Rutherford Laboratory

Technical Leaflet

THE PROTON LINEAR ACCELERATOR

It was almost exactly four years ago, on 20th April, 1960 that the Proton Linear Accelerator was first scheduled for nuclear physics experiments.

THE HISTORY OF THE P.L.A.

By 1952 π mesons had been produced artificially in the 180 inch synchrocyclotron at the Radiation Laboratory, Berkeley. It was well established that this particle was closely concerned with the nature of the nucleon-nucleon interaction and consequently a study of its mode of production, its properties and the details of its interaction with the nucleon were essential for the development of the theory of elementary particle physics. However the yields, particularly of positive pions, from synchrocyclotrons limited the scope and precision of the experiments and thinking at Harwell turned to the possibility of building a 600 MeV proton linear accelerator.

The linear machine would have no magnet to constrain the protons and the positively charged pions and it was calculated that with a modest current of 1 microampere there would be an improvement of almost four orders of magnitude in the yield of positive pions over existing synchrocyclotrons. In many other ways too the linear machine had very desirable characteristics - low background, good energy resolution, variable energy and excellent experimental access to the beam.

The technical and engineering problems were tremendous. A 600 MeV machine would be almost 300 yards in length; it would be operated for part of its length at a frequency of 200 Mc/s and at 400 Mc/s for the rest. At these frequencies the total peak r.f. power that would be required was almost 100 million watts and no suitable valves for producing this amount of power were available commercially in Britain. There were also many uncertainties in the physics of the accelerator, such as the best method of focussing the beam, the problem of phasing and control and the engineering tolerances that were necessary in manufacture. Moreover, the only accelerator of this type in the world being used for research was a 32 MeV single tank accelerator built by Alvarez and his collaborators at Berkeley, although there was a 68 MeV 3-tank accelerator under construction at the University of Minnesota in the U.S.A. No machine of comparable size was being contemplated anywhere.

Nevertheless a decision was made to go ahead with the project. The Valve Development Group in A.E.R.E. was given the job of producing the necessary r.f. power and a P.L.A. Group under Dr. Pickavance was formed in the General Physics Division of A.E.R.E. to design and build the accelerator. By 1955 it was predicted that the 600 MeV machine would be complicated to operate. Furthermore, its big advantage over synchrocylotrons in the yield of positive pions available for experiments had been reduced by the success achieved on the Liverpool cyclotron with a new method of beam extraction. Also the Bevatron had produced antiprotons and it was known from cosmic ray studies that there was a whole new family of unstable "Strange Particles" that might be produced with machines with energies of a few thousand MeV. So it was decided to limit the energy of the P.L.A. to 50 MeV and to concentrate the major scientific and constructional effort that was available on a completely different higher energy machine - NIMROD.

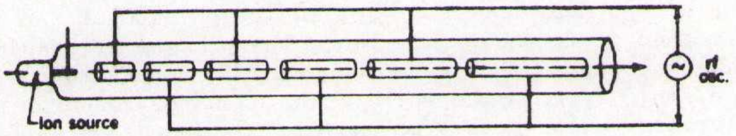
There is therefore nothing particularly significant about the energy of the 50 MeV proton linear accelerator, yet it has turned out to be a very interesting energy region from the point of view of nuclear physics for, until quite recently, the energy region between that available with Van de Graaf generators (a few MeV) and synchrocyclotrons (100 MeV upwards) was not very easily investigated. We have not quite entered virgin territory because the 68 MeV P.L.A. at Minnesota has been working for some considerable time. However, we have something like a 100 times more proton current, a very successful source of polarized protons and a sophisticated time-of-flight device - quite exceptional facilities which make open to us many experiments that other laboratories in the world would find difficult to do.

Protons were first accelerated to 10 MeV in the P.L.A. on 10th November, 1958 and to the full energy of 50 MeV on 12th July, 1959. By this time the Rutherford High Energy Laboratory had come into existence and the ownership of the P.L.A. had been transferred from A.E.R.E. to the National Institute. The machine is now working very well and indeed its reliability has proved much better than was predicted, largely due to the incorporation of recently developed components and techniques. We operate on a 24 hour per day schedule and in the last 12 months have provided 4,400 hours of experimental machine time for the 50 experimenters who are using it for their research work.

