Reprinted from "Nuclear Engineering," April, 1959

The 7 GeV Proton Synchrotron

UNITED KINGDOM ATOMIC ENERGY AUTHORITY
Atomic Energy Research Establishment
HARWELL · DIDCOT · BERKS.

Reprinted from "Nuclear Engineering," April, 1959

7 GeV Proton Synchrotron
—Contractors and Suppliers

Construction of Proton Synchrotron

BRITISH BROWN BOVERI, LTD., 75 Victoria Street, London.
Converter equipment.
ENGLISH ELECTRIC CO., LTD., Magnet House, Kingsway, London.
Rotating machinery for power supply.
MARSTON EXCELSIOR, LTD., Wobaston Lane, Wolverhampton.
Development and manufacture of main vacuum vessels.
METROPOLITAN-VICKERS ELECTRICAL CO., Trafford Park, Manchester.
Manufacture of magnetic coils.
J. SANKEYS, LTD., Regent Street, London.
Magnet sectors.

BRITISH COPPER REFINERS, LTD., Prescot, Lancs.
Blister copper for magnet coil.
J. BOOTH AND SON (BOLTON), LTD., Nechells, Birmingham.
Extrusion of copper for magnet coils.
EDWARDS HIGH VACUUM, LTD., Crawley, Sussex.
High vacuum equipment for injector, main vacuum pumping equipment.
LONDON ALUMINIUM (CONTAINERS), LTD., Westwood Road, Witton, Birmingham.
R.F. liner for injector.
MATTHEW HALL AND CO., LTD., 26 Dorset Square, London.
Supply of daywork mechanical labour.
H. AND E. LINTOTT, Horsham, Sussex.
Sector test rigs, etc.
PHILIPS GLOEILAMPENFABRIKEN, Eindhoven, Holland.
Ferrite frames for R.F. unit.
S.A.M.E.S., FRANCE, Grenoble, France.
Electrostatic generator for injector.
VICKERS-ARMSTRONGS (AIRCRAFT), LTD., Vickers House, Broadway, London.
Design contract plant.

ANDERSON CLYDE ENGINEERS, Chadderston, Manchester.
25-ton mobile gantry.
BABCOCK AND WILCOX, LTD., 209 Euston Road, London.
Vacuum vessel for linear accelerator.
N. G. BAILEY, Ilkley, Yorks.
Daywork electrical labour.
BRITISH THOMSON-HOUSTON CO., LTD., Rugby, Warwickshire.
Modulator for R.F. supply to injector.
DAVID BROWN CONSTRUCTION EQUIPMENT, LTD., 96 Piccadilly, London.
Towing tractor.
CARRIMORES SIX-WHEELERS, LTD., North Finchley, N.12.
Transporter for sectors.
C. AND N. ELECTRICAL, LTD., Gosport.
Supply of electrical and electronic control equipment.
ENGLISH ELECTRIC CO., LTD., Marconi House, Strand, London.
Rectifiers for test rigs.
ELECTRO-DYNAMIC CONSTRUCTION CO., Orpington, Kent.
H.F. alternator for injector.
FIRTH-VICKERS, LTD., Weedon Street, Sheffield.
S.s. frames for linear accelerator.
GENERAL ENGINEERING (RADCLIFFE), CO., Radcliffe, Lancs.
Vacuum roughing pumps.
C. W. GLOVERS AND PARTNERS, Francis Street, London.
Consulting engineers. (Loan of staff.)
HACKBRIDGE AND HEWITTIC ELECTRIC CO., LTD., Hersham, Walton-on-Thames, Surrey.
R.F. bias support.
J. AND E. HALL, Dartford, Kent.
R.F. cavity cooling equipment.
HILGER AND WATTS, 98 St. Pancras Way, London.
Survey consultancy.
A. IMHOF, LTD., Uxbridge, Middx.
Control racks
H. AND E. LINTOTT, Horsham, Sussex.
Miscellaneous components for main machine.
LIVINGSTON LABORATORIES, Retcar Street, London.
Oscilloscopes.
MARSTON EXCELSIOR, LTD., Wobaston Lane, Wolverhampton.
R.F. cavity, experimental vacuum chamber.
MOORES (BOURNEMOUTH), LTD., Bournemouth, Hants.
Miscellaneous components for main machine.
NATIONAL PHYSICAL LABORATORY, Teddington, Middx.
Survey consultancy.
PORTSMOUTH AVIATION, The Airport, Portsmouth.
E.H.T. mechanical equipment, miscellaneous components for main machine, design contract, E.H.T. platform for injector.
TALBOT-PONSONBY, LTD., Langrish, Hampshire.
Support stand and rails for injector D.C. gun.
JOHN A. SMITH, Wolverhampton, Staffs.
Design contract (plant).
SPEEDY AND EYNON (1951), LTD., Warstone Lane, Birmingham.
Miscellaneous components for main machine.
S.A.M.E.S., FRANCE, Grenoble, France.
650-kV H.V. equipment for injector, H.V. supply for proton gun.
TECHNICAL DESIGN AND TOOL CO., Reading, Berks.
Design contract (plant).

