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BHABHA ATOMIC RESEARCH CENTRE

SUPERCONDUCTING LINAC BOOSTER

by

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Nuclear Physics Division
and
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60 Abstract :The report on superconducting LINAC Booster, which is a joint project of BARC and TIFR, brings out the work accomplished so far towards the development of the technology of superconducting LINAC to boost the energy of ions from the 14UD Pelletron. The LINAC is modular in construction with each module comprising of a helium cryostat housing four lead-plated quarter wave resonators. The resonators are superconducting for temperatures below 7.19K. An energy boost of 2 MeV/q per module is expected to be achieved. The first module and the post-tandem superbuncher have been fabricated and tested on the LINAC beam line. This report gives a summary of the technological achievements and also brings out the difficulties encountered during the R&D phase.

70 Keywords/Descriptors :PARTICLE BOOSTERS; LINEAR ACCELERATORS; RESONATORS; RF SYSTEMS; OXYGEN IONS; SILICON IONS; CRYOSTATS; SPECIFICATIONS; BEAM INJECTION ;SUPERCONDUCTING DEVICES

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SUPERCONDUCTING LINAC BOOSTER

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1.Introduction:

As a collaborative BARC-TIFR activity, a 14UD Pelletron accelerator has been installed at TIFR, Mumbai to accelerate heavy ions. Beams above 5 MeV/nucleon for $A \leq 20$ have been available for nuclear physics experiments since 1989. In order to extend the range of target-projectile combinations it was proposed to add a Superconducting LINAC Booster to the Pelletron to increase the beam energy further.

A Superconducting linear accelerator is not a commercial proposition. In 1986, only two advanced laboratories in USA - one at SUNY, Stony Brook and the other one at ANL, Argonne - had built such accelerators. A Superconductiong LINAC utilises independently phased superconducting RF resonator cavities as accelerating elements. Therefore, developmental efforts in diverse areas of precision machining, electron beam welding, lead electroplating, cryogenics, RF electronics and computer control are involved. A project for the development of a Superconducting LINAC booster was sanctioned in Jan.1986, at a total cost of Rs. 250 lakhs.

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. 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 include:

- 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, and procurement of a closed cycle Helium refrigerator.
- Development of RF electronic circuitry for resonator control.
- Fabrication of appropriate beam transport components, to be used in the LINAC beam line for optimum beam transport.
- Monitoring and control of all LINAC parameters by a dedicated computer.

The present report details the technological developments that have been done to achieve successful acceleration of heavy ions using one module consisting of four quarter wave resonators (figs.1a, 1b).

2: Technological Developments:

The initial objective of the project has been to develop the technology for the construction of linear accelerator for heavy ions based on independently phased superconducting RF Quarter wave resonators. In what follows, we review the progress made during 1987-1996 in the project.

a) RF Resonators:

A heavy ion LINAC consists of a series of RF resonators each individually phase-locked so as to have proper accelerating voltage across the gaps at the instant the ion bunch passes through it. Two important parameters of the resonator are its resonant frequency and the β (=v/c) value. The basic accelerating structure presently developed for the LINAC is a 150 MHz, β=0.1, Quarter Wave Resonator (QWR) made out of OFHC copper (fig.2a, 2b). A typical LINAC would have several such identical structures serving to accelerate the beam. The main advantage in using Superconducting cavities as accelerating structures is the high Q- value (=10^8) that can achieved, so that RF power requirements are reduced to only about 7W as compared to several tens of kilowatts required by a normal conducting cavity (Q=5000) operating at the same electric field. The resonators are coated on the inside with a thin layer of lead (2μ), which is a superconductor at temperatures below 7.2K. The resonators are thus operated at liquid Helium temperature in order to use the superconducting properties of lead for the generation of high accelerating fields with low RF power dissipation in the cavities.

i) Quarter Wave Resonators (QWR) :

The manufacture of the QWR's is being carried out by CWS, BARC. The fabrication involves precision machining of the OFHC copper to close tolerances* and the required surface finish**. Apart from this, a crucial step in the fabrication is the electron-beam welding of the central conductor / shorting plate assembly to the outer can. In order to ensure a minimal thermal resistance between the two parts, this must be a deep penetration weld, nearly approaching the thickness of the material. After the can is welded in place, a cosmetic weld is carried out on the inside surface of the shorting plate to close the crevices on this side and have a porosity free surface, which is essential for the electroplating of the superconducting material. The cosmetic weld has been the most difficult to implement since the beam has to travel nearly 600 mm after entering the cylinder, and even a slight misorientation is sure to damage the central conductor or the can. The difficulties are also compounded by the fact that the heat retention property of copper is very poor on account of its high thermal conductivity.

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* The large Q -value of the resonator implies a frequency stability of 10^{-8} which in turn demands similar dimensional tolerences. This can be relaxed by three orders of magnitude by the provision of tuner mechanism.

** A coating of thin lead film assumes a surface finish of at least 10 μm at the fabrication stage which is further prepared to the required finish by mechanical polishing.

Lead Plating:

In order to achieve acceptable cavity Q-values electroplating of lead places stringent requirements on the surface finish and cleanliness of the resonator's surface. 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 resonator is then electroplated with lead in a fluoborate bath, washed in de-ionised water, and stored under vacuum after thorough drying in dry inert gas atmosphere. A quantitative evaluation of the Pb surface requires a measurement of the resonator's Q-value 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. A measurement of the decay time τ gives the quality factor through the relation $Q = \omega\tau$, where ω is the resonant frequency. The average electric field is inferred from a measurement of the voltage induced in the cavity.

b) Cryogenics:

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 a transfer tube for transferring the liquid Helium from the refrigerator to the cryostat is required. Typically, each module has a standing heat load of 35 Watts and 126 Watts for the Liquid Helium and liquid Nitrogen circuits respectively. Therefore any such accelerator envisaging 10 modules will mean a provision of large closed-cycle Helium refrigerator of $\cong$ 350 Watts and a 4 kW capacity (including pre-cooling for the Helium refrigerator) liquid Nitrogen plant. Since these modules will have to be physically spread out, such a system would require a complex distribution network of transfer lines.

i) Cryostat:

The cryostat (fig. 3) is a vertical cylinder with cryogen storage tanks suspended from the top flange. 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 entire assembly is maintained under ultra high vacuum. For such a large system maintained at 4.5K, the standing heat load is predominantly due to radiation from the surrounding warmer surfaces. This heat load is reduced by enclosing the Helium tank and the resonators in a radiation shield maintained at 77K. The radiation shield consists of an annular liquid nitrogen vessel surrounding the Helium tank, a cylindrical shield attached to the bottom of the nitrogen vessel and an intermediate copper plate placed on top of the nitrogen vessel. In order to reduce the heat load and minimize the consumption of cryogens, the shield and nitrogen vessel are wrapped with about 20 layers of aluminised mylar, which serves as the superinsulator. Similarly, the Helium vessel is also superinsulated to minimize the radiation heat load. The conduction heat load on the Helium circuit due to supports is reduced by increasing the thermal path length using a low thermal conductivity material with good mechanical strength.

Furthermore, thermal anchoring at liquid nitrogen temperature of the various electrical and mechanical penetrations into the Helium circuit is done to reduce the heat load.

ii) Transfer tube:

The two phase mixture of gas and liquid helium produced by the refrigerator is to be transferred to the liquid helium vessel of the cryostat, where the liquid gets collected while the boil off gas returns to the referigerator. The low latent heat of liquid helium puts severe constraints on the design of the transfer tube. A triaxial transfer line (fig.4) is used in which the liquid is carried in the innermost tube, the return gas flows through the intermediate space surrounding the liquid line and the outermost region serves as the vacuum jacket. Teflon spacers are used between the vacuum jacket and the gas return line for support and are designed such that the conduction heat load from the spacers to the gas return line is minimum. Layers of aluminised mylar are wrapped on the gas line to reduce the radiation heat load.

c) RF Electronics:

The LINAC can add energy coherently to the beam only if the resonator's electric field is set and maintained at a stable amplitude and phase , with a stability better than 0.1% to preserve the quality of the beam from the Pelletron.. Sophisticated RF electronic circuitry is required to achieve this. A schematic of the RF controller is shown in fig 5. Depending on the frequency and amplitude errors, Quadrature and in-phase power are added to the self-excited loop to achieve phase and amplitude stability of the field in the resonator .