There is no doubt that the original arguments which led to the start of the 600 MeV project were correct. The P.L.A. has proved to be a very satisfactory machine to use for experiments and in many parts of the world now plans are being made to build very high intensity proton accelerators - pion factories, as they are called. Some of the groups favour proton linear accelerators, others cyclotrons making use of the recently invented principle of sector focussing.

THE MACHINE ITSELF

The principle of a linear accelerator (or "linac") was first developed from the earlier ideas of Wideröe by Sloan and Lawrence, who constructed a machine at Berkeley (U.S.A.) in 1931 to accelerate mercury ions to an energy of 1.25 MeV in a length of just over 1 metre. The diagram shows the principle of their device.



Early linear accelerator for heavy ions

The positive mercury ions were accelerated in a series of "kicks" by forces they experienced in crossing the gaps between the thirty or so cylindrical electrodes (or "drift tubes"). These formed part of a resonant circuit fed with power at a radio frequency of 10 Mc/s. A radio frequency (r.f.) field is produced in the gaps between the electrodes and the particles are accelerated across successive gaps once each half cycle of the applied r.f. voltage. During the half cycle when the electric field is reversed in direction the ions are passing through a drift tube and are screened from the field. The gap spacings are arranged so that the stably accelerated ions always arrive at a gap when the r.f. field is in the correct direction to give them a further "kick". Obviously the spacing and drift tube length must gradually increase as the ions gain energy and travel with greater velocity.

In the 1930's it was difficult to generate much power at high r.f. frequencies and it was impractical to extend this type of machine for much higher particle energies or lighter particles than mercury ions. It was not until after the development of high power r.f. generators up to microwave frequencies during the 1939-45 war that interest was revived in linear accelerators. Development concentrated at first on linear electron accelerators and dozens of machines were constructed ranging in energy from 4 MeV upwards. The first successful proton linac was the 32 MeV machine built by Alvarez at Berkeley in 1947 and its success led to the building of many others, several of which are used as pre-accelerators for proton synchrotrons. All the proton linacs work on the same principle and, with very few exceptions, all are designed to operate at an r.f. frequency of about 200 Mc/s.

Basically, the principle of operation is similar to that of the Sloan and Lawrence machine but, due to the high frequency necessary to keep the gap spacing short, the r.f. techniques required are different. Lumped component circuits are no longer practicable and the drift tubes have to become part of a resonant cavity structure. This cavity is cylindrical in shape and about 3 to 3½ ft. in diameter. As in the Sloan and Lawrence case, when high power r.f. is fed into the cavity, high electric fields are produced in the gaps between the drift tubes, which are supported along the axis of the cavity. Now, however, the field is in the same direction in all the gaps at the same time and accelerated protons travel from one gap to the next in one complete r.f. cycle.

The Rutherford Laboratory machine is about 100 ft. long and accelerates protons up to an energy of 50 MeV (their velocity is then about 1/3 that of light). This means that the protons have the same velocity as they would acquire by being accelerated directly between two electrodes at a d.c. potential difference of 50,000,000 volts: it is virtually impossible due to the insulation problems, to produce such a steady d.c. voltage.

The machine has three main copper resonator sections or "liners". Each is enclosed in an outer cylindrical steel vacuum envelope which is connected to a number of large (20 inch diameter) oil diffusion pumps to maintain a pressure below 10^{-5} torr in order to prevent scattering of the proton beam and avoid voltage breakdown in the resonator.

The first tank is about 18 ft. long and accelerates protons from ½ to 10 MeV energy; the second and third tanks are each about 40 ft. long and take the protons successively to energies of 30 and 50 MeV. The drift tubes are made of copper and are supported on the axis of each resonator by two radial "stems". There are 42 in tank 1, 41 in tank 2 and 27 in tank 3. A proton thus receives about 110 separate "kicks" to accelerate it up to the 50 MeV energy.

Very high r.f. powers are needed to produce the fields required, amounting to about 600 kW for tank 1 and about 1.25 to 1.5 MW in tanks 2 and 3. It is only practicable to produce such high powers in very short pulses, using radar type modulator techniques. Even then approximately 0.5 MW of mains power is required to run the whole machine!

On the P.L.A. 50 pulses per second are used, each 400 millionths of a second long. Because of the high "Q" of the accelerating tanks the r.f. fields take between 100 and 200 microseconds after the beginning of each pulse to build up to their full amplitude, so the machine can only accelerate protons for about 200 microseconds during each pulse. The power is produced by a series of grounded grid triode amplifier valves, each capable of producing 1 MW of pulsed power.