Contracts for Building and General Service

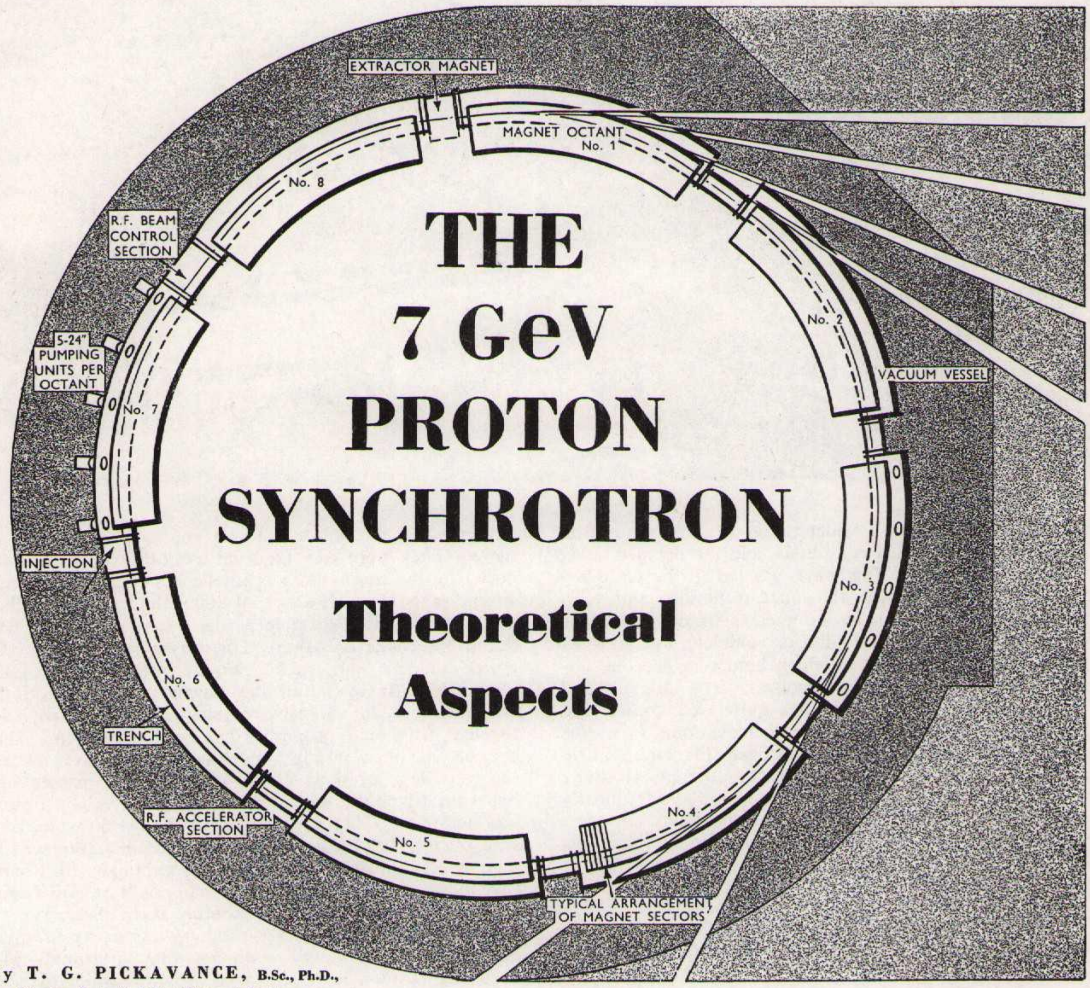
FAULKNER AND PARTNERS, 39 Bedford Square, London.
Quantity surveying.
MERZ AND McLELLAN, 32 Victoria Street, London.
Consulting engineers.

W. E. CHIVERS AND SONS, Devizes, Wilts.
Main civil contractors.

N. G. BAILEY AND CO., Ilkley, Yorks.
Lighting and small power installation.
Z. D. BERRY AND SONS, LTD., 25 Stanley Street, Warrington.
Heating and hot water services.
DUDLEY AND DOWELL, LTD., Cradley Heath, Staffs.
Metal duct covers and cellar flaps.
MATTHEW HALL AND CO., LTD., 26 Dorset Square, London.
Air-conditioning equipment.
FILM COOLING TOWERS (1925), LTD., Brentford, Middx.
Evaporative cooling units.
RUBERY OWEN AND CO., LTD., Wednesbury, Staffs.
Structural steel.
TAYLOR WOODROW CONSTRUCTION, LTD., Southall, Middx.
Arcon buildings.
WHARTON CRANE AND HOIST CO., Station Road, Reddish, Stockport.
25-ton crane assembly and test building, 3 E.O.T. cranes, magnet buildings and 5 E.O.T. cranes.
WHITEHEAD IRON AND STEEL CO., Tothill Street, London.
Reinforcing rods.

ABERFREN CABLE AND CONSTRUCTION CO., Green St., Kidderminster.
Cables.
D. ANDERSON AND CO., LTD., Stretford, Manchester.
Metal decking and waterproofing.
AYRSHIRE DOCKYARD CO., LTD., Irvine, Ayrshire.
Steel partitions.
JOHN BARNSLEY AND SONS, LTD., Netherton, near Dudley, Worcs.
Shield block lifting and turning over equipment.
J. BOOTH AND SON (BOLTON), LTD., Nechells, Birmingham.
Structural steel.
THE CEMENTATION CO., LTD., 20 Albert Embankment, London.
Exploratory boring.
COWANS SHELDON, LTD., Africa House, Kingsway, London.
80-ton O.E.T. crane, motor alternator building.
D.S.I.R., Regent Street, London.
Research on shielding beam.
DEANS BLINDS (PUTNEY), LTD., 329 Putney Bridge Road, London.
Blinds and curtains.
ENGLISH ELECTRIC CO., LTD., Marconi House, Strand, London.
Distribution switch fuseboard.
J. ERRINGTON (ENGINEERS), LTD., Sandyford Square, Newcastle-on-Tyne.
Lifting plugs for concrete shielding blocks.
EVANS LIFTS, LTD., Abbey Lane, Leicester.
Lift to control building.
W. T. GLOVERS AND CO., Francis Street, London.
Cable.
W. T. HENLEYS TELEGRAPH WORKS CO., LTD., 51 Hatton Garden, London.
Cable.
JOHNSON AND OLIVER CO., LTD., Walkergate, Newcastle upon Tyne.
Lifting plugs for concrete shielding blocks.
MELLOWES AND CO., LTD., 54 Victoria Street, London.
Dome lights.
MORELAND HAYNES AND CO., 80 Goswell Road, London.
Structural steel.
THE PERMUTIT CO., LTD., Gunnersbury Avenue, London.
Water treatment plant.
POTTER RAX, LTD., Shepperton Road, London.
Folding doors and partitions.
RAGUSA ASPHALT PAVING CO., LTD., 2 Hartopp Road, Alum Rock, Birmingham.
Built-up felt, roofing-magnet and ancillary buildings.
N. F. RAMSEY, 5 Victoria Street, London.
Ballustrades and handrails.
READ AND PARTNERS, Stamford Street, London.
Electrical installations.
RESILIENT TILE AND FLOORING (EALING) CO., LTD., 3 Replingham Road, London.
Linoleum floor covering.
A. REYROLLE AND CO., LTD., Hebburn, Co. Durham.
Switchgear.
ROBERT HUDSON, LTD., Meadow Lane, Leeds.
Shielding block trolleys and traction unit.
JOHN SMITH (KEIGHLEY), LTD., Bradford Road, Keighley.
10-ton O.E.T. crane, motor alternator building.
STERLING CABLE CO., 292 High Holborn, London.
Cables.
THOMAS SUMMERSON AND SONS, LTD., Mowden Hall, Darlington.
Rail track materials.
WILLIAM PRESS AND SONS, LTD., 22 Queen Anne's Gate, London.
Steam, gases, compressed air and cold water services.
WILLIAMS AND WILLIAMS, LTD., Reliance Works, Chester.
Metal windows and curtain walling.
YORKSHIRE ELECTRIC TRANSFORMERS, LTD., Dewsbury, Yorks.
Transformers.

