry would suffice for the entire Linac booster since the range of velocities delivered by the 15 UD Pelletron at NSC in mass range $A = 12$–150 lies between 0.05 and 0.12. Our design was focused on reducing construction costs and developing a high performance structure. The QWCL cavity chosen as the accelerating element for the NSC Linac is made of Nb operating at a frequency of 97 MHz (ref. 2). A sketch of the cavity is shown in Figure 2. The cavity has exceeded the design goal and achieved a maximum field of 5.0 MV/m @ 8 W of RF input. The prototype cavity has been developed as a joint collaboration between NSL and ANL. NSC personnel have been involved in design, fabrication and testing stages of the project at ANL. To complete the Linac booster in the shortest possible time, it was decided to continue collaboration with the ANL to build resonators for the initial modules. Each module would have 8 QWCL cavities and three such modules are planned. This would allow the energy of the particles to be boosted to double that achieved by the Pelletron alone.

During the development of the prototype resonator, several new diagnostic techniques were devised to locate the regions of RF losses in the cavity resonator. These are helium bubble collection and on-line video monitoring while feeding RF power to the resonator fully immersed in a helium bath. It was only through these methods that the regions of high RF losses could be identified and rectified.

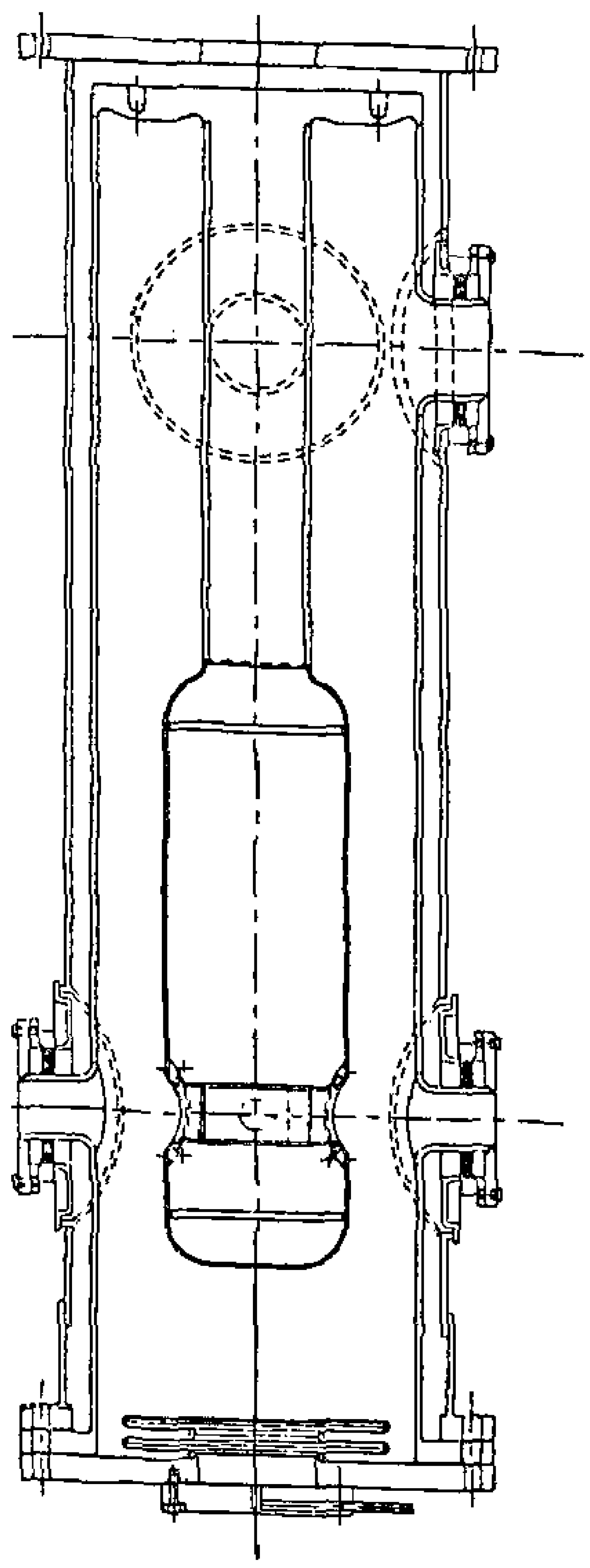

Figure 2. Sketch of the QWCL cavity optimized for NSC Linac.