These valves were designed and developed by the A.E.R.E. valve group and are unusual in their "inside out" construction - having an external, directly heated, cathode and a central anode. The associated r.f. circuits take the form of "built in" resonant sections of co-axial line. Vac-ion pumps are used to produce an operating vacuum better than 10^{-6} torr.

Drive power for the main amplifiers is produced by the frequency multipliers and amplifying stages of a common drive chain, starting from a very stable, temperature controlled, crystal oscillator operating at a frequency of 2.5 Mc/s. The 80 KW pulsed power output from the drive chain is divided in the correct proportions and relative phases by a complicated series of co-axial line components. The power is transmitted through very large co-axial lines coupled into each resonator by a large loop. The r.f. power is practically all dissipated in the walls of the liners and drift tubes and these must be water cooled.

The accelerated protons come from an ordinary bottle of compressed hydrogen gas. The hydrogen is fed into a glass tube (the "ion source") at a low pressure and an electro-magnetic field, produced by surrounding the glass tube with a coil carrying an r.f. signal of 20 Mc/s frequency, causes a discharge in which many of the hydrogen molecules are broken up into atoms and further, into protons and electrons. The positively charged protons are "extracted" from the discharge by a negatively charged electrode and pass through a series of focussing electrodes. The ion source is mounted on the insulated end of the "injector column", the opposite end, nearest to tank 1 being earthed. The insulated end is connected to a Cockcroft-Walton generator producing a d.c. potential of 500,000 volts. The protons emerging from the source are accelerated down the evacuated injector column ready for injection into tank 1.

One problem not yet mentioned is that of keeping the proton beam focussed as it traverses the accelerator. If nothing is done, the beam will gradually spread out and most of it will be lost by collision with the drift tubes. Two focussing methods are used on the P.L.A. Grids are fitted in the entrance aperture of every drift tube in tank 1 and cause a distortion of the r.f. field pattern which results in a weak focussing effect. A better method is used in tanks 2 and 3. This is called "Alternating gradient focussing" and is produced by placing special "quadrupole" electro-magnets inside every drift tube. These are arranged to give alternate focussing and de-focussing forces in two mutually perpendicular planes. (A similar effect can be produced for a light beam using suitably spaced converging and diverging lenses.) The beam is confined to a given diameter by this method with no loss of particles.

The beam leaving the end of Tank 3 is transported along evacuated flight tubes to either of the two experimental areas beyond the end of the machine. Further quadrupole magnet lenses are used to keep the beam focussed. In each area a large bending magnet (weighing about 30 tons) can be used to deflect the beam along a number of different beam lines, on each of which a different nuclear physics experimental apparatus can be set up.

When the machine is operating the levels of radiation produced around the machine and in the experimental areas are such that it would be dangerous to health for any person to remain there. The machine is therefore surrounded by concrete screening walls and earth banks and must be operated remotely from the main control room. This is the reason for the array of buttons, meters and oscilloscopes which are provided to monitor and control the machine performance and output beam at all stages. Adjacent to the control room are two counting rooms where most of the electronic equipment associated with the nuclear physics experiments is located.

NUCLEAR PHYSICS ON THE P.L.A.

Associated with the P.L.A. are some fifty experimental nuclear physicists, the majority from Universities; in addition there are two teams largely made up from N.I.R.N.S. staff, and one from A.E.R.E.

Before outlining their programme of experiments, let us consider what properties a 50 MeV proton has, because these largely determine what can be done with it. First, it is not energetic enough to produce mesons, or the 'strange' particles. But it has enough energy to overcome easily the repulsion from the positive charge on any nucleus, even uranium; and once within a nucleus it can cause havoc, for each neutron or proton within a nucleus needs only 6 MeV or so of energy to set it free. There is enough energy to knock many nucleons out of any nucleus, and they can come out singly or in small groups; the main problems in our research are to design experiments which single out the least complicated of all the events that can happen.

There are other consequences of the high energy. The protons lose energy to the electron clouds, which surround atoms, rather slowly, so they have good penetrating power (their range is about 5 mm of copper) and can see many nuclei along their path through targets. We need not be restricted to very thin layers of target material. Large currents of protons and thickish targets give plentiful yields from nuclear reactions (and considerable levels of residual radioactivity - usually just a nuisance).