Reprinted from " Nuclear Engineering," April, 1959



THE 7 GeV PROTON SYNCHROTRON

Theoretical Aspects

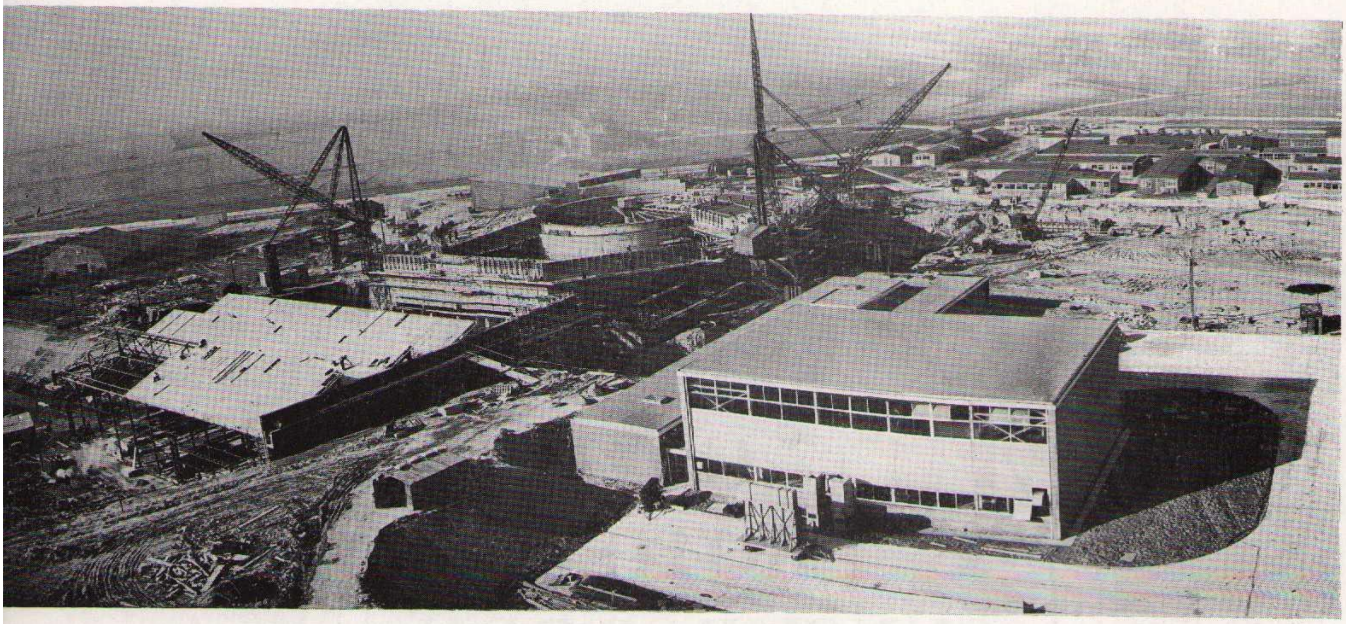
by **T. G. PICKAVANCE**, B.Sc., Ph.D.,
Director, Rutherford High Energy Laboratory.

THE Rutherford High Energy Laboratory is the first laboratory of the National Institute for Research in Nuclear Science, and will be used by scientists from the Universities, the Atomic Energy Authority, and other bodies, and by staff of the Institute who will also operate the research facilities. The main activity at present is the construction of the new 7 GeV proton synchrotron, which has been undertaken by the Atomic Energy Authority at the request of the Institute. The specifications were adopted by the Institute after discussion with the Universities and the accelerator specialists of the Authority.

The high energy particles produced by this machine will be used in fundamental studies of nuclear and sub-nuclear phenomena, a field in which no direct practical applications can as yet be foreseen. The justification for the great expense and the efforts of teams of highly qualified scientists and engineers is to be found in the fact that the unsolved problems in this field closely involve the most fundamental forces of nature. In these circumstances the question as to whether valuable practical application will be based directly on the results of the work need not normally be asked, but most advances in practical affairs have been made possible by inquiry of a kind in which the practical developments were neither sought nor foreseen, and this field may not be an exception. Moreover, there are certain to be other benefits. The most obvious one is a prime reason for initiating the project, namely the effect on the young scientists trained in the Universities when these modern facilities for research are used by the University departments. Others, perhaps no less valuable, are the advances in engineering and technology in the industrial firms which contribute to the construction, and the training of the young men who pass through the design and development teams during the course of the work. The range of practical problems encountered in a large accelerator project, and the subsequent nuclear research, is exceptionally broad.

