THE RUTHERFORD LABORATORY 70-MeV LINEAR ACCELERATOR

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Summary

A 70-MeV proton linear accelerator, originally built as an injector for the Nimrod proton synchrotron, is described. The accelerator is now being modified to serve as the injector for a new rapid-cycling synchrotron which is being constructed for a pulsed neutron source facility.

Introduction

The linear accelerator was originally constructed in the years 1973-76. It was built as a new injector for the Nimrod 7-GeV proton synchrotron, to replace the 15-MeV injector, with the object of increasing the synchrotron beam intensity. The injector was required to provide a 500 µs pulsed proton beam of 75 mA, at a maximum repetition frequency of 1 Hz.

Shortly before the construction of the accelerator was completed, a firm date for the closure of Nimrod was announced, which made a change-over to the new injector no longer worthwhile. In view of a possible future use for the accelerator, however, work was continued to complete its construction and to commission an accelerated beam. The first 70-MeV beam was produced in May 1976, and operational tests continued until a shutdown in March 1977.

In June 1977, approval was given for the construction at the Laboratory of a pulsed spallation neutron source (SNS). The neutron source will be based on an 800 MeV, high intensity, rapid-cycling synchrotron with the 70-MeV linear accelerator used as the injector. Injection will be by stripping of H^- ions and the linear accelerator is to provide 500 µs, 20 mA pulses of H^- ions at a repetition rate of 50 Hz.

A description of the linear accelerator in its original form as an injector for Nimrod will be given, followed by an account of the modifications which are underway to convert it for use with the SNS.

The Nimrod Injector

The 70-MeV new injector for Nimrod was proposed as a way of increasing the synchrotron beam intensity at a minimum cost, by utilizing equipment taken from the Laboratory's 50-MeV proton linear accelerator (PLA) which had been closed down in 1969. With the addition of another cavity to raise the energy to 70-MeV, it was hoped to gain a factor of five in the space-charge limited intensity at injection.

A layout of the accelerator is shown in Fig.1. The accelerator is housed in a new building alongside the existing 15-MeV injector, with the 70-MeV beam taken via a short tunnel through the synchrotron earth shielding and then to a straight section in the magnet ring. The building is divided into a 200-m^2 Faraday screened room for the pre-injector, a 350-m^2 linac equipment area and a 250-m^2 shielded enclosure of concrete blocks containing the accelerating cavities. The cavities are supported on a steel framework above a basement, which provides the height necessary to accommodate the rf amplifiers and vacuum pumps.

The Pre-injector

The ion source, which has been described in detail elsewhere[1], is a compact duoplasmatron with a 20-mm diameter expansion cup. Typical performance figures are given below.

		On test rig		On Column	
Extraction gap	(mm)	21.3	18.3	12.5	12.5
Extraction volts	(kv)	30	50	18	14.5
Arc Current	(A)	35	60	34	24
Beam Current					
- at source exit	(mA)	200	600	-	-
- at 665 keV	(mA)	-	-	210	125

The accelerating column, also described elsewhere[2], was designed for an energy of 665 keV and a target value of beam current of 200 mA. It is constructed from a stack of 16 titanium electrodes, bonded to pyrex spacer rings by PVA adhesive, and enclosed in an outer glass-fibre reinforced epoxy resin vessel pressurized with SF_6. To ensure reliable operation, the column is designed for the modest value of accelerating gradient of 1.5 kV/mm. At this gradient it is possible to include a large value of reservoir capacity in the high voltage supply without the danger of voltage deconditioning in the event of a spark-over. It is also about the lowest value at which a 200-mA beam can be satisfactorily accelerated to 665 keV and matched to the input of a practical beam transport line. The column is evacuated by turbo-molecular pump.

A view of the pre-injector high voltage equipment is shown in Fig.2. The high voltage supply is a Haefely generator, rated at 750 kV, which charges a 0.01 µF storage capacitor. The capacitor limits the voltage drop due to a beam pulse to 10 kV which in turn is compensated by a bouncer stabilizer circuit connected to the low voltage terminal of the capacitor. The bouncer employs a transformer coupled control tube which takes its error signal from a special capacitive potential divider. By suppressing the bouncer between pulses, the operating voltage is determined by the fundamental d.c. stability of the high voltage supply. The stabilizer has a frequency response of 500 kHz and at full pulse loading provides stabilization to within 0.4 kV.