3) Development of the prototype Accelerating Module:

A brief report on the development of quarter wave resonators, liquid helium cryostats, recommissioning of the close cycle cryogenic generator, R.F. electronics and other beam line components which has culminated in the demonstration of beam acceleration through the first module is given below:

a) Quarter Wave Resonators (QWR):

The manufacture of the QWRs using OFHC Copper was carried out at central workshops, BARC. Salient activities involved in the manufacture were

- Design and construction of a special purpose vacuum chamber,jigs and fixtures,work handling devices and link up of various controls.
- Modification in the custom defined Electro Beam Welding gun models and provision of optical viewing device for monitoring the job during welding.
- Precision machining of dough nuts precisely to contour defined by the mathematical function using CAD and CAM facility on CNC milling machines as a CIM process.
- Vacuum brazing of selected items.

Since OFHC copper has high thermal conductivity, quality e-beam welds pose a technological challenge and it took a lot of time and trials to arrive at appropriate weld designs and e-beam parameters to obtain reproducible high quality welds on the QWR structures. This aspect has been the most unpredictable step in the fabrication of resonators. After a lot of innovative experimental runs we have now reached a success rate of around 60-70 %.

In all, 8 QWRs have so far been fabricated of which two were prototypes. From the remaining six, four have been successfully lead plated and tested to give good performance at Superconducting temperatures. The remaining two resonators have e-beam weld defects which are damaging to the quality of the lead films deposited on these resonators. However, attempts are being made to repair these defects by hydrogen brazing. Apart from these eight, another five QWRs are in various stages of fabrication. Using these resonators, two acclerating modules are being set up.

While the work on the development of resonators and other components were taken up, a proposal to take up beamhall construction and to buy a closed cycle refrigerator was made in 1988and again in 1991 to TIFR. However, as per the suggestion of TIFR, this part of the work was deferred till the development of all necessary superconducting technologies and succeesful construction and testing of one module. This decision had to be taken partly due to the constraints of further construction at TIFR, difficulties of procuring the liquid Helium refrigerator and the fact that the available budjet for this project needed considerable rervision to meet these objectives.

Inspite of the constraints, a conscious decision was taken to continue working on the difficult technology and the project was redefined to achieve this objective of successful completion of all the hardware needed for successful testing of one module (alongwith the superbuncher) on the Pelletron beam line.

To summarise,

- *One module at least should be tested before placing a purchase order for importing the closed cycle Helium refrigerator involving a financial commitment close to Rs. 6.0 Crores.*
- *The civil work required for the beam hall should be pursued only after the testing of the first module.*

For the purpose of testing one module, supply of liquid Helium could be managed through the existing plants at TIFR and BARC. With this in mind, a partial support of Rs.25 lakhs was provided for the purchase of a Helium liquifier to the Solid State Physics Division of the BARC.

b) Lead Plating Facility:

A laboratory for polishing, chemical preparation and lead plating of the OFHC Copper resonators has been set up at TIFR. 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 lead plating procedure has now been well established. Plating the QWRs with good quality lead film in routine operations is being currently achieved. Several people have acquired the necessary expertise to do this job. We have also fabricated big vacuum storage vessels to store the lead plated resonators so that the lead films do not deteriorate.

c) RF Test Facility:

For conducting RF tests at Superconducting temperature on these lead plated resonators, we have fabricated a liquid helium test cryostat in TIFR central workshop. The necessary RF test set up to make measurements of the quality factor Q of the cavities as a function of the electric field in them is also developed (fig.6). Using this cryostat and the RF set up we have individually tested performance of the resonators at 4.2K. The 4 QWRs with acceptable performance (about 2.-2.5 MV / m electric field for a power dissipation of 7 watts at 4.2K) were selected for use in the accelerator module after being tested in this test set-up.

d) Liquid Helium Cryostats:

Three 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 on the beam line. This cryostat was fabricated mostly in the TIFR central workshop. Only the vacuum jacket had to be fabricated in an outside workshop because of its large size. 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 designs were done in consultation with 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 modular cryostat was 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 commissioning of the first cryostat. Vacuum testing of the second cryostat has been successful.

e) Electronics and Power Amplifiers:

A few RF controller boards were initially imported from M/s. Applied Superconducting Inc., USA for gaining experience in resonator control. Based on a design similar to that used at The University of Washington, Seattle, an RF controller has been designed and fabricated by Electronics Division, BARC. Using this the phase and amplitude lock characteristics of the QWR have been studied.

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 and tested wherein the CPM's have been simulated using easily available functional modules and which has proved to be more reliable.

Apart from the RF controller, electronic circuits for the control of various components in the injection path of the LINAC are being designed. The details of the computer control and scheme for interfacing the RF control and monitor parameters and other beam transport and cryogenic parameters have been finalised in conjunction with the CAMAC group of Electronics Division,BARC

RF Power amplifiers with a capacity of 100 watts and band width of 20 MHz at 150 MHz have been developed by the collaborative effort of ECIL, Hyderabad and Electronics Division, BARC for this project. One amplifier of this design has been tested on the cavities in our laboratory. Two amplifiers have been procured and more such amplifiers will be made by ECIL in the future for our need.

f) Quadrupole magnets and magnet power supplies:

The miniature, high gradient (47 T/m) Quadrupole doublet magnets needed for periodic focusing of the beam through the LINAC has been designed in-house and fabrication done by a local firm. One magnet has been delivered to us by this firm. Even though magnetic field mapping has shown satisfactory performance, we still have to make some improvement in reducing the overall size of the magnet. This can be achieved by using hollow conductors for the field coil in place of solid conductors used in the present design.

The high current power supplies with a rating of 120 Amps at 12 volts and 300 ppm stability have been developed by a firm at Bangalore in collaboration with us. The Quadrupole magnet has been tested with these power supplies.

g) Commissioning of the Superconducting Buncher:

In the injection path of the proposed Superconducting LINAC Booster for the Pelletron accelerator at TIFR, Mumbai, a crucial component is the superconducting buncher, required to compress the 1-2ns beam bunch at the exit of the Pelletron to 200ps, in order to achieve phase matching for subsequent acceleration through the LINAC. The superbuncher is a 150MHz, β =0.1, split-loop resonator made of OFHC copper and plated with lead (T_c = 7.2K), having a low field Q=1.6 X 10^8 (fig. 7)

The resonator mounted in its cryostat and other beam transport and diagnostic elements were aligned along the new LINAC beam line. The Phase detector and the Sweeper were not installed. The resonator was operated at its resonant frequency, 150.17392MHz, and the beam bunching tests were performed with ^{28}Si at 90 and 100MeV and ^{16}O at 66MeV, on a 300 mg/cm^2 ^{103}Rh target. The γ rays above a threshold of 600keV (to eliminate gammas from radioactivity) detected in a BaF_2 and a plastic detector were used as a start signal, and the stop being the RF. The evolution of the time spectra obtained with the Oxygen beam at various field levels in the resonator is shown in fig.8 alongwith the fitted bunch widths. The optimum bunch width estimated after deconvoluting the detector resolutions is 150ps.

h) Cryogenic Circulation System:

To cool and maintain the accelerating module at 4.2K, we have reinstalled the 15 year old Koch 1410 Helium liquefier (taken from LTF, TIFR) in the LINAC hall. This machine is now configured to work in a close cycle mode using helium gas from a medium pressure storage tank installed on the roof of the LINAC beam hall. After recommisioning, this machine is producing 5 to 6 litres of liquid helium per hour in the liquefier mode, equivalently, it gives about 26 watts of cooling at 4.5K. This machine has been coupled to the modular cryostat using a special helium delivery tube manufactured by a company in Bangalore to our specifications. This transfer-tube acts as a heat-exchanger and hence could not be used satisfactorily to transfer liquid Helium to the modular cryostat. The transfer tube was taken up for modification to transport the Helium gas-liquid two phase mixture and have the J-T action at the cryostat end rather than at the liquifier end. This was achieved by attaching a porous plug onto the cryostat end of the transfer line. The cold gas in the transfer line, expanding through the porous plug produced liquid Helium in the cryostat, and it was possible to cool the resonators down to 4.2K.