Historical Background

The original motive for research with fast particles was to study nuclear structure. It was known 30 years ago that nearly the whole of the mass of matter is concentrated in the nuclei of atoms, and that the nuclei are extremely small in relation to the size of the atoms themselves. It was also known that the nuclei of certain heavy atoms undergo spontaneous transitions into other nuclei, with the emission of particles and electromagnetic radiation. Bombardment of nuclei with artificially accelerated



particles made possible a wider range of nuclear transmutations under controlled conditions, and the detailed study of nuclear structure. This work has led to the discovery of artificial radioactivity and nuclear fission, and to a mass of detailed knowledge of nuclear structure, but the fundamental problem of finding a complete and accurate understanding of the forces which bind together the particles in a nucleus remains unsolved. The strength and range of action of the forces are quite well known, but their detailed mechanism is not well understood. For some years the study of this problem has been following a fairly familiar pattern in scientific research; attempts to study certain details of a particular phenomenon have frequently resulted in the discovery of unforeseen effects and new phenomena, which then have to be studied in their own right.

New Particles

It has been believed for many years that the nuclear forces are characterized by the exchange of unstable particles (π- mesons or pions) between the protons and neutrons of the nucleus; the observed masses (about 280 electron masses), lifetimes (about 10^{-8} sec for the electrically charged varieties of the pion) and other properties of these particles can be broadly reconciled with the range and strength of the forces and many of the characteristics of nuclei.

Particles of such a short life as the pions, having merely a transitory existence inside nuclei, can only be observed directly by creating them artificially in nuclear collisions and the bombarding particles must be at least sufficiently energetic to create the pion "rest mass" of 280 electron masses (i.e., about 140 MeV). The binding energy of an individual neutron or proton inside a nucleus is only a few MeV, so that a much greater energy is needed to create a pion than to induce a simple nuclear transmutation. A principal reason for making more powerful accelerators than the early Cockcroft-Walton generators and cyclotrons, which had been used in the first experiments on nuclear structure, was therefore to attempt to create pions and then to study their interactions with other particles. Engineering and technology were sufficiently advanced for such machines to be built just after the war, but the machines are expensive and public recognition of the importance of large-scale scientific research was also an essential feature, in order to ensure the necessary public patronage. Pions were created, and can be produced by any efficient accelerator with an energy of 200 MeV or more. They were also (and earlier) observed to be produced by the much more energetic but much less intense cosmic radiation. However, at about the same time other, and more massive, unstable particles were seen to be produced by cosmic radiation. This was a spur to the accelerator builders, and, so far mainly with the help of the Cosmotron (3 GeV) and the Bevatron (6 GeV) in the U.S.A., quite an extensive catalogue of these particles together with their properties has been developed. They can be classified into groups now called heavy mesons (K- particles), of mass about 1000 electron masses, and hyperons which are somewhat more massive than protons and neutrons. They are believed to be closely concerned with nuclear forces, because they are readily produced in high energy nuclear collisions, and although short-lived, they live for a much longer time than could be understood according to the ideas current before their discovery.

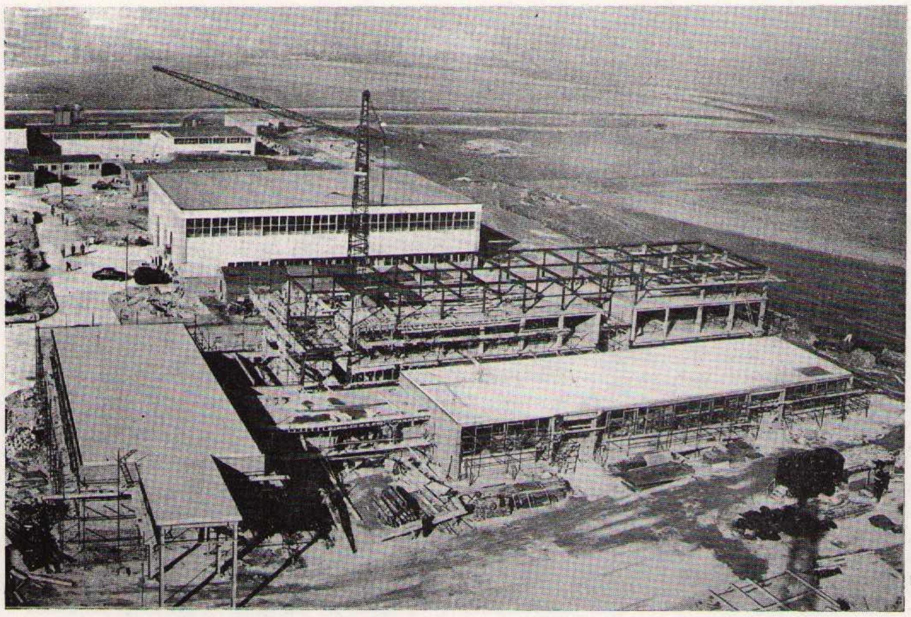
Certain other particles are produced, as decay products of unstable particles, which do not interact strongly with nuclei; an example is the μ- meson or muon, which lives for about 2 μ sec before decaying into an electron and is produced by the spontaneous decay of a pion.

Another class of particles, produced by the Bevatron, are the antinucleons (i.e., antiproton, antineutron) which are stable, but are annihilated in encounters with protons and neutrons; the proton or neutron is also annihilated, with the release of the energy originally expended in the creation of the antinucleon. The existence of antiparticles had been postulated on theoretical grounds before their discovery; the first antiparticle to be discovered, long ago, was the positron or positively charged electron.