The 665-keV Beam Transport Line

A beam line containing three quadrupole magnet triplets connects the pre-injector to the first tank of the linac. The first triplet is mounted inside the vacuum system of the pre-injector column in order to capture the emerging beam before it diverges too far, while the final triplet is mounted as close as possible to the linac to achieve the short characteristic length matched beam parameters, required at the input to the first accelerating gap. The first two triplets have element lengths of 100/200/100-mm, apertures of 90 mm and provide maximum gradients of 5 T/m. Corresponding figures for the third triplet are 80/160/80-mm, 60-mm aperture and 17 T/m.

A single fundamental frequency buncher cavity is used in the beam line for longitudinal matching. The buncher drift distance is 800 mm and the peak proton energy change is 23 keV. The cavity, which is of the half wavelength coaxial line design, is fed with rf power from an adjustable coupling loop in the first linac tank.

The Linear Accelerator

The accelerator is divided into four separate cavities, the parameters of which are given below. A view of the accelerator cavities is shown in Fig.3.

Tank No.	1	2	3	4
Construction	Cu clad steel	Vac vessel & Cu liner		Cu clad steel
Length, m	7.15	11.96	11.24	12.11
Energy out, MeV	9.91	30.44	49.71	70.44
No. of cells	56	41	27	24
DT aperture, mm	20-25	38.1	38.1	30
Acc rate, MeV/m	0.84-1.55	1.72	1.71	1.77-1.66
Q-theoretical	76,100	70,900	56,800	66,000
- measured	60,900	58,600	39,700	55,100
Power for $\phi_s=30^\circ$				
-theor loss, MW	0.44	1.31	1.40	1.51
-practical incl 75 mA beam	1.24	3.12	3.45	3.36
Focusing magnets				
-period	FDFD	FFDD	FFDD	FFDD
-excitation	Pulsed	DC	DC	DC
-gradient, T/m	85-29	7.5-6.1	4.6	5.3
-length, inches	1.0-2.75	4.5-6.0	9.0	7.5

For the design value of accelerated current it was considered essential to use the FDFD focusing mode at the input end of the linac. Tank 1 of the PLA had used grid focusing and although conversion to quadrupole focusing would have been possible, because of an unfavourable drift-tube shape only the FFDD mode could have been achieved. A new tank was required therefore, and to save effort it was decided to base this on an existing design. This was made possible by the generous supply of information by Fermilab on the design of their 200-MeV linac. To adapt the design to the 70-MeV linac, a new set of unit cell lengths was interpolated to give an output energy matching the input to tank 2, and the design was extrapolated forwards to produce an acceptable input energy, arbitrarily put at less than 700 keV. With the exception of minor details the tank and drift-tube construction is identical to that at Fermilab.

Tanks 2 & 3 are taken from the PLA and used with only minor modifications. These were originally built in the late 1950's, and are constructed with separate sheet copper cavities and outer steel vacuum vessels. The drift-tubes contain d.c. powered quadrupole magnets which are limited to the FFDD operating mode. Tank 4 is another new tank built to the Fermilab design, including the use of post couplers, but with the drift-tubes fitted with d.c. powered quadrupoles. The quadrupoles have solid cores and low current windings, and by operating them in the FFDD mode the dissipation is sufficiently low to allow them to be cooled by conduction to the drift-tube body.

In order to save cost, tanks 2 & 3 are still fitted with the oil diffusion pumps used earlier on the PLA and tanks 1 & 4 are fitted with oil diffusion pumps which were surplus from elsewhere on Nimrod. An operating pressure of better than 2×10^{-6} torr can be achieved on all tanks.

The Rf System

The high power rf system[3] consists of a common low power drive-chain which feeds four separate two-stage amplifiers, one for each tank. The drive-chain provides four outputs, at a maximum level of 12 kW each, by means of four adjustable loops coupled to the anode circuit of the output stage. The two-stage amplifier comprises an RCA 4616 tetrode operating in grounded cathode followed by a Thomson-CSF TH116 triode operating in grounded grid. The circuit for each of these valves uses tunable coaxial resonators for input and output circuits, with input and output coupling via adjustable taps. The RCA 4616 operates at an output of up to 500 kW and the TH116 has been tested at a maximum output of 4.25 MW into a dummy load.