There are two very important features of a P.L.A. - it has a beginning and an end, both accessible. Protons can be selected before being put into the machine, and they come out in a well defined beam which can be transported to any one of a dozen or so experimental rigs. There can be many protons, 10^{13}/second or more, or very few (we have worked with 10/second), and they have their energy fixed to better than 1% at present, with scope for further improvement. Their worst feature is that they are only present for 1% of the twenty four hours per day the machine works, and high speed electronic circuits are needed to collect data while the beam is on, and send pulses to more leisurely equipment, such as pulse height analysers, in between bursts of protons. Within this generally unwelcome 'coarse' time structure there is a much more useful 'fine' structure, due to the use of very high frequency r.f. fields for accelerating the protons. Protons arrive at targets in bursts less than 10^{-9} secs long, and by suitable preselection these bursts can be spaced up to 0.2 μsecs. apart, so that all secondary particles produced from one burst will have passed a detector before the next burst arrives. Similar timing precision is possible at the detector, so that velocities of secondary particles can be measured very accurately and without confusion, by the 'time of flight' method. The other use we make of 'preselection' of protons to be accelerated is in the polarized proton source, which enables us to prepare beams of protons whose axis of spin points in any direction we wish.

With all these techniques available, and teams of experimenters with a variety of interests, there are many different types of experiment. One major activity is the study of the forces between isolated protons; here the interacting entities are simple, the energy too low to introduce the complication of meson production, but the nature of the force so complex that many different experiments, each of high precision are needed. We have measured the absolute scattering cross section to 1% (this represents the area a target proton presents to a proton in the beam). Next comes a measurement of the asymmetry in scattering - it turns out that the tendency of a proton to be scattered to the left rather than the right depends on whether its spin is pointing upwards or downwards relative to the plane of scattering. For proton proton scattering the tendency is very feeble (only 3% more of the protons in a completely polarized beam will choose to go left rather than right at 50 MeV), but exact magnitude is very important, and has been determined as 0.0316 ± 0.0017, an accuracy unattainable without a polarized source (and much hard work too). The next generation of experiments on the proton proton system is to show how the spin direction changes in the scattering process, and three of these measurements have been carried out successfully. Already much of the proton proton interaction can be explained in terms of the clouds of the π mesons tied to the protons. Other features may be due to ω and ρ mesons; this is a field where Nimrod and the P.L.A. may 'interact'.

We are also studying proton-α-particle collisions, where the asymmetry effects can be enormous - 90% of spin up protons going left for one angle of scattering; change the scattering angle 20°, and 75% go to the right. Similar oscillations in the effect happen with heavier elements. There is a large programme to study these 'polarization angular distributions', as well as the 'differential cross sections' and the total probability of the proton reacting with the nucleus and to interpret all the results together on the 'optical model'. The 'model' attempts to correlate elastic scattering of protons from a variety of nuclei over a range of energies in terms of a few numbers describing the size of the nucleus, the fuzziness of its boundary and so on.

Apart from elastic scattering, there is an enormous variety of 'reactions' that can occur at 50 MeV. One of the simplest is radiative capture. The proton is absorbed and only γ -rays are emitted, sometimes even only one gamma ray. Experiments show this particular reaction to be relatively rare, but not so rare as present theories predict.

Neutron emission can be studied very precisely by the time of flight method. When a proton striking a deuterium nucleus knocks the neutron out in a forward direction in most cases the neutron has a very well defined energy. This is a particularly good source for neutron experiments. Interesting things happen with the more complex nuclei, in which neutrons outnumber protons. It seems that a proton can eject one of the 'excess' neutrons and occupy the hole left by the neutron. The energy of the neutron does not then depend on which 'hole' the neutron came from; the neutron energy differs from the proton's by an amount fixed by the Coulomb repulsion felt by the proton. The effect changes in importance with energy and size of the nucleus, and more work is needed to understand it properly.