I) Performance of the First Accelerating Module:

Four lead plated and tested quarter wave resonators were mounted in the modular cryostat. For useful acceleration of the beam through the module, it is necessary to match the resonant frequency of each resonator to a common reference. This was achieved for three of the resonators by adjusting a mechanical frequency tuner attached to each of them. The resonant frequency of the fourth resonator was about 150 kHz away from the mean resonant frequency of the other three resonators. This deviation was beyond the available frequency tuning range (approx. $\pm$ 5 kHz) and hence this resonator could not be used for beam acceleration. The cryostat was connected in a closed-loop mode to the Helium liquifier, which provided the necessary cooling for the resonators. The power dissipation in each of the resonators was fixed at 6W using the variable power coupler. With a dc beam of ^{28}Si at 90 Mev injected into the module, an energy boost of 5.765 MeV was measured by Rutherford scattering of the beam from a thin ^{197}Au foil (fig.9).

4) Summary of achievements :

- Technology of design and construction of superconducting RF Quarter Wave Resonators has been sucessfully achieved.
- Superconducting thin film lead plating technology has been developed for the first time in the country and has been perfected.
- Electron beam welding experience on Copper developed during the course of the project will be useful for cavity manufacturing for similar accelerator facilities in future.
- The resonator controller, developed for the LINAC control, will be useful for development of accelerator technology.
- Expertise is now available for the manufacture of large scale cryostats, transfer lines and other cryogenic components.
- Power amplifiers and directional couplers developed for the present project are,in fact, general purpose devices and find wide scale application in the field of communication.
- Special quadrupole magnets for beam focussing and high current power supplies for these magnets have been developed - the know-how of which is available to other users in the country.

5) Proposed Programmes:

A mention has been made earlier in the report regarding the decision taken in respect of delaying investment of large amount of money for buying closed-cycle Helium refrigerator. In view of large inflation that took place during the period of development (Rupee to Dollar parity was changed by factor of more than 2) such large sum of money required for the purchase was not available in the Project. At that point of time, the decision looked fair in view of the long time the developmental activity has taken, for, even if funds became available, this facility could not have been optimally used, leading to wasteful investment.

However, this decision had also another aspect which needs to be appreciated - namely, lack of such a critical facility also hampers the progress of the Project. To illustrate this point further, a second cryostat is now ready and the four resonators that go into it will be made ready in the near future. Had such a facility been available, one could have put at least these two modules on stream to further increase the energy of ions from the Pelletron so that experiments could be planned.

The future outlook must immediately, therefore, include the step of purchasing the full closed-cycle Helium refrigerator system. Assuming that such a decision will be forthcoming, a IX plan project has been drawn up for building a Superconducting Booster Accelerator based on the R & D carried out during the period of the report. The proposal for such a project, which includes provision of new experimental beam hall has been submitted to DAE through TIFR, the scope of which is included below for the sake of completion.

The configuration of the Booster would comprise of a total of 7 accelerating modules, each containing 4 Superconducting Quarter wave resonators . With 2 moduls in various stages of completion, an additional 5 modules are proposed to be built. This will provide an energy gain of 14 MeV/charge state.

The refrigeration at 4.2K will be provided by a closed cycle liquid Helium refrigerator, while that at 77K will be provided by an integrated liquid Nitrogen generator. The LINAC will be built in two sections, having a 110^0 isochronous and achromatic bend between them (fig.10), along with suitable periodic focusing and beam diagnostic elements. All the beam transport components, cryogenic parameters and the resonator control electronics will be interfaced via dedicated CAMAC modules to an upgraded accelerator control system into which the Pelletron accelerator control will be integrated.

A new user beam hall will have to be constructed for experiments with the accelerated beam from the LINAC (Fig.11).

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We are thankful to Dr. S. S. Kapoor, Director, Physics & E & I group, BARC and Prof. Virendra Singh, Director, TIFR, for their constant encouragement and support during the R & D phase of the present project.

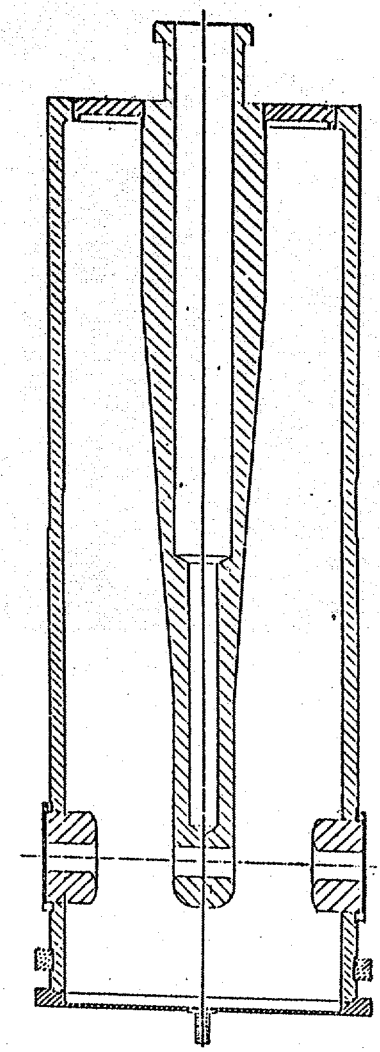


Fig. 2a: QWR schematic

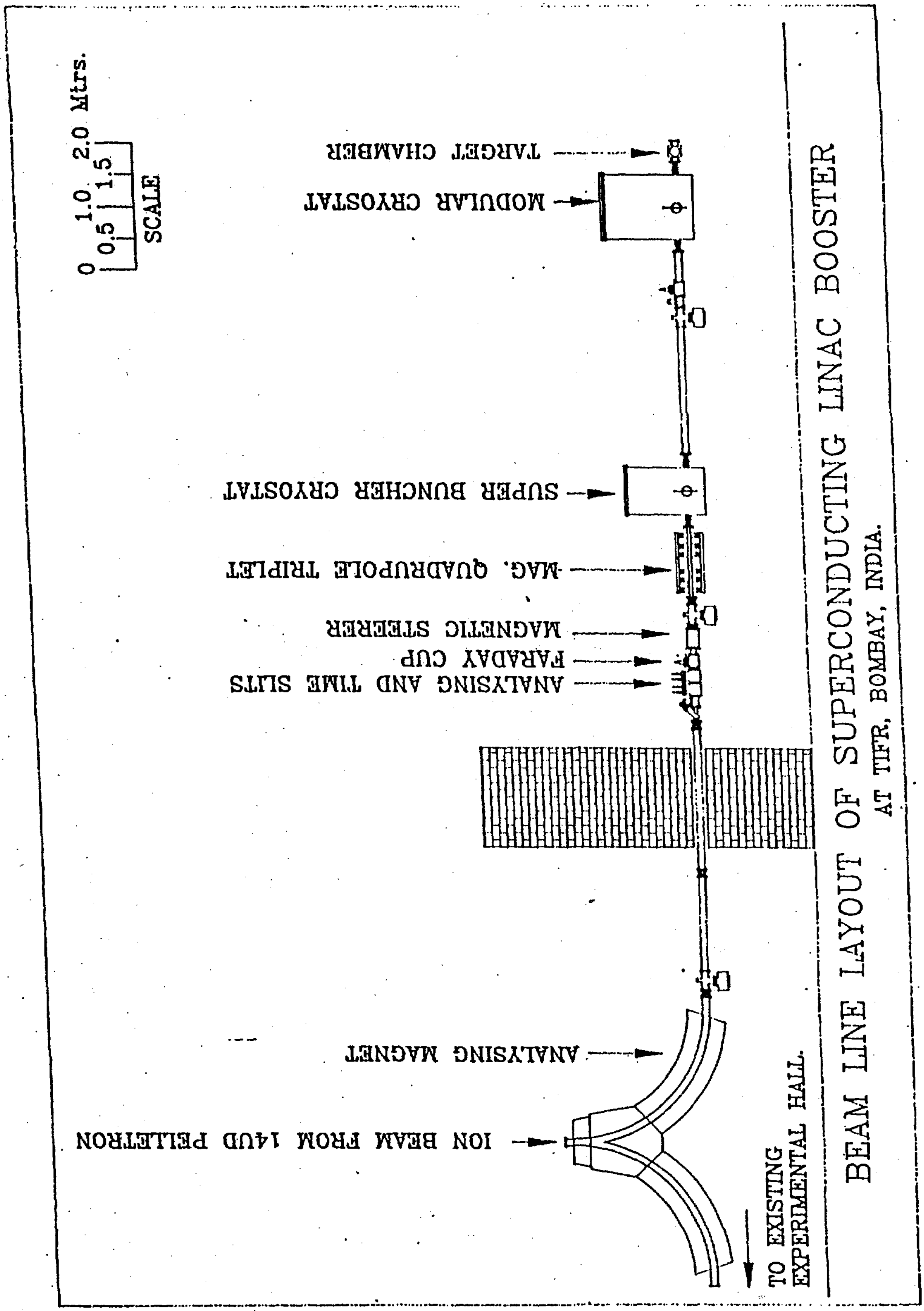


Fig. 1a : Schematic of the LINAC beam line upto first module.