Rf power is coupled to each tank by an adjustable loop situated on the air side of a vacuum window of cross-linked polystyrene. The power is fed via a 300-mm diameter transmission line, polystyrene disk supported, which incorporates a trombone phase shifter and a calibrated reflectometer. The tank phase is set by a trombone phase shifter in the TH116 drive line.

Anode power for the TH116 valves is provided by individual pulse modulators, consisting of a pulse forming network feeding a $2\frac{1}{2}$:1 step-up pulse transformer via a CX1174 deuterium thyratron. The pulse transformer also supplies the anode of the RCA 4616 via a series resistor. Stabilization of the field level in the tank is arranged by anode modulation of the RCA 4616, by controlling an ML 8786 tetrode placed in shunt with it. This system has provided satisfactory stabilization against beam loading up to the full design value of beam current.

70-MeV Beam Transport Line

Beam transport between the linac and synchrotron is provided by a line containing two achromatic bends and an electrostatic inflector as the final element. Focusing throughout the beam line is by triplet quadrupole magnets, of which the end elements are air-cooled magnets taken from the PLA and the higher strength center element is a proprietary water-cooled magnet. The beam alignment can be adjusted by four steering magnets located at the linac exit. A debuncher cavity is installed to reduce the beam energy spread, but the cavity was also intended to be fast phase ramped to provide energy modulation of the beam during the pulse. At the time the injection project was abandoned, a 100 kW fast ferrite phase shifter was under development for this purpose, power for the debuncher being coupled from tank 4 by an adjustable loop.

Beam Monitoring

The pulsed beam current is measured by a system of 14 beam transformers which provides both analogue pulse and digital panel meter display. The other main monitoring device is a multiwire beam profile monitor, consisting of a number of 0.02-mm tungsten wires at 2-mm spacing which can be inserted into the beam. The output is available as an oscilloscope histogram display or can be stored in a transient recorder for subsequent digital readout. To prevent melting these can only be used in the 665-keV beam with short beam pulses.

The emittance of the 665-keV beam is measured using a multi-slit plate followed by a traversing slit. Data taking is semi-automatic but data analysis is carried out off-line. Other equipment available includes threshold foils to identify accelerated from unaccelerated beam, and also a momentum spread measurement system using a slit bending magnet and profile monitor.

Control System

An original plan to provide computer control had to be abandoned because of financial constraints. The system chosen, however, was one which could be later adapted to computer control and yet was no more expensive than a totally hardwired system. Communication with the machine equipment, from either the injector control center or the Nimrod control room, is via a CAMAC system operated by an autonomously cycling control unit. At either control point the operator selects the device to be controlled on a push button selector panel, which gives control of the device parameters at a central control panel. All controls are of the push button, on-off or raise-lower, type. Device selection also switches appropriate parameters for display on digital panel meters.

Operation

Operating experience with all components of the pre-injector has been generally very satisfactory, with the reliable production of a 665-keV beam over an 18-month period and the achievement of the design values of pulse current and duty cycle. As expected, 200 mA has proved to be about the maximum current obtainable at the output of the column, and even at this current there is evidence that the beam is scraping the bore of the first triplet magnet. Measurements of the 665-keV beam emittance area have yielded: 160-mA beam, 90% of current inside 38π μmr; 100-mA beam, 90% of current inside 40π μmr, 95% inside 50π μmr and 95% inside a circumscribed ellipse of 66π μmr.

Commissioning of the linac beam commenced with the first operation of tank 1 in February 1976. Although a 10-MeV beam was established fairly quickly, operation was severely troubled by a multipactor problem which caused the loss of 50% and upwards of all pulses. Following unsuccessful attempts at conditioning the tank, carbon black was applied to all the drift-tube faces. This produced an improvement, but it was not the complete success that it had been on the 15 MeV linac, and only after many weeks of running was it possible to achieve adequately reliable operation. Even then, periods of multipactor could still arise, particularly at the full 1 Hz repetition rate. A further problem has been the failure of the quadrupole inside drift-tube number 8. However, by reversing the polarity of all upstream magnets, a satisfactory beam acceptance has been achieved giving, for example, an 80-mA beam at 10 MeV for 135 mA at the tank input.