Indigenous development of resonators

After gaining expertise from ANL through collaborative research, a project is underway to fabricate niobium superconducting resonators indigenously. M/s Kerala Hitech Industries, Thiruvananthapuram, will fabricate one resonator in interaction with NSC personnel.

Cryogenics

Since the resonator material, niobium, becomes superconducting below 9.2 K, it is necessary to cool the resonators below this temperature. This requires liquid helium. It is not enough to just cool the cavities below the superconducting temperature of Nb, they have to be maintained at that temperature in presence of RF losses in the cavity at the required accelerating fields. The heat loads on the system are thus of two types, one static, i.e. the load present in the absence of RF fields and the dynamic load induced by the RF fields. In order to reduce the heat load at helium temperature, liquid nitrogen cooled shields are employed. The cavities are housed in special high vacuum containers termed cryostats. The cryogenic system is one of the vital components of the superconducting Linac and consists of the helium liquefier, nitrogen liquefier, cryostats, helium purification and monitoring units. The entire system is schematically shown in Figure 3. The cooling capacity of the helium and nitrogen plants were decided by considering the load of the cryostats and the distribution system.

A 600 W @ 4.5 K helium reliquefier plant supplied by CCI, USA has been installed and commissioned. In the first phase this system will provide 330 W cooling capacity without liquid nitrogen in the pool boiling heat exchanger. The machine can deliver an additional capacity of 1200 W at 60 K with the addition of another expansion engine in parallel to the warm engine.

The helium gas needed for operation should not have more than 50 ppm impurities for trouble-free operation. In order to maintain the purity of the gas, a helium gas purifier operating at 78 K has been designed and built indigenously. This has been used successfully to purify helium gas obtained from the vendors before using in the refrigerator. A helium impurity monitor working on the principle of arc-cell has been designed and fabricated locally. This monitor is able to detect impurities in the 1–100 ppm level in helium.

The closed loop liquid nitrogen reliquefier of capacity 5000 W at 82 K, designed jointly by NSC and M/s Stirling Cryogenics and Refrigeration (SCR), The Netherlands, has been supplied by SCR and commissioned. It has been tested for the full load of 5000 W at 82 K with a spare capacity of 15% and when used as a liquefier, the machine has delivered 50 l/h of liquid nitrogen. In the closed loop operation, which is first of its kind in a Linac laboratory, substantial amount of electric power is saved (almost 40%).

The resonators are mounted in specially designed vacuum cryostats. A multipurpose test cryostat, 0.9 m in diameter and 1.8 m in height, has been fabricated and tested up to liquid nitrogen temperature. This would be used for cold tests of resonators and solenoids. Several such cryostats, viz. a buncher cryostat and the Linac cryostat are being designed and manufactured indigenously. The buncher cryostat would house a single resonator whereas the Linac cryostat would house eight resonators and a superconducting solenoid. Three such cryostats for Linac modules are being planned to be installed in the beam line. The distribution of cryogens, i.e. liquid helium and liquid nitrogen to the cryostats calls for a complex arrangement of cryogenic valves and piping. The piping has to be vacuum jacketed and the pipes carrying the cryogens have to be properly insulated to minimize the heat load. The entire cryogen distribution system is being designed in-house and local industries are being involved in the fabrication process.

Beam optics

The energy gain, layout of the beam line and ease of operation of the Linac, depend very much on a thorough