Time of flight is also a useful technique when charged particles are ejected. Their energy can be measured from the intensity of the light flash they produce in a scintillation counter, and with velocity from the time of flight apparatus, electronic circuits can do the not too difficult sums to work out the particles' mass ($E = \frac{1}{2}mv^2$ - or very nearly). With additional counters to measure rate of loss of energy, the charge can be found too. By this method protons, deuterons, H^3, He^3 and α-particles have all been identified as reaction products, and the angular distributions relative to the incident protons shown to agree with calculation in some cases. The (p, He^3) and (p, H^3) reactions are particularly interesting; they can be pictured as resulting from the incident proton plucking a proton-neutron pair, or a pair of neutrons, out of a nucleus. To be effective, the 'pair' must be preformed in the nucleus. It seems that whereas in light nuclei the existence of the two sorts of pairs, and so the probabilities of the two sorts of reactions, is equally likely, in heavy nuclei neutron pairs predominate, because the Coulomb force due to all the other protons acts on protons but not on neutrons, and breaks up the neutron proton pairs.

It is evident to us all that many years of interesting work lie ahead; improvements to the machine and new experimental techniques constantly come along to help us look at more and more complicated behaviour in the nucleus.

THE P.L.A. TEAM

The P.L.A. Division of the Rutherford Laboratory comprises over 100 physicists, engineers, technicians and instrument makers. About 18 of the scientific staff are members of the Nuclear Physics Group, using the machine for nuclear physics experiments. A further local team using the P.L.A. is from the Nuclear Physics Division of A.E.R.E. The other users of the machine are mostly from British Universities, in particular Birmingham, London (King's College, Queen Mary College, University College and Westfield College), Oxford and Queen's University, Belfast. Experiments are often carried out by joint teams of N.I.R.N.S. staff and University visitors. From time to time visitors from Canada, the U.S.A. and Poland have participated in experiments. The growing number of successfully completed experiments is evident from the many papers which have already been published by the participating scientists and by more than a dozen higher degrees which have now been awarded to members of the various teams.

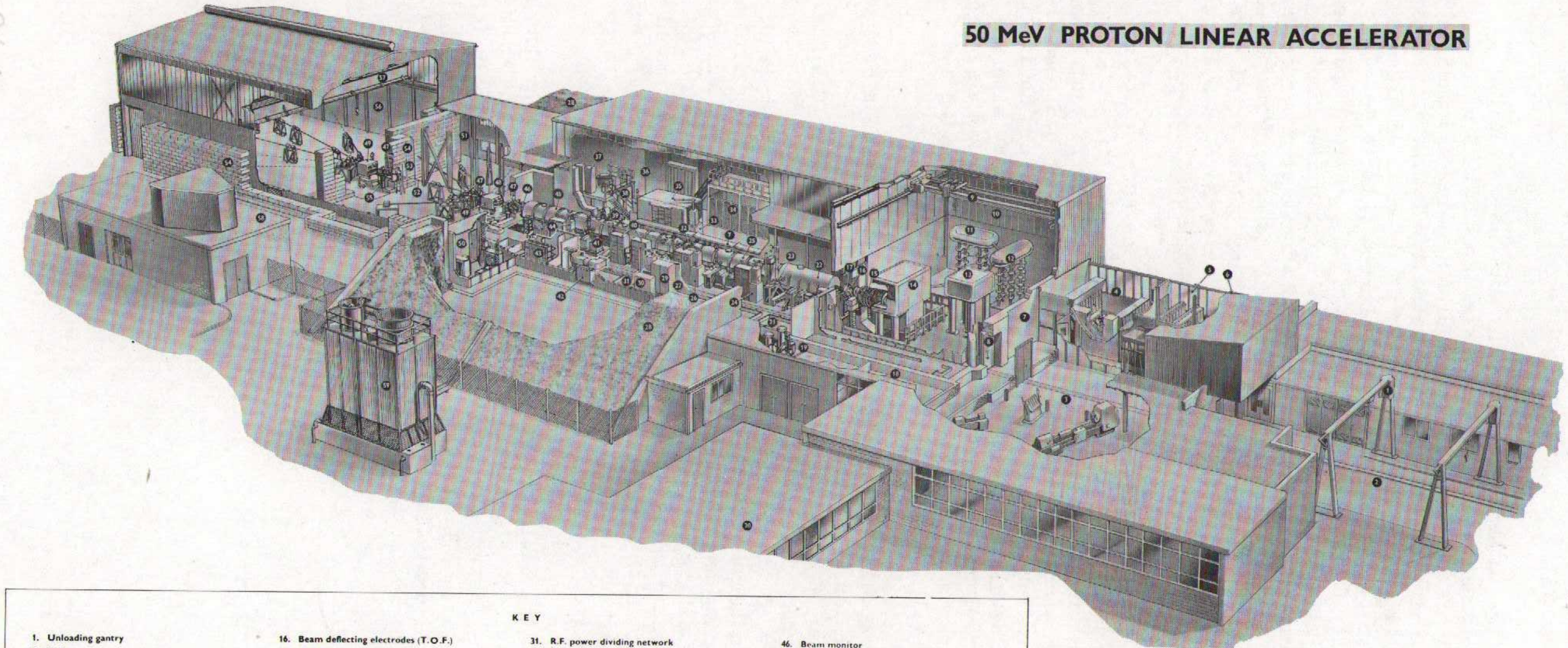
A further 26 of the scientific staff are members of the Accelerator Physics Group. This Group concerns itself with improvements to the existing P.L.A. and with design studies aimed at producing better, larger and more efficient linear accelerators in the future. A notable improvement to the machine has been the design of an efficient and reliable polarized proton source and this device is at present being still further developed. Tank I is being redesigned, with the inefficient grid focussing replaced by alternating gradient quadrupole magnets inside the drift tubes. Work is in hand on equipment to stabilize the r.f. fields inside the tanks during the r.f. pulses.