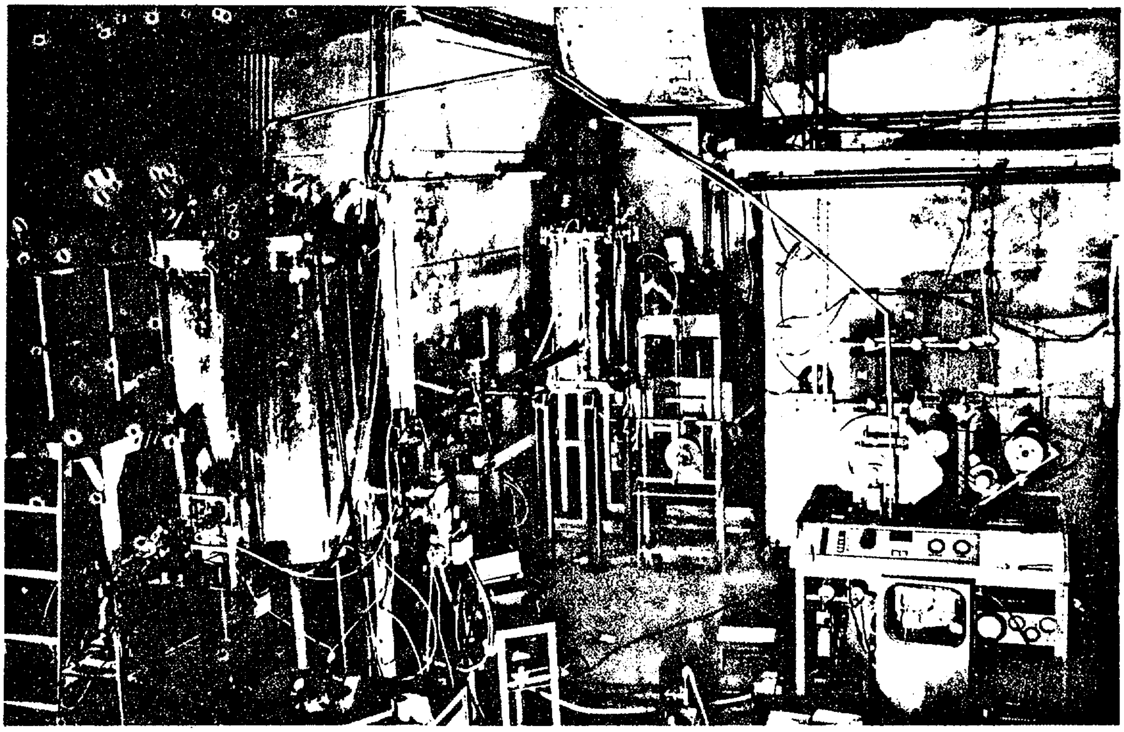


Fig. 1b: LINAC beam line upto first module

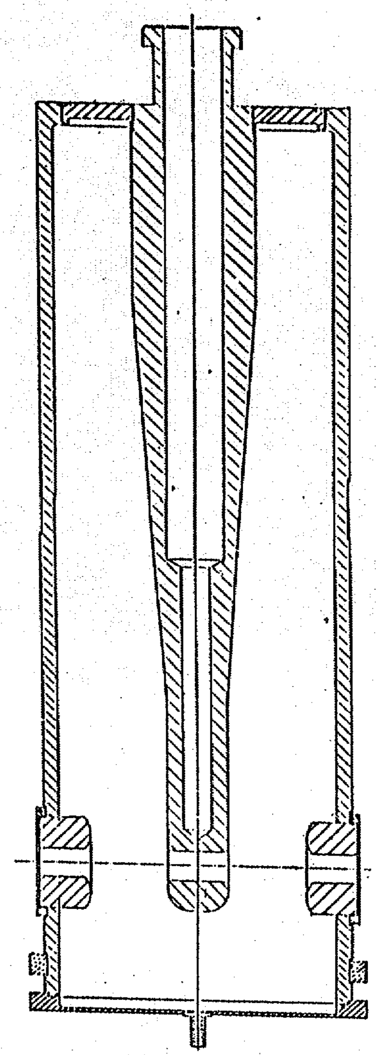


Fig. 2a: QWR schematic

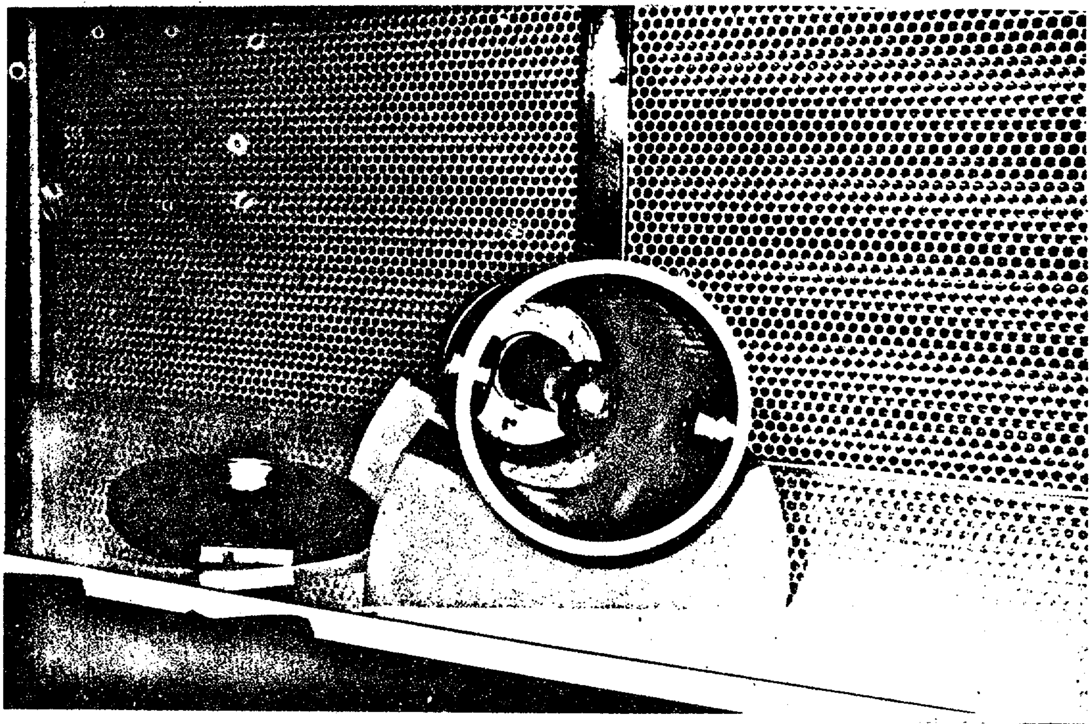


Fig. 2b: Quarter Wave Resonator

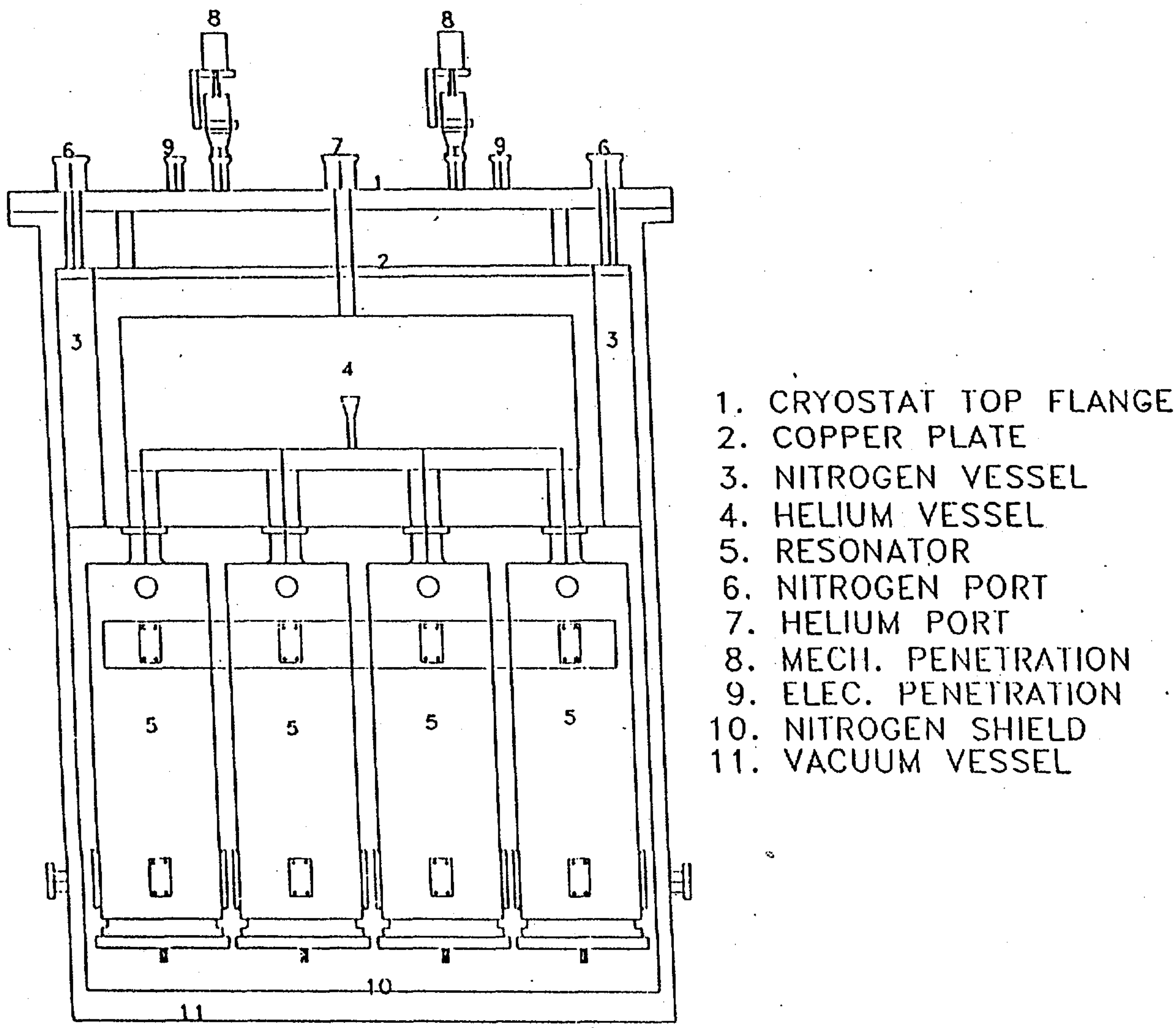


Fig. 3: Modular Cryostat.