The study of the modes of creation and the detailed properties of all these new particles, and the way in which they interact with other particles, is the main object of present-day high energy research, and will be the principal field of the Rutherford Laboratory. It should be mentioned in passing that the nuclear structure studies, at lower energies, are by no means complete and are still being pursued vigorously with modern equipment.

Choice of Machine

The minimum energy required for the production of the known particles of interest is about 6 GeV. This was a starting point when attempts were first made to choose a particular machine for national use. However, there are other factors which influence a choice. The yield of



Panoramic view of the accelerator site showing the progress of construction at the end of February, 1959. The synchrotron circle can be seen between the cranes on the left-hand page.

particles, per incident particle, increases with energy, but the accelerated beam intensity decreases with increasing energy. Accelerators may be designed to produce beams of electrons or protons, but not both, and therefore the relative merits of these particles have to be considered. Beam intensity is an important consideration and, as a field of research becomes more sophisticated, further progress needs higher intensity and more refined measuring techniques, partly to achieve greater precision and partly to study rarer processes. Versatility is important in any research tool. Large machines are costly, and the cost of a given type increases rapidly with both energy and intensity. Clearly the relationship with other existing and planned machines, at home and abroad, must be taken into account. It may not be possible to build a machine to beat all others, but it is certainly important not to be outclassed.

The choice of protons versus electrons is a difficult one. Protons are more effective in producing the mesons and other particles, because they are themselves closely connected with nuclear forces. On the other hand, electrons can usually be accelerated in greater numbers, which partially offsets their disadvantage, and can also be used in research into electromagnetic phenomena, which cannot be tackled with protons. On the whole, proton accelerators have been more productive in high energy research and, after careful consideration, a proton machine was chosen as the first major accelerator for the National Institute. If, and when, a second large accelerator is contemplated, an electron machine will be a strong contender, on grounds of diversity of research equipment.

Six GeV was taken as the minimum proton energy, but the upper limit was not simply a question of economics. Although all the particles known at present should be produced at about this energy, no accelerator has yet operated at full intensity above 6 GeV and we should expect that there will be other important phenomena which can only be investigated at higher energies. Higher energies can be obtained at comparable cost, but only by sacrificing intensity. A 25 GeV proton machine is being built by CERN in Geneva, and since the United Kingdom participates in the work of CERN, with eleven other European nations, this machine will be accessible to British physicists. Therefore the decision was made to work in the highest energy range through CERN and to construct a machine for more intense beams at a lower energy. The two machines will thus be complementary.

The specification finally adopted, after much discussion with physicists and accelerator specialists, was for a proton energy of 7 GeV, with a beam intensity greater than 10^{11} protons/sec. Naturally this had to take into account the possibilities of the various types of equipment. In principle, two main types of accelerator may be considered: a linear machine or a circular machine using a magnet. A proton linear accelerator for this energy would be over a mile in length and, in the present stage of technological and industrial development in respect of some of its major components, would involve several times the construction time and several times the capital cost of a comparable circular machine. Two comments on linear accelerators are apt at this stage. First, electron linear accelerators have as yet no rival for energies greater than 10 GeV or so, on account of fundamental difficulties in circular electron accelerators; the light electrons radiate energy as they circulate, to an extent which increases as the cube of the electron energy in comparable circular machines. At 7 GeV it is already difficult to make good this energy loss from the accelerating system; the problem does not exist in linear machines. Secondly, linear accelerators have important advantages, as research tools, over circular machines. These are: the particle beam emerges intact from the end, instead of having to be extracted from a magnet with inevitable loss of intensity; much higher beam intensities can be accelerated to high energy; the machine may readily be extended at any time. The National Institute will shortly have a 50 MeV proton linear accelerator which has been built by the AEA at Harwell; this will be a most useful tool for "medium energy" physics and may eventually be extended to somewhat higher energy.

However, for the high energy work a circular machine was an inevitable choice. The only circular machine for which the required intensity can be guaranteed using established techniques is a proton synchrotron.

Operating Principles

The protons circulate in a vacuum vessel between the poles of a ring-shaped magnet, in orbits of constant radius. On each circulation they are accelerated by the application of a relatively small alternating potential difference (a few kilovolts) from a radiofrequency generator. As the particle energy increases, the magnetic field strength has to be increased in order to confine the orbits to a constant radius within the ring. The magnet is therefore laminated like a transformer to reduce eddy current effects, and the current through the magnet windings has to grow during each pulse of the acceleration process and to decay back to zero between pulses. The acceleration process is complete, on each pulse, when the magnetic field has grown to the maximum economic value consistent with satisfactory operation (about 12,000 to 16,000 gauss in iron-cored magnets of normal design).

Similarly, the frequency of the alternating accelerating voltage must be increased during the acceleration process, in order to keep in step with the increasing frequency of rotation of the protons around the ring. This frequency tracking has to be done with great accuracy, if serious loss of particles from the beam is to be avoided. Departures of more than one part in a thousand from the proper values of frequency and rate of change of frequency would be inadmissible, in a practical case.

The protons have to be injected into the magnet ring from a subsidiary accelerator, since for example the magnetic field cannot be precisely zero on account of remanent field and stray field effects.

The protons have to travel long distances during the acceleration process (about 100,000 miles in a large machine), and they must therefore be kept in a narrow beam by focusing forces to prevent too many of them from straying away in the presence of the disturbances caused by unavoidable errors. This is achieved by causing the magnetic field intensity to vary with position on and near the paths of the protons, in a carefully controlled way. Magnetic forces can then be made to direct the protons towards their proper orbits. In the conventional or constant gradient synchrotron the magnetic field is made to decrease slightly with increasing radius, but to be uniform in azimuth. The focusing requirement may be expressed mathematically by stating that a parameter n, defined as

$$n = -\frac{r}{B}\frac{dB}{dr}$$

where r is the orbit radius and B is the magnetic field, must be kept within about 10% of the value selected, which is between 0 and 1. The actual value of n must be chosen after a careful study of the equations of motion of the particles for the particular accelerator design, and the condition just defined must be satisfied throughout the acceleration pulse and in all regions of the magnet gap occupied by the protons. If this is done, the particles will execute stable oscillations of position about an equilibrium orbit, and the remaining requirement is to make the gap between the magnet poles big enough to contain these oscillations. Great care must be taken with magnet design, and with quality control in manufacture, to realize these conditions in practice. It is customary to divide the magnet into a number of sections separated by field-free regions which are convenient for injection, acceleration and extraction equipment.