Following operation at 10 MeV, the three remaining tanks were progressively commissioned, with the first 70-MeV beam produced in May 1976, and the 75-mA design current obtained by the end of that year. Operation at the 1-Hz repetition rate and 500-μs pulse length were separately achieved, but the accelerator was always operated at less than the combined full duty cycle because of incomplete installation of the radiation shielding. Probably the greatest operating problem experienced was in setting up the tank phases, with the aid of the energy threshold foils, and in maintaining the phase from one operational period to another. The difficulty was largely due to phase variations during the rf pulse which were of a different form for each tank. It is thought that these may be caused by reactive loading due to multipactor type discharges at the operating field level. Another problem was the collapse of the buncher cavity field with long beam pulse lengths, thought to be due to thermionic emission from the grids in the gaps. This could usually be avoided by careful focusing of the 665-keV beam.

The emittance of the 70-MeV beam was determined by measurement of the beam width at a single profile monitor for a range of settings of an upstream triplet quadruple magnet. Measuring at the 10% signal level, the emittance area for a 50-mA beam was found to be approximately 11π μmr in both planes. Assuming a gaussian density distribution this area contains 90% of the beam current.

Prior to the linac close down in March 1977, the performance of tank 1 was examined with the quadrupoles re-connected for the FFDD mode, since this was relevant to its future use. With the gradients approximately halved, except for the magnets adjacent to the faulty number 8 which were empirically optimized, the transmission factor for the tank was found to be only about 50% compared with the previous value of 60% or better. Some improvement in this figure can be expected with the faulty magnet replaced and with more careful optimization.

Conversion of the Linac to an Injector for the SNS

Following the approval given for the SNS project, work has been underway to modify the linear accelerator to act as the injector for this new machine. The main changes are concerned with the increase in repetition rate to 50 Hz and in the change of accelerator beam to H^- ions, but other necessary improvements suggested by the previous operating experience will also be carried out. A brief discription will be given of the principal changes.

The Building. Because of the anticipated increase in radiation levels, additional shielding will be installed and all electronics will be removed from the linac enclosure. Increased room for equipment will be provided by building extensions to house the water plant and a new local control center.

Ion Source. An H^- ion source of the Penning surface plasma type is now under development. This has the basic discharge chamber geometry of the Dudnikov source, described by Allison[4], and is fitted with a pulsed gas valve and external cesium boiler. Operation in the cesium mode, at an arc current of 100 A and a pulse length of 500 μs, has been maintained for over 40 hours at the reduced repetition rate of 14 Hz. A source with improved cooling and fitted with a 90° analysing magnet is about to be tested.

Pre-injector. A new bouncer circuit has been designed to accommodate the reversal in high voltage polarity.

Linac Tanks. A change to the FFDD focusing mode and the design of an improved pulsed power supply to give shorter pulse rise and decay times, will allow the quadrupole magnets in tank 1 to be operated at 50 Hz without overheating. On all tanks, the diffusion pumps are being replaced by turbo-molecular pumps and all water-cooling circuits are being modified to provide the required increased flow rates.

Rf System. It is believed that the 4616 and TH116 circuits will be satisfactory at the new duty cycle with only minor modifications. Four separate low power drive systems will be built to enable fast phase and amplitude control to be carried out at low power level. New anode power supplies now under construction include a hard valve modulator for the TH116 which uses the ML8786 as the series control valve. A prototype of this modulator has been operated successfully and has enabled preliminary tests to be carried out on the rf amplifiers at the full duty cycle.

Controls. The control of the injector will be integrated into a computer control system being designed for the SNS. This uses a central GEC 4070 computer linked to three similar peripheral computers, one of which is dedicated to the injector. A new interpretive control language called GRACES is being written for the 4070. Much of the injector equipment will have to be modified to accept digital control.

70-MeV Beam Transport. A new beam line will make use of the existing design of quadrupole magnets, many of which will now be operated as singlets, and a number of ex-Nimrod beam line dipoles will be used as bending magnets. Injection into the SNS will involve the use of orbit bump magnets and a stripper foil. With a mean beam current of 500 μA from the injector, the monitoring of beam loss in both the linac and the beam line is expected to be an important function of an up-rated beam diagnostic system.