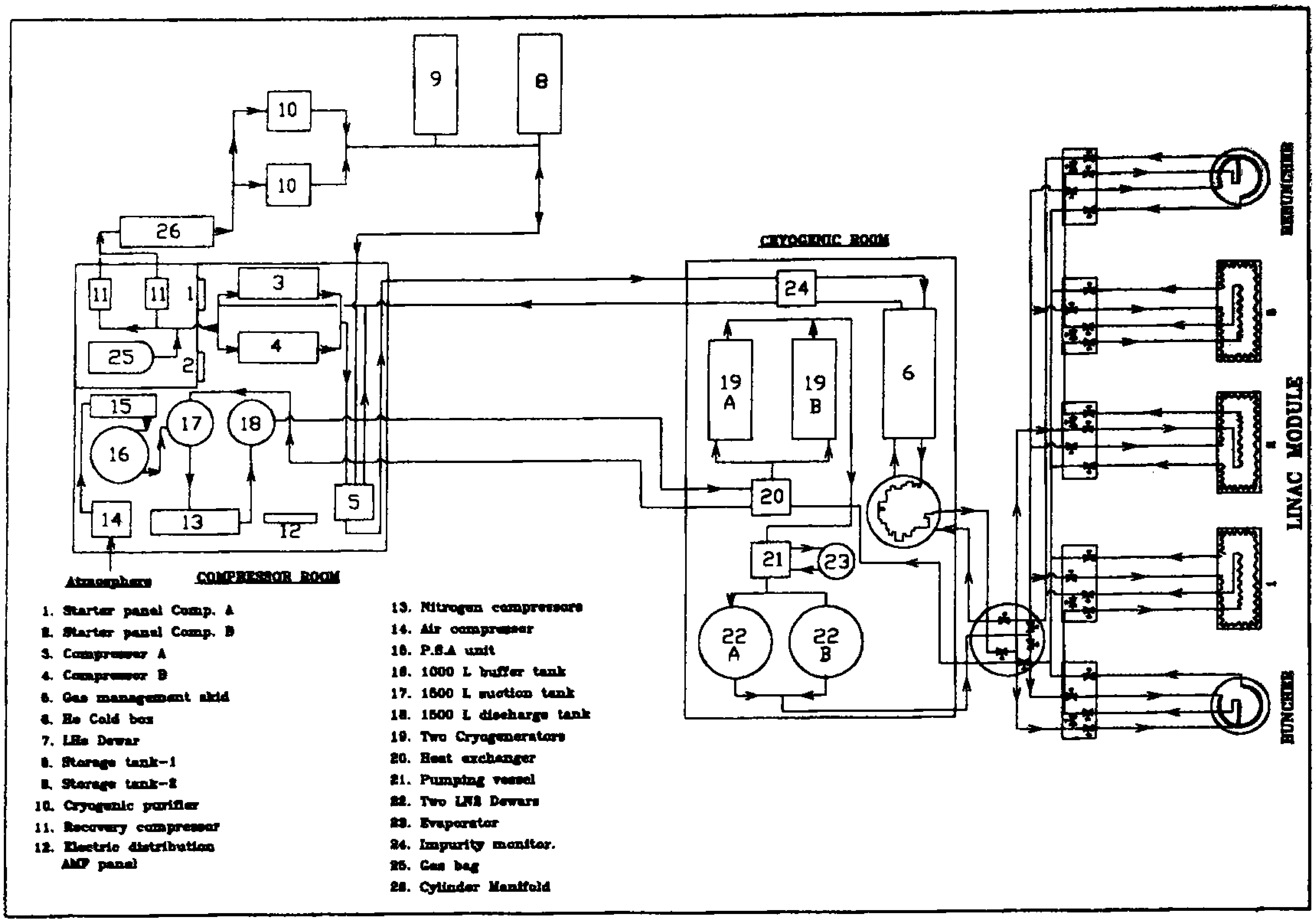

Figure 3. Overall scheme of the cryogenic system at NSC.

understanding of the beam optics and transport of the accelerated ions. Most experiments require a well focused beam spot on the target as well as a narrow time bunch. The transverse or space focusing is achieved through the use of magnetic lens systems such as quadrupoles or solenoids. The focusing of the beam in time (also termed longitudinal focusing) is achieved through the use of time varying electric fields in a device termed appropriately, the buncher. The buncher works on the principle of decelerating the particles arriving early and accelerating those arriving late by suitably varying the electric field across a gap. An ideal buncher would have a saw-tooth variation of the field. A Linac would produce a train of bunches of accelerated ions separated by the time period of the RF field if we inject a continuous beam from the Pelletron. In order to utilize this periodic nature of the Linac, the ion beam from the Pelletron is bunched into narrow time bunches of widths ~ 100 ps. This is achieved in two stages. First, a prebuncher situated before the beam entry to the Pelletron produces bunches of widths ~ 1 ns and then these bunches are further compressed to about 100 ps using a superconducting cavity. The prebuncher for the Linac[3] has been made in collaboration with ANL. The mechanical assemblies for two such units were made at NSC and the electronic parts were assembled at ANL. One unit has been brought to NSC and has been installed in the low energy end of the Pelletron. Once the beam is bunched, suitable detectors for measuring the bunch width are required. For this purpose, a spiral cavity phase detector[4] has been built in-house. This has been installed in the beam line after the analysing magnet of the Pelletron and has been providing a stable reference pulse for timing experiments. This would provide the reference phase for control of the Linac.