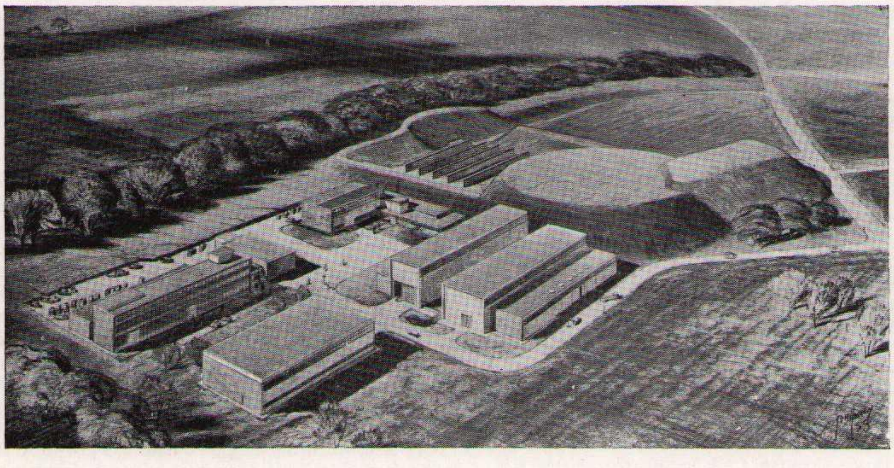
In the alternating gradient synchrotron the focusing method is modified. The magnet ring is divided into a large number of individual units separated by field-free regions, and a periodic variation of n is used in the units around the ring. If n is made very large (i.e. $\gg 1$), and alternatively positive and negative, then in certain conditions a strong focusing effect can be produced—much stronger than that which can be obtained in a constant gradient magnet. The oscillation amplitudes and therefore the size of the magnet gap can then be correspondingly reduced, with considerable savings in steel and energizing power. This type of machine is therefore more economical to build than the constant gradient type, especially at high energies, but its smaller aperture reduces the beam intensity which can be obtained under practical conditions. A constant gradient machine is therefore more appropriate for those energies at which its cost is not too great. The 25 GeV CERN machine is of the alternating gradient type; a constant gradient machine for 25 GeV would be very much more costly and would have almost insuperable problems of magnet design, consequent upon its very large size.

RUTHERFORD LABORATORY ACCELERATOR

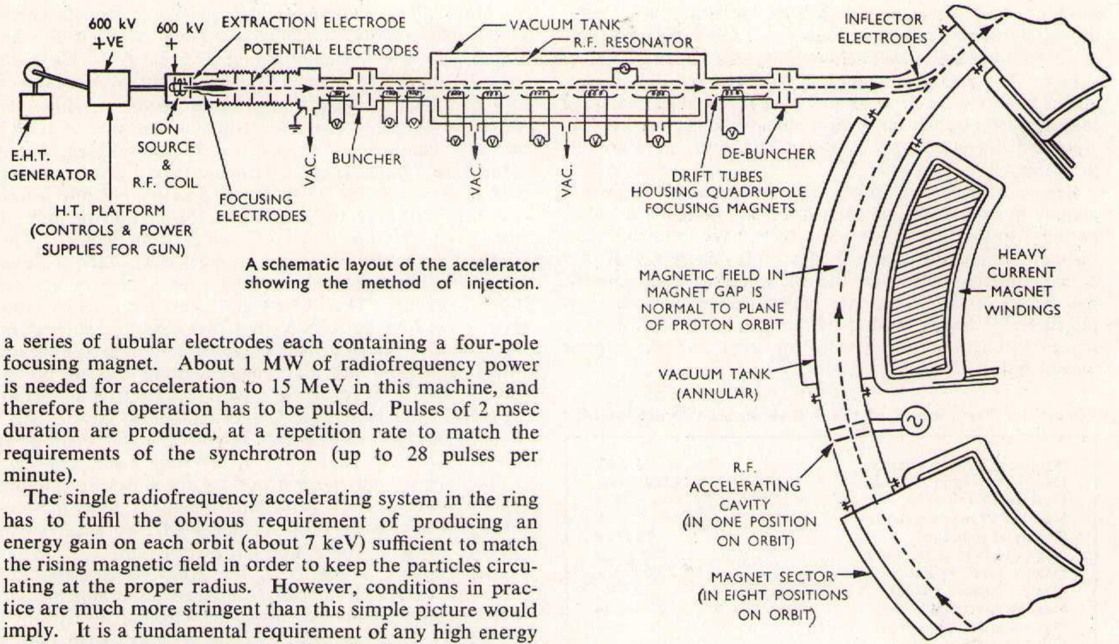
The new 7 GeV machine is a constant gradient proton synchrotron. The magnet ring is about 150 ft in diameter, and contains about 7,000 tons of special magnet steel mainly in ¼-in. plate. The useful dimensions of the magnet gap are 36 in. radially and 9½ in. vertically, and the maximum magnetic field, for the full energy of 7 GeV, is 14 kilogauss. The injector accelerator, from which a narrow jet of protons is guided into the magnet ring by electric fields between curved electrodes, is a 15 MeV proton linear accelerator. At the injection energy of 15 MeV the magnetic field is 300 gauss.