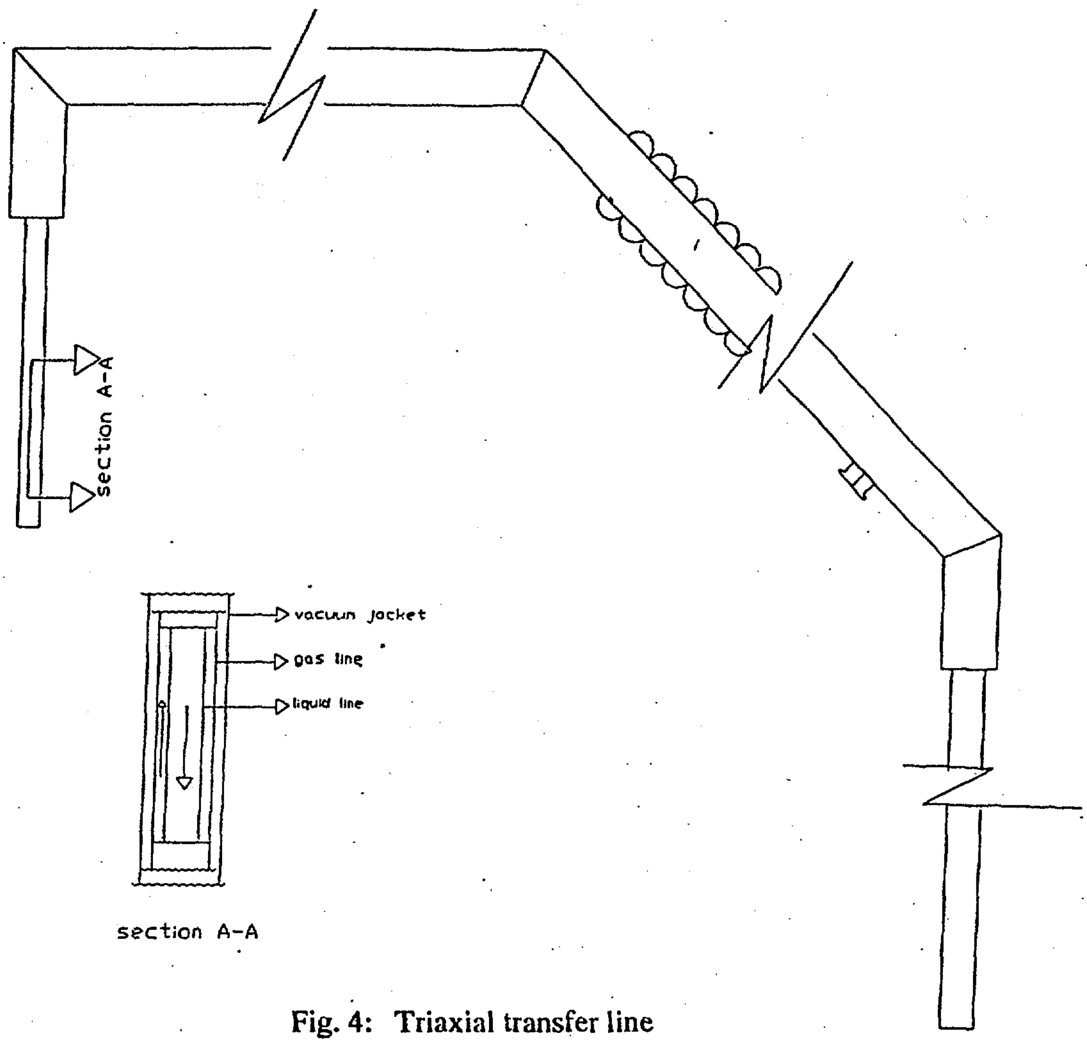


Fig. 4: Triaxial transfer line

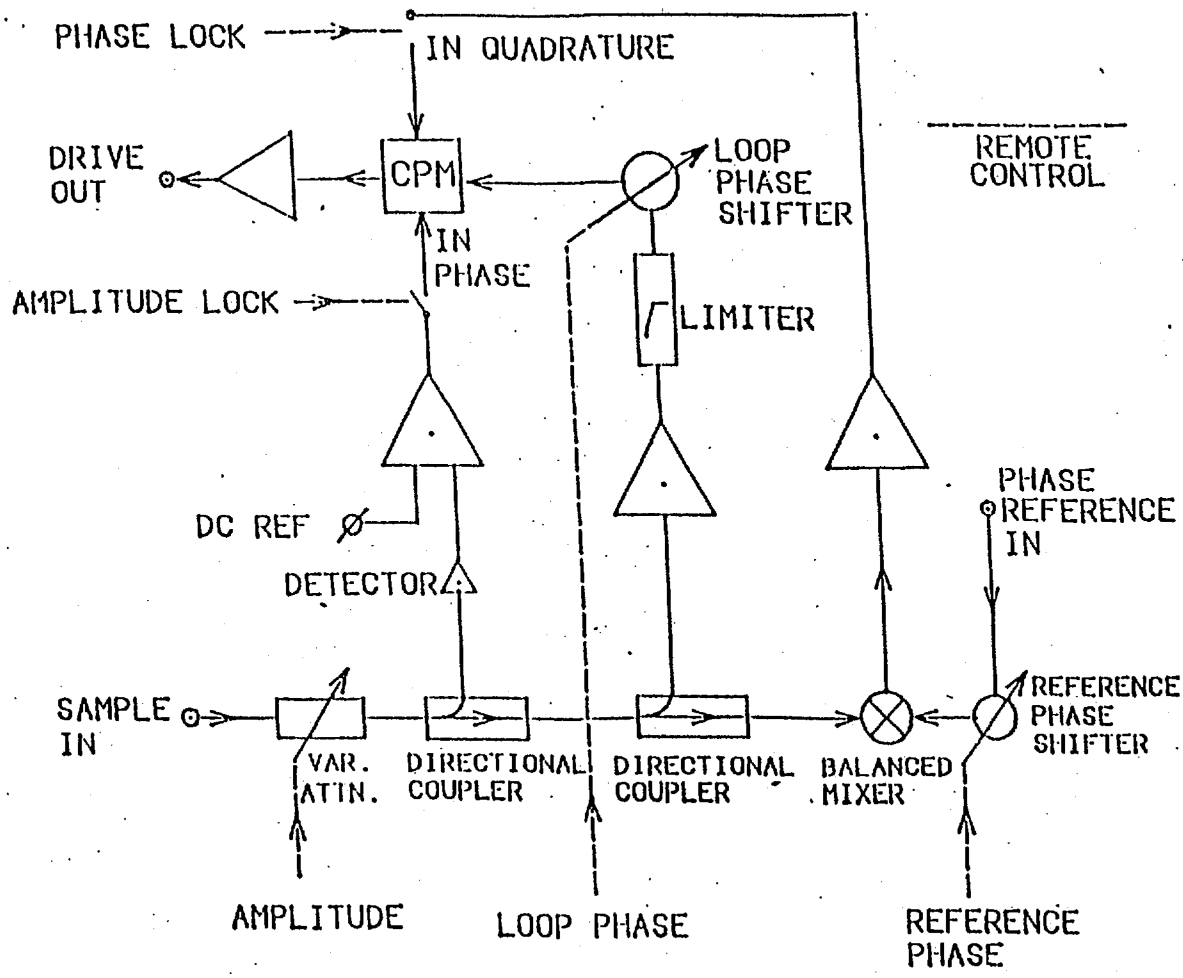


Fig. 5: RF controller schematic