Conclusion. It is anticipated that the accelerator can be converted to a high duty cycle injector for the SNS with only minor modifications to major components such as the d.c. and rf accelerating structures and the rf system amplifiers. In other areas, far more extensive changes are required. Work on most of the areas of modifications is now in progress. It is planned to produce a 665 -keV H^- beam in the second half of 1980 and work on the remainder of the linac is aimed at a target date for the completion of the SNS towards the end of 1982.

Acknowledgements

Construction of the original 70-MeV injector was the work of a number of the staff of the former Nimrod Division, under the leadership of the late Norman Venn. The author wishes to acknowledge the contribution of these individuals to the work described and also that of his colleagues in the smaller, and largely new, group who are engaged on the present modification work.

References

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DISCUSSION

A. Wadlinger, LASL: Why does carbon black help the multipactoring and how did that idea originate?

West: Carbon black has a secondary emission coefficient of less than unity. The mechanism of operation is like a cliff wall with lots of holes in it. If you throw a ball at the wall, there is a good chance that it will enter the nearest cave, bounce around and never come out again. So, I do not think it is the fact that it is carbon that matters; I think it is the structure of carbon black. To make it, you take carbon black, mix it with alcohol and just paint it on. You get a nice black surface just like a flame-smoked surface. It's very crude - it sounds like a terrible thing to put in a rf cavity; in fact it has no effect on the rf power, but it really stops multipactoring.

D.A. Swenson, LASL: Did you put post-couplers in the fourth tank of your new linac, and if so, were your experiences of tuning the post-couplers satisfactory?

West: We did put post-couplers in; there seems very little reason to have done so if you remember that we have three other tanks without any stabilization, but we chose to make it identical to the FNAL tank. Setting up the post-couplers was satisfactory - we have not done any tests on the tank to see how good the stabilization is, but it's only a 20-MeV tank, so perhaps the problems are very small anyway.

C. Curtis, FNAL: You mentioned the phase shift during a beam pulse. Can you speculate on what causes this - is it associated with your rf tube?

West: We do not think it is the rf tube because it varies from one tank to another and it is a function of the tank tuning. I believe it is an electron resonant discharge somewhere in the structure of the accelerator cavity at a high level, multipactor discharge essentially, but well away from the drift tubes. Tanks 2 and 3 have lots of pumping slots and there is opportunity for rf to leak out of these areas. We have the same trouble in Tank 4 and that is copper-clad steel construction. I can only assume it is some sort of multipactor discharge around the support stems. But this is speculation - I mean we haven't any direct experimental evidence as to what is causing it.

R.L. Witkover, BNL: With the high duty factor for the H^- injection that you envision, do you foresee any problems with the stripper foil?

West: So far we have not done any work on stripper foils, but the Argonne experience would suggest that a solution should not be too difficult. I think the life of stripper foils should be all right providing we can have a suitable mechanism for replacing them at perhaps fairly frequent intervals.

J.P. Blewett, BNL: It seems sort of surprising to me that this multipactoring only happens in England. Is there an explanation of this?

West: It is not that it only happens in England - it only happens to me!

E.A. Knapp, LASL: What is the schedule of operation of the SNS, and also of the injector linac?

West: The present construction schedule for the SNS is that we should have a beam to the neutron target by the end of 1982; however, that depends very much on the rate at which we receive funds and that is something that is adjusted from one year to another. I would hope to have a beam from the linac 6 to 12 months before that date.