As the beam is transported through a large distance it is also necessary to periodically refocus the beam towards the axis, so that the transverse beam size does not grow too much. The beam optics through the entire Linac has been worked out by developing computer codes at NSC for this purpose[5]. The transverse focusing in the accelerating sections would be performed by superconducting solenoid magnets. Care has been taken to ensure that energy of the beams delivered at the target can be varied over a very wide range.

The study of beam transport showed that alignment of some components is extremely critical for effectively transporting the beam. The misalignment of solenoids by more than 0.1 mm is found to produce a noticeable steering effect. Hence a small magnetic steerer has been designed to correct for such steering effects. The quadrupoles and steering magnets for the beam lines have been designed in-house and some of these have been fabricated indigenously. Laying of the beam line for the Linac has started and several beam transport and diagnostic devices built in-house are being used for this beam line.

RF instrumentation

Energizing of superconducting resonators require special circuitry due to their high Q-factor. A Q-factor of 10^9 at a frequency of 100 MHz amounts to a bandwidth of 0.1 Hz for the response function of the cavity. Thus even the smallest vibrations (of about 10^{-8} cm) would cause the cavity to go out of resonance and power would not be transferred to the cavity. A schematic of the system required is shown in Figure 4. It consists of a power amplifier working at around 100 MHz for feeding the power to the cavity, a resonator controller module to maintain amplitude and phase stability with the help of a fast tuner and a slow tuner. The fast tuner works on the voltage controlled reactance principle and takes care of frequency excursions of the cavity in the microsecond range and the slow tuner takes care of slower drifts in frequency in the seconds scale. The power amplifiers are designed for 200 W load. A prototype of the power