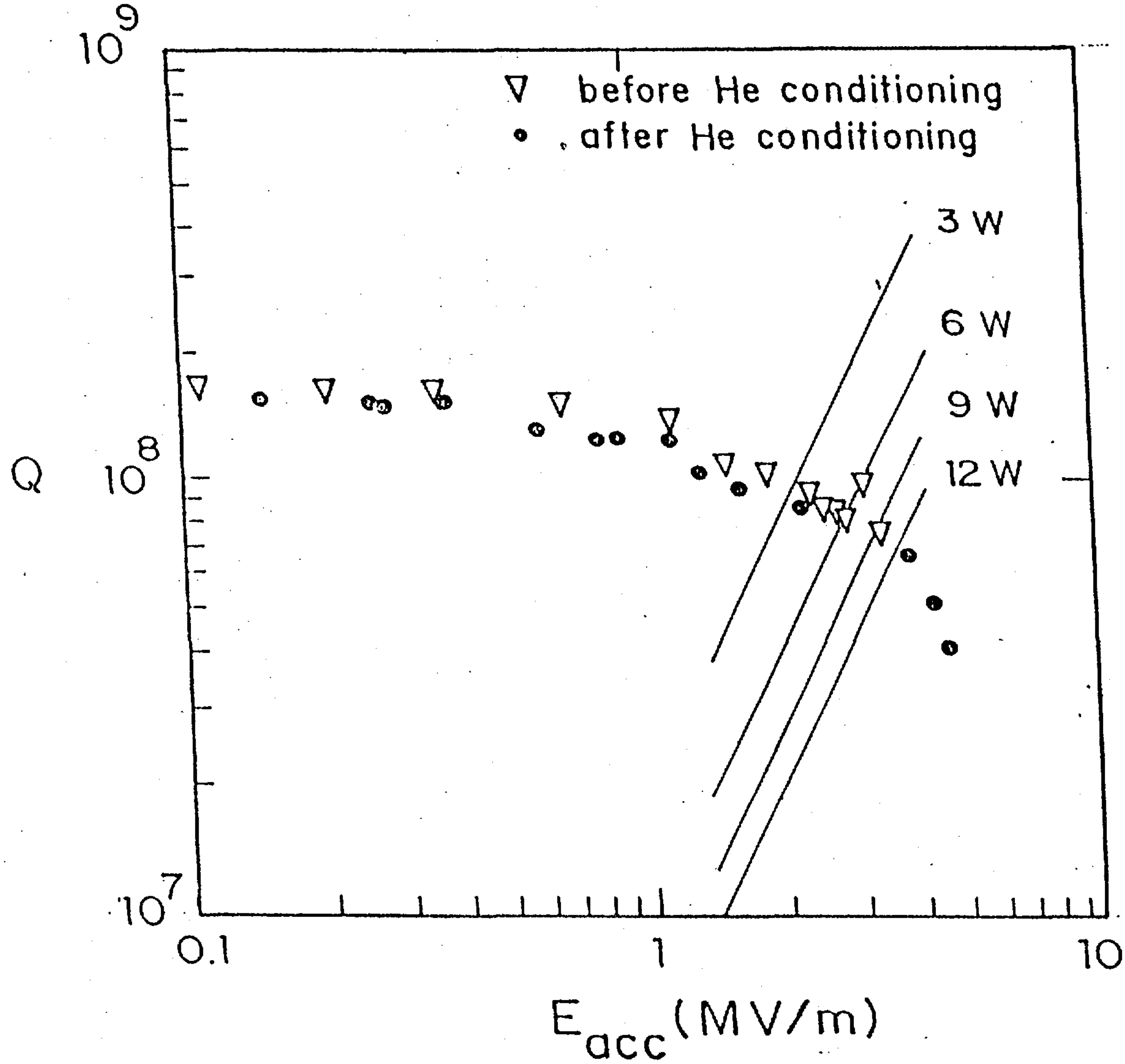


Fig. 6: Q vs E curve

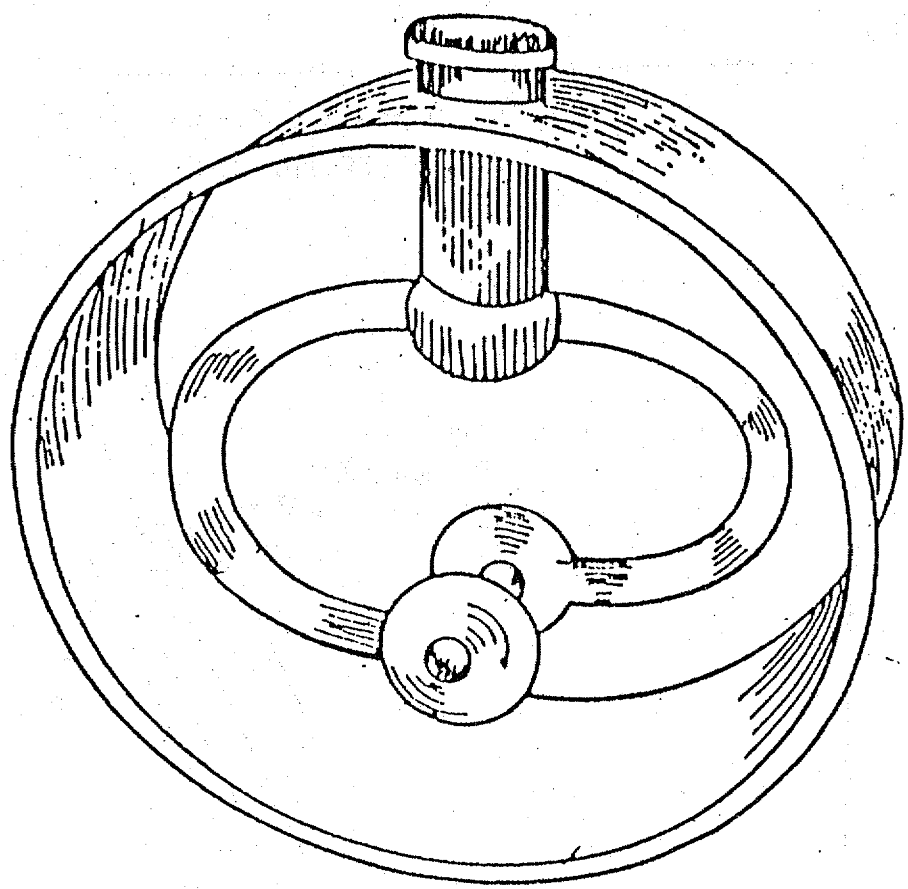


Fig 7. Split-loop resonator.