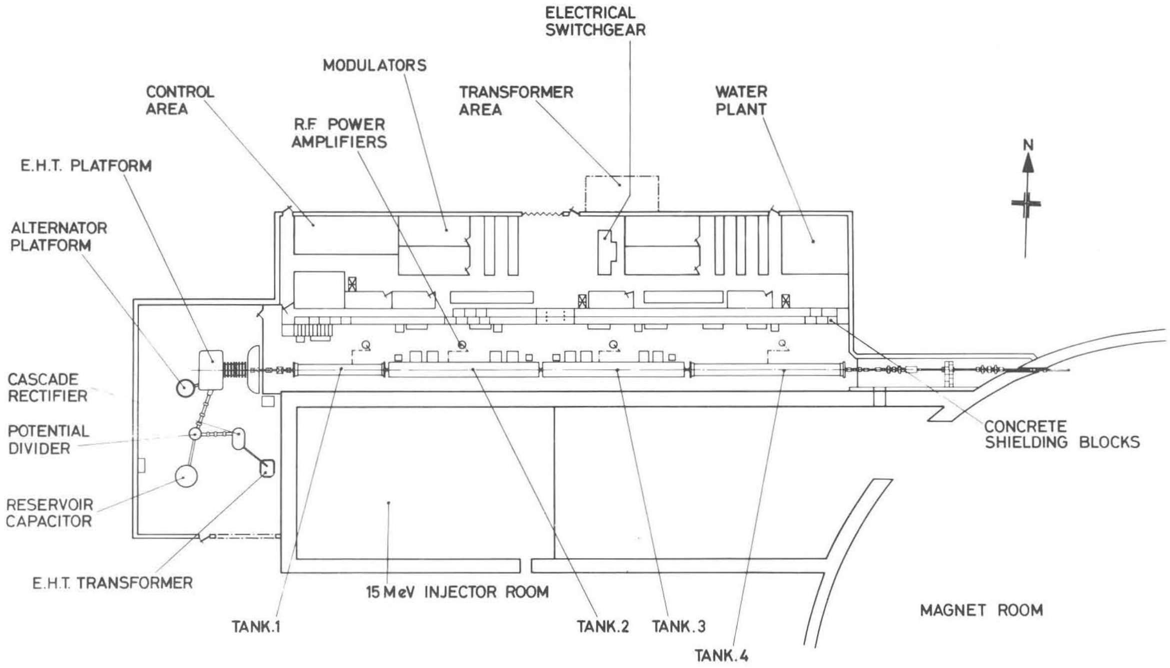

Fig. 1 Layout of the 70-MeV accelerator

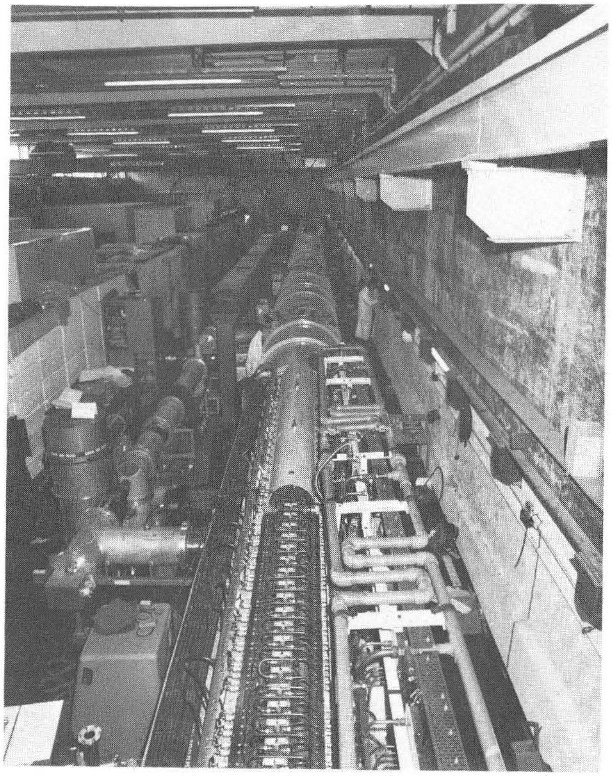

Fig. 2 The pre-injector high voltage area

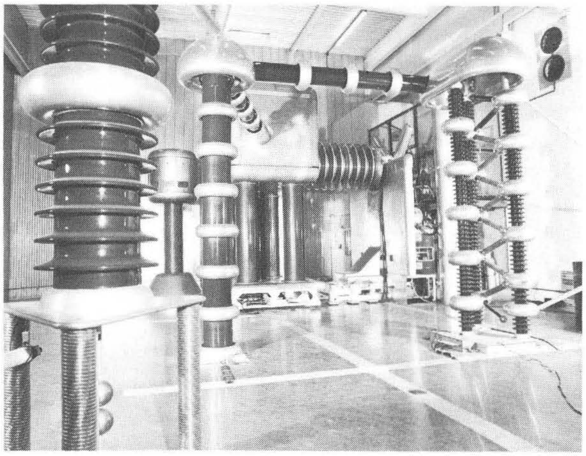

Fig. 3 View of the linac from tank 1