Several members of the Accelerator Physics Group are engaged on a design study for a 200 - 250 MeV proton linac for use as an injector for a 300 GeV proton synchrotron, the construction of which is now under consideration at C.E.R.N.. A feasibility study is in progress for a P.L.A. using superconducting resonators operating at the temperature of liquid helium (4.2°K). The r.f. power requirements of such an accelerator would be very small and so it could be operated with a 100% duty factor, thereby overcoming one of the principal disadvantages of existing linear accelerators. The "beehive" accelerator is another method of producing very high intensity proton beams which is being studied here. In this machine a magnetic field would be applied to constrain the particles into circular orbits, but the orbits would be separated in space so that the particles would follow a path resembling a spiral helix.

The remaining staff of the Division are members of the Engineering Group. Some 14 of these are professional electrical and mechanical engineers, 20 are technicians and about 27 are instrument makers. The Group is responsible for operation and maintenance of the P.L.A. and for supporting the work of the other two Groups; in particular by designing and manufacturing, either locally or in collaboration with outside firms, much of the apparatus which they require.

~ Apl 1964

50 MeV PROTON LINEAR ACCELERATOR



KEY

1. Unloading gantry
2. Railway
3. Workshop
4. Control room
5. Counting room No. 1
6. Counting room No. 2
7. Concrete shielding wall
8. Concrete doors
9. 1½ ton crane.
10. Injector room
11. Cockcroft-Walton high voltage generator
12. Filter stack
13. Ion source power supply platform
14. Polarised proton source bun
15. Injector column
16. Beam deflecting electrodes (T.O.F.)
17. Buncher
18. Laboratory workshop
19. Water softening plant room
20. Crew room
21. Modulator cubicles
22. Tank 1
23. Tank R.F. feed line
24. Valve A cubicle (Tank 1 main R.F. amplifier)
25. Tank 2
26. Valve C cubicle (Tank 2 main R.F. amplifier)
27. R.F. drive
28. Earth bank shielding
29. Valve B cubicle (High power R.F. drive amplifier)
30. Foster regulator
31. R.F. power dividing network
32. R.F. power combining bridge
33. Valve E (Tank 3 main R.F. amplifier)
34. Power supplies for beam transport system
35. Tank 3 R.F. amplifier cubicle for valves E and F
36. Auxiliary plant room
37. Bending magnet supply stabiliser
38. Valve F (Tank 3 main R.F. amplifier)
39. Generator supplying bending magnet
40. Local control racks
41. Vacuum pumping unit
42. Modulator cooling refrigerator
43. Pulse forming network
44. Valve D cubicle (Tank 2 main R.F. amplifier)
45. Tank 3
46. Beam monitor
47. Beam focussing quadrupoles
48. High speed shut-off valve and vacuum pump
49. Beam bending magnet
50. Modulator E.H.T. supply transformer
51. Experimental area No. 1
52. Beam transport pipes
53. Beam stop
54. Concrete block wall
55. Vacuum pumping unit
56. Experimental area No. 2
57. 10 ton crane
58. Pump house
59. Cooling towers