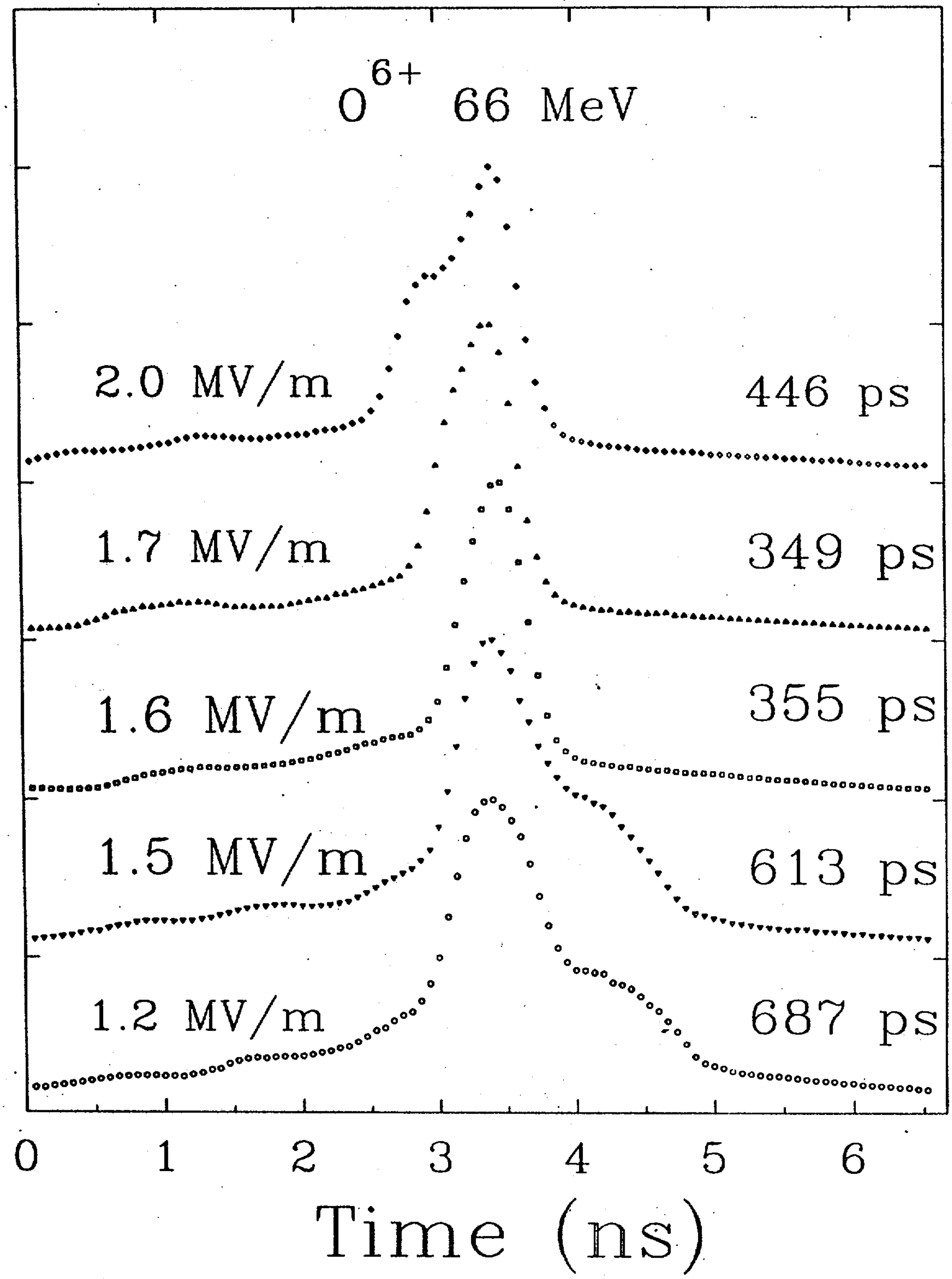


Fig. 8: Time bunch widths from the superbuncher

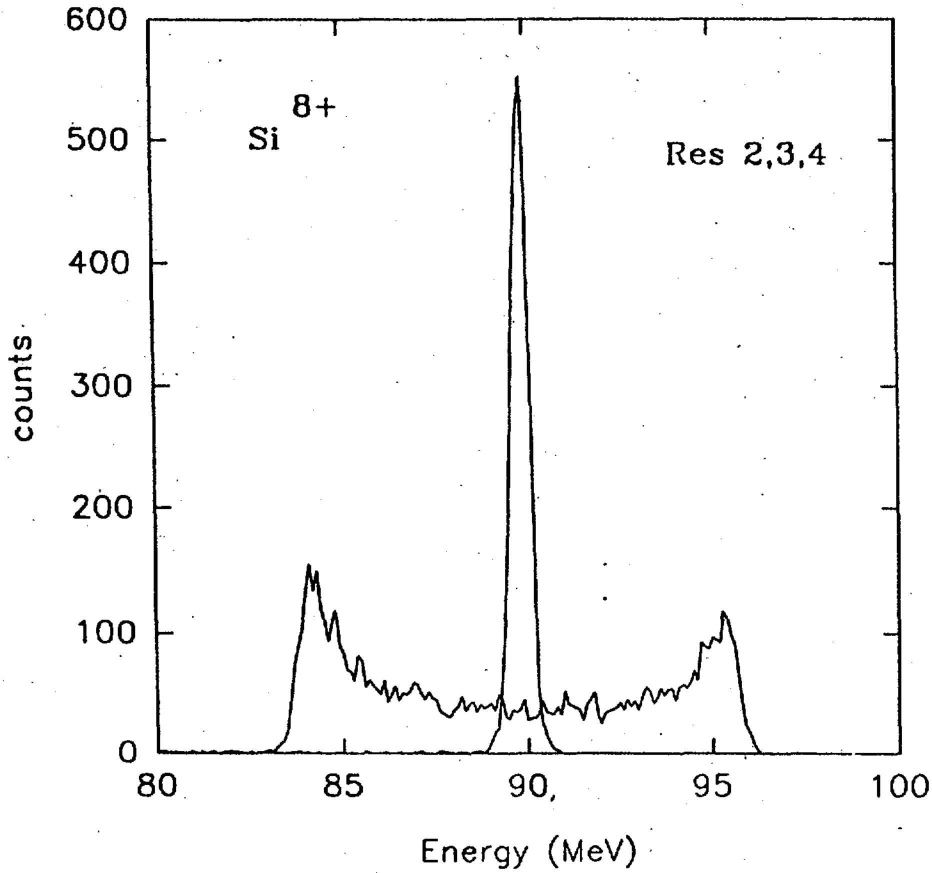
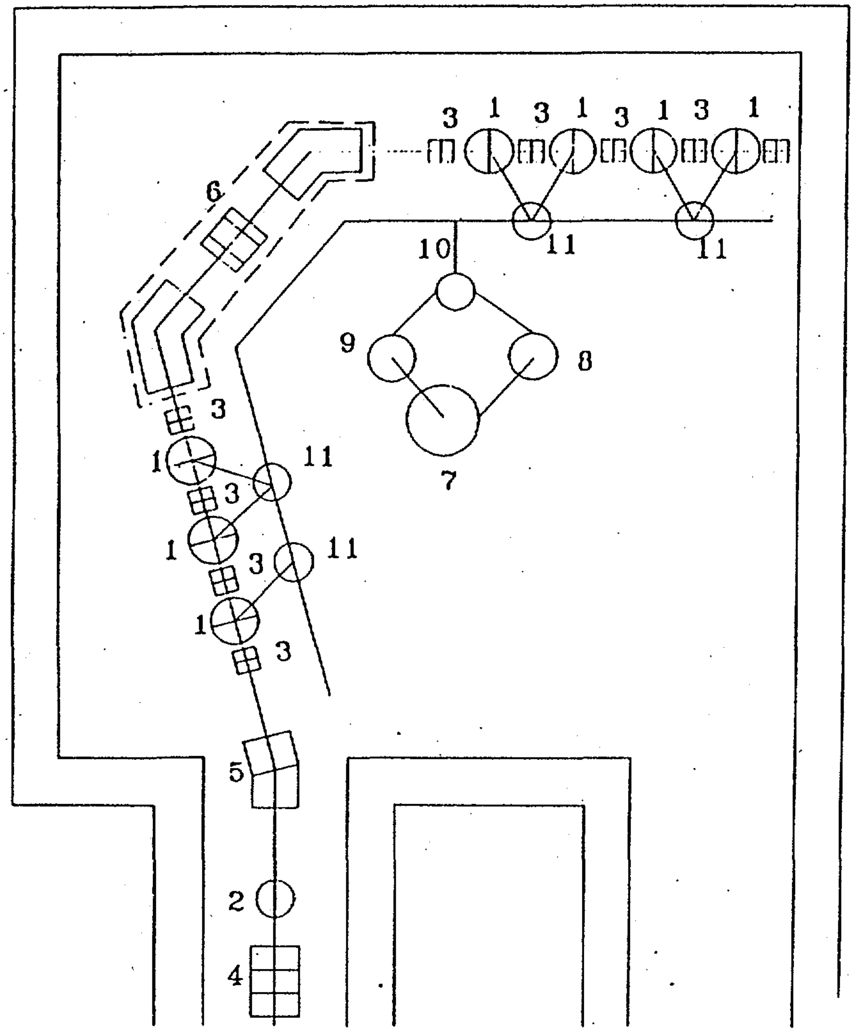