The injector consists of two main units, the ion gun and the linear accelerator proper. In the ion gun, protons are produced at low velocity in an ion source, which operates by maintaining an electrical discharge in hydrogen gas at low pressure. The protons are extracted from the ion source and focused into a beam, with the help of suitable electrodes to which high voltages are applied, and are then accelerated down an evacuated pipe, also with focusing electrodes, to an energy of 600 keV.

The 600 keV beam is admitted into the linear accelerator, which consists essentially of an evacuated copper cylinder excited in resonance by a 110 Mc/s radiofrequency source. The axial electric field generated by the radiofrequency system drives the protons along the axis, through



An artist's impression of the completed works. The mound covers the synchrotron and injector, the experimental area being on the left. Centre right are the buildings housing the motor alternator equipment with the control buildings alongside. In the foreground are laboratories and offices (left) and the magnet test and assembly buildings (right).



A schematic layout of the accelerator showing the method of injection.

a series of tubular electrodes each containing a four-pole focusing magnet. About 1 MW of radiofrequency power is needed for acceleration to 15 MeV in this machine, and therefore the operation has to be pulsed. Pulses of 2 msec duration are produced, at a repetition rate to match the requirements of the synchrotron (up to 28 pulses per minute).

The single radiofrequency accelerating system in the ring has to fulfil the obvious requirement of producing an energy gain on each orbit (about 7 keV) sufficient to match the rising magnetic field in order to keep the particles circulating at the proper radius. However, conditions in practice are much more stringent than this simple picture would imply. It is a fundamental requirement of any high energy accelerator that there must be "focusing" of the phase of the particles with respect to the RF field, as well as focusing of the direction of motion of the particles. In other words, if any disturbance should cause the particles to slip behind or run ahead of the alternating accelerating voltage as they rotate, there must be a positive influence at work which will correct the error. Disturbances are inevitable in practice; they are caused for example by departures from the correct frequency and noise in the electronics control circuits. With a million orbits in the acceleration cycle, any attempt to keep the particles in step by "dead reckoning" is bound to fail and the particles will not be accelerated. Fortunately, investigation of the equations of motion of the particles shows that this condition of phase stability can be achieved, but that very accurate matching of magnetic field and frequency and of the rates of change of these two quantities is required, particularly in the early stages of the acceleration. Since very great amounts of power are needed to energize the magnet (about 100 MVA peak), and the highly inductive magnet windings have a time constant of many seconds, it is chosen to make the radiofrequency variation follow the magnetic field variation, and not vice versa.

Probes are inserted in the magnet to deliver, through suitable electronic circuits, information to the master frequency generator of the RF system which determines the frequency of the accelerating voltage. The magnetic field cycle, on each pulse of operation, therefore determines the frequency law. Eventually a more refined system will be used, in which the motion of the particles themselves will transmit control information to the master frequency generator; this cannot be done initially because the intensity will be too small on first commissioning the machine.

Accelerator design is a struggle against the effects of errors and practical limitations in engineering. One aspect of this struggle is the phase stability problem. Another is the beam focusing problem already mentioned. However carefully the magnet steel is specified, however good quality control and "randomizing" of inevitable variations in magnet components is carried out in the factory, and however carefully the magnet units are aligned and installed (as summarized in the following article) it is certain that the machine will not operate unless further drastic measures are adopted. The stability of the particle beam is so delicately balanced that, with the utmost care and using the best known machining measurement and installation techniques, the remaining errors in the magnet will cause disastrous instability and loss of the beam. The additional measures to be taken are the following:

(1) Each of the 336 units which comprise the magnet yoke will be subjected to individual rigorous magnetic measurement on equipment which has had to be specially developed, and the resulting information programmed into an electronic computer which will then determine the optimum position in the ring for each unit.

(2) Correction windings between the magnet poles will have carefully determined currents passed into them, on the basis of accurate magnetic field surveys on the finished magnet, to reduce errors still further.

(3) Special electronics circuits will be devised to eliminate effects of ripple from the magnet power supply upon the particle motion.

Another problem is scattering of the protons by residual gas in the vacuum chamber. This causes the amplitudes of the particle oscillations to increase, and in a severe case virtually all the protons would be lost to the walls of the chamber. The magnet gap has to be kept to a minimum for reasons of economy, and also because of the practical limits imposed by the size of the magnet power plant. The scattering decreases with increasing energy, so that this is a factor in deciding the energy of injection. With the parameters chosen for the 7 GeV machine, successful operation demands a pressure not greater than 10^{-6} mm Hg. This is easily obtained in small vessels in the laboratory but in the special conditions of this large machine it is difficult.

Finally, there is the serious problem of radiation shielding. A beam of 10^{12} protons/sec at 7 GeV, such as may eventually be produced by the Rutherford Laboratory machine, will produce very intense radiation in coming ultimately to rest. It is necessary to reduce the radiation in all occupied areas well below the agreed health tolerance values. The energetic radiation produced by high energy beams is very difficult to absorb, and it has been necessary to enclose the synchrotron in a shield with 6 feet of concrete and 20 feet of earth overhead, and much more around the sides.

Beams of particles, either protons extracted from the magnet by equipment which is still being designed or other particles sprayed from internal targets, have to be admitted through collimating channels in a 30-ft concrete wall into an experimental hall where the nuclear research equipment will be set up. The experimental apparatus will be complicated and heavy, and there has to be a profusion of cranes throughout the synchrotron area and the experimental hall.