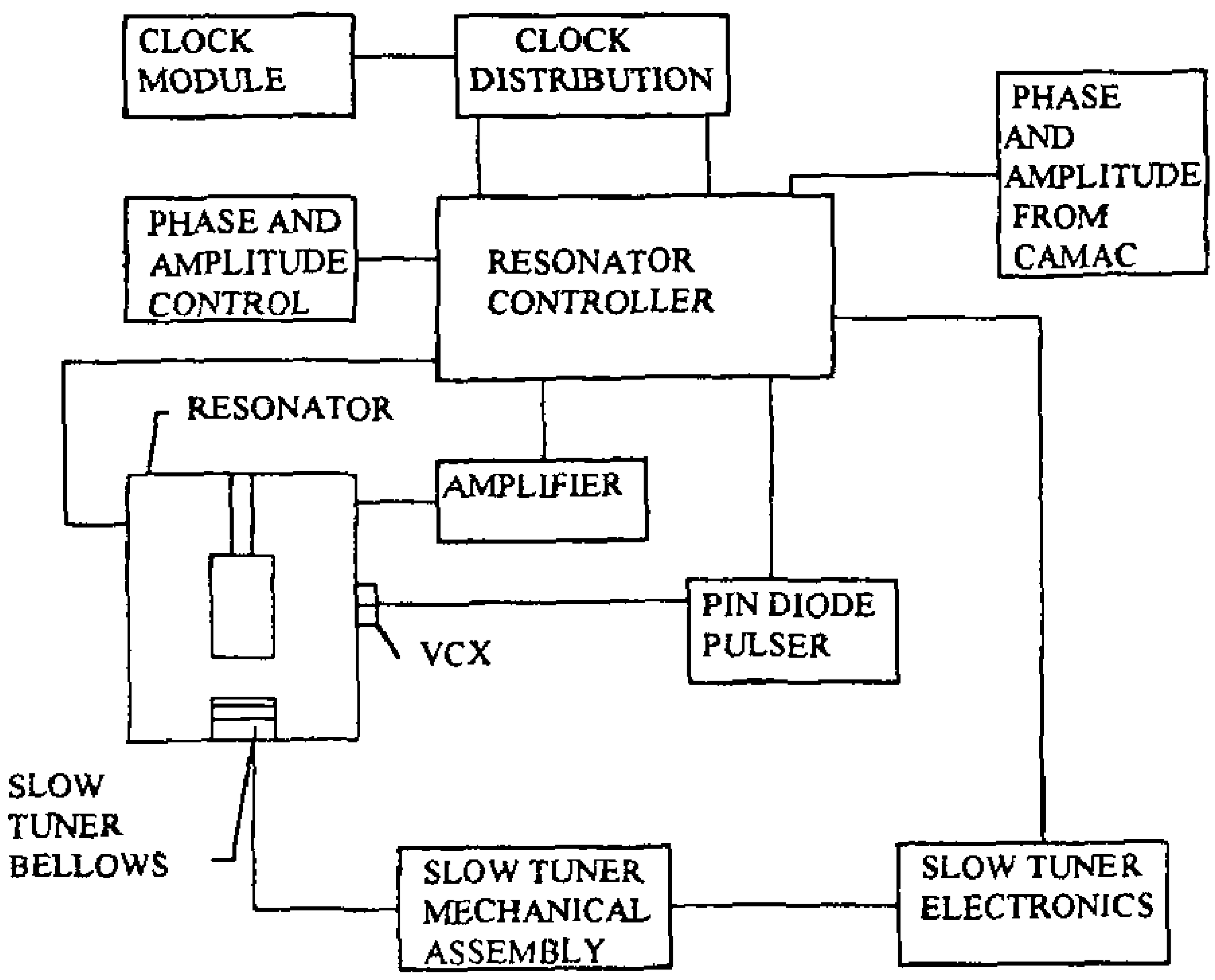

Figure 4. Block diagram of the resonator control electronics.

amplifier was first developed at NSC and was then improved in collaboration with ANL. Most of the other prototype electronic modules were developed in collaboration with ANL and are being built indigenously. A clock signal distribution system to provide phase reference signals at 97 MHz and its subharmonics has been designed in-house.

As a spin-off from the RF developments for the Linac, an RF assisted plasma deposition set-up has been developed under a grant from the Department of Science and Technology, and the technology has been transferred to an Indian industry.

Control system of Linac

The entire Pelletron–Linac system is being planned to be controlled using a network of PC/AT586 computers. A preliminary design has been developed based on a client server model with the server directly connected to the accelerator by using a CAMAC serial highway which maintains an on-line database of all the accelerator parameters. All other computers would be connected to the server by an ethernet link. The concept of such a system with two consoles and a server has been tested by running the beam.

Conclusion

The prototype resonator has been successfully tested and surpassed the design accelerating field. Production of the resonators for the first Linac module has started at ANL. Indigenous fabrication of resonators using the expertise obtained has been initiated. The civil construction for housing the Linac and beam hall is complete. The cryogenic facilities comprising liquid helium and liquid nitrogen systems are now ready. Beam optics studies have been completed and the beam line for the superbuncher installation has been laid. Several RF modules have been fabricated and tested. The collaboration with ANL has helped in fabricating the niobium resonator and multiharmonic buncher indigenously. International exposure has also led us to design the beam transport system, RF system, cryostat and cryogenic distribution in-house.

1. Reformulated Project Report for Phase II Accelerator Augmentation Programme, Nuclear Science Centre, Dec. 1992 (Unpublished); P. N. Potukuchi, *et al.*, Proceedings of 6th Workshop on RF Superconductivity, CEBAF, 1993, p. 1184.
2. Shepard, K. W. and Roy, A., Proceedings of 1992 Linear Accelerator Conference, Ottawa, 1992, p. 425.
3. Lynch, F. J., Lewis, R. N., Bollinger, L. M., Henning, W. and Despe, O. D., *Nucl. Instrum. Methods*, 1979, **159**, 245.
4. Ghosh, S., Ahuja, R., Rao, S., Sarkar, A., Avasthi, D. K., Kanjilal, D., Bhowmik, R. K. and Roy, A., *Nucl. Instrum. Method Phys. Res.*, 1995, **A356**, 185.
5. Prakash, P. N., Roy, A. and Patro, A. P., NSC Technical Report, Ref: NSC/TR/PNP/95/110 (unpublished).

ACKNOWLEDGEMENTS. This work has been the effort of the Phase II group of NSC partly in collaboration with staff of ALTAS laboratory, ANL. I thank Prof. G. K. Mehta, Late Prof. A. P. Patro, Dr N. Anantaraman and Dr L. Bollinger for their help and encouragement.

Received 18 May 1998; revised accepted 5 December 1998