Fig. 9: Energy gain with the first module



1 MODULAR CRYOSTAT
2 SUPER BUNCHER
3 QUADRUPOLE DOUBLET
4 QUADRUPOLE TRIPLET
5 15° BENDING MAGNET
6 110° ACHROMATIC BEND
7 HELIUM REFRIGERATOR
8 LIQ NITROGEN GENERATOR
9 LIQ HELIUM DEWAR
10 JUNCTION BOX
11 FILLING STATION

Fig. 10: The proposed LINAC beam line

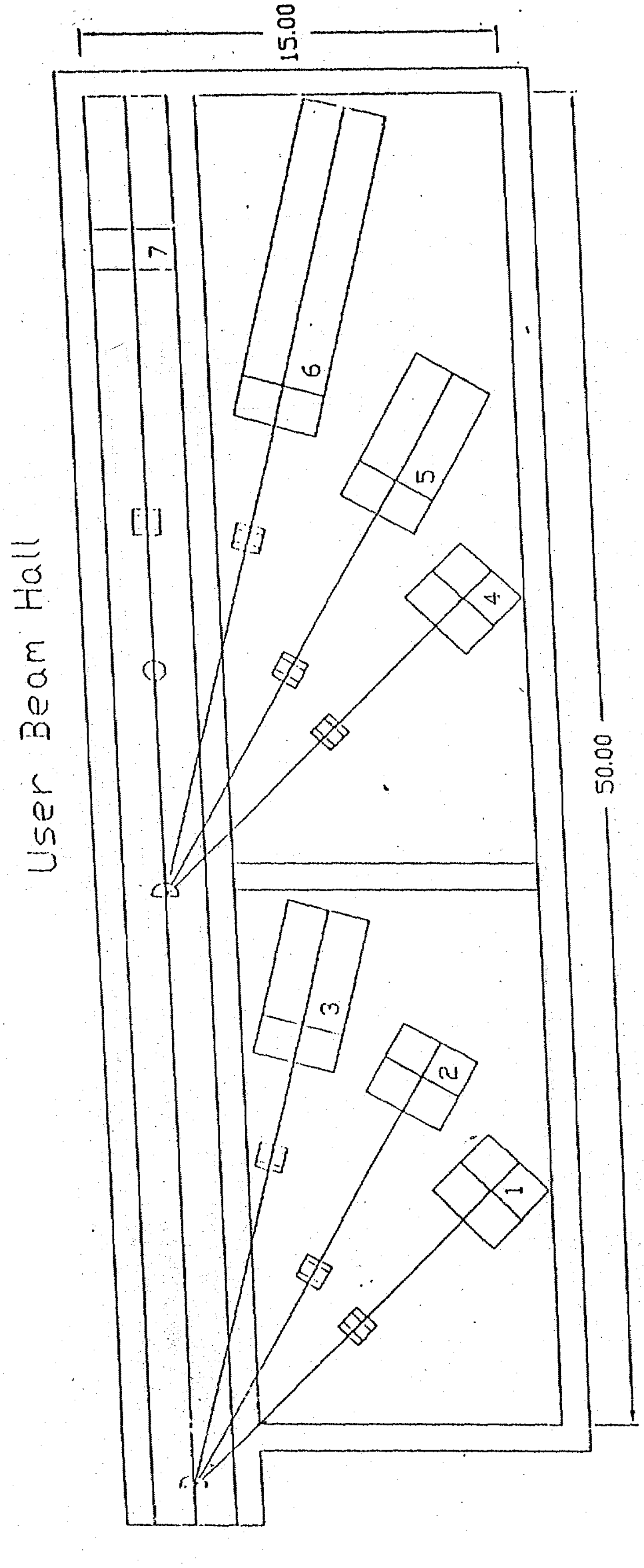


Fig. 11: The proposed user beam line

List of Publications:

A) In Refereed Journals:

1) Superconducting LINAC Booster for the Pelletron accelerator at Bombay;
R.G.Pillay, M.B.Kurup, A.K.Jain, D.Biswas, S.A.Kori and B. Srinivasan, Ind. J. Pure Appl. Phys. 27(1989)671.

2) Status report on the BARC-TIFR Superconducting LINAC Booster;
R.G.Pillay, M.B.Kurup, M.K.Pandey, B.Srinivasan, M.G.Betigeri, Ind. J. Pure. Appl. Phys. 35(1997)152.

3) Cryogenics for BARC-TIFR LINAC;
R.G.Pillay and M.K.Pandey, Ind. J. Pure. Appl. Phys. 35(1997)156.

B) Presented in International Conferences:

1) Performance of a Superconducting accelerator module for the Pelletron at Bombay;
M.B. Kurup, R.G. Pillay, M.K. Pandey, B. Srinivasan and M.G. Betigeri, ECAART-4, 29 Aug - 2 Sept. 1995, Zurich.

2) Performance of the first Superconducting accelerator module for the Pelletron at Bombay;
M.B.Kurup; International. Nucl.Phys.Symp. Bombay (1995)pp528.

C) Presented in National Symposia:

1) Bead test on the Quarter Wave Resonator; B.Srinivasan, S.A. Kori, A.K. Jain, R.G. Pillay and M.B.Kurup, Proc. DAE. Symp. Nucl. Phys. 32B(1989)O9.

2) Quarter Wave Resonator design; B.Srinivasan and R.G. Pillay, Proc. DAE. Symp. Nucl. Phys. 33B(1990)317.

3) Superconducting test on the Quarter Wave Resonator; B. Srinivasan, N.M. Thakur, M.B. Kurup and R.G. Pillay, Proc. DAE. Symp. Nucl. Phys.35B(1992)474.

4) Design of a Sweeper-Corrector; N. M. Thakur and R.G.Pillay, Proc. DAE. Symp. Nucl. Phys.35B(1992)508.

5) Superconducting LINAC Booster for the Bombay Pelletron; B. Srinivasan, Invited talk presented in Nucl.Phys.Symp.,Calicut, Nucl Phys.(DAE) 36A(1993)157.

6) In-Beam Superconducting Buncher Tests; R.G.Pillay, M.B.Kurup, M.K.Pandey, B.Srinivasan, N.M.Thakur, M.G.Betigeri, M.Y.Vaze, P.J.Bhalerao,S.K.Gupta, P.V.Bhagwat, Proc. DAE. Symp. Nucl.Phys.37B(1994).

7) In-Beam tests with the Prototype Module of the Superconducting LINAC Booster; R.G.Pillay, M.B.Kurup, M.K.Pandey, B.Srinivasan and M.G.Betigeri, Proc. DAE. Symp. Nucl.Phys. 39B(1996)368.

Appendix 2

Financial Outlay:

1) Sanction No. And date of sanction : F .S.No. 31/24/85/(BARC)/R dt. 2-1-1986.

2) Date of commencement of Project : 1986.

3) Estimated Cost : Rs. 250 Lakhs.

4) Sanctioned Cost : Rs. 250 Lakhs.

Expenses (Rs.in Lakhs) incurred in the project during the VII and VIII plan period under various heads is summarised below.

Resonators	5.627
RF Electronics	50.379
Lead Electroplating	3.201
Cryogenics	53.652
Beam line components	30.752
Niobium Sputtering activity	14.536
Computer Control	3.020
Total	161.167

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