Principal Parameters of the 7 GeV Proton Synchrotron

Maximum proton energy	7 GeV
Maximum magnetic field	14,000 gauss
Mean orbit radius	75 ft
Number of magnet sectors	8
Energy at injection	15 MeV
Magnetic field at injection	299 gauss
Magnet steel weight	7,000 tons
Magnet copper weight	250 tons
Magnet aperture, width	36 inches
Magnet aperture, height	9 inches
Pulse repetition rate	25-30 per min
Expected output	10^{12} protons/pulse
Acceleration system frequency	1.4 to 8.2 Mc/s
Number of accelerating units	1 (double)
Number of orbits during acceleration	10^6
Acceleration time	0.7 second
Total peak rating of motor-alternators (2) in magnet power supply	100 MVA approx.
Number of rectifiers in magnet power supply	96

Comparison with other Machines

The only other British machine in the GeV range is the 1 GeV proton synchrotron constructed some years ago at Birmingham University. In the United States there are two proton synchrotrons already operating, the 3 GeV Cosmotron at Brookhaven and the 6 GeV Bevatron at Berkeley. In the U.S.S.R. there is a very large 10 GeV machine at Dubna, with a 36,000 ton magnet. This has been operating for over a year, but so far at rather low intensity. With all these large accelerators a long period of careful development is needed, from first operation, to increase the intensity and the Russian machine will undoubtedly produce comparable intensity with the two American machines. It is hoped that the Rutherford Laboratory machine will produce a somewhat higher intensity, so that its energy disadvantage with respect to the Russian machine should not be a serious drawback. All these machines are of the conventional constant gradient type, and the Rutherford Laboratory machine differs only in that certain refinements have been incorporated as a result of the experience gained by the Americans and the Russians.

A slightly different type of " weak focusing " machine, using uniform field and obtaining focusing by non-perpendicular entry of particles into the edges of the magnet sectors, is being built at the Argonne National Laboratory in the U.S.A. This is planned for 12 GeV but its dimensions and other characteristics are not very different from the Rutherford Laboratory machine; its intensity will probably be somewhat lower. There are two smaller conventional proton synchrotrons, one for 2-3 GeV at Saclay in France, just completed, and one for a similar energy but higher intensity under construction at Princeton and Pennsylvania Universities in the U.S.A. A 10 GeV unit with an air cored magnet is being built in Australia.

Two 25 GeV alternating gradient proton machines are in an advanced state of construction; the one at CERN, already mentioned, and another at Brookhaven, U.S.A. These are " pioneering " machines. They will explore an energy region not yet tapped with accelerators, and no one can say what exciting phenomena may be discovered. In the Soviet Union a 50-60 GeV unit is being planned.

There are also many electron machines, which represent an alternative approach to high energy physics as mentioned already. The highest energy so far reached is just over 1 GeV in the U.S.A., but two electron synchrotrons for about 7 GeV are under construction in Cambridge, Mass., and Hamburg. The most exciting electron project, not yet started, is for a two-mile linear electron accelerator at Stanford University in California, for 40 GeV. This is a plan on the grand scale, requiring 1,000 high power microwave klystrons for the accelerating field.

Still bigger and more expensive machines are contemplated, based on new principles, but they are at the stage of laboratory models and complicated theoretical studies with computers. Some are still pipe dreams.

Against this background, the Rutherford Laboratory machine, as a high intensity source of important but little understood phenomena, should be a sound investment as a research tool for many years. We have tried hard to make the machine as adaptable as possible to the changing needs of research, and to profit from the experience of others who first built large machines. If the further development of high energy research throws up new requirements for very large machines, the Institute and the AEA should be able to provide them for use by the Universities. A programme of accelerator research is continuing in parallel with the construction of the 7 GeV machine.

Le Synchrotron de Protons 7 GeV.

En construction au Laboratoire de Haute Energie de Rutherford, situé aux côtés de l'Etablissement de Recherches d'Energie Atomique de Harwell, dont le personnel a fourni une grosse somme des efforts de conception, le synchrotron de protons 7 GeV représente l'activité principale de l'Institut National de Recherches en Sciences Nucláires.

Dans le premier de ces articles, Dr. Pickavance retrace l'arrière-plan historique du projet, les raisons présidant au choix d'énergie et aussi le type de machine, et conclut par une description générale de l'Accélérateur du Laboratoire Rutherford et une comparaison avec les accélérateurs à haute énergie dans les autres parties du monde.

Le travail de la conception a été entrepris par Harwell. Dans le second article, Mr. Bowles donne, en détail, la conception des parties de mahines qui ont été finalement mis au point—certains éléments étant encore au stade de la planche à dessin—et discute les problèmes particuliers associés au maintien de la stabilité du faisceau et au maniement—d'une manière impulsée—des très grandes quantités d'énergie impliquées.

La construction de la machine entraîne un nombre de techniques de génie civil nouvelles et dans le troisième article de la série les principales caractéristiques sont décrites y compris la prévision de facilités expérimentales douées de souplesse.

Das 7 GeV Protonen Synchroton

Das im Rutherford Hochfrequenz Laboratorium, neben dem " Atomic Energy Research Establishment " in Harwell, im Bau befindliche 7 GeV Protonen Synchroton, an dem der Stab des " Establishments " mitgearbeitet hat, ist z. Zt. die Hauptarbeit des " National Institute for Research in the Nuclear Science " (Nationales Forschunginstitut für die Atomwissenschaft).

Im ersten Artikel behandelt Dr. Pickavance die historische Entwicklung des Projektes, die Gründe für die Wahl der Energie und ferner des Maschinentyps, und gibt am Schluss eine allgemeine Beschreibung des Accelerators im Rutherford Laboratorium und vergleicht ihn mit anderen Acceleratoren hoher Energie in anderen Teilen der Welt.

Reprinted from "Nuclear Engineering," April, 1959

7 GeV PS

Engineering Design

By **P. BOWLES, M.Sc., M.I.Mech.E., M.I.E.F.**
(Project Engineer, A.E.R.E., Harwell)

The overall design of the proton synchrotron is now well established while the design of some details continues. Safety has been a dominant consideration followed by performance and reliability; these last are frequently antagonistic and require compromise solutions.

FROM the engineer's point of view, the proton synchrotron comprises six main installations: the injector which must accelerate protons to 15 MeV, this being the energy required to ensure that the protons will rotate in an orbit of the required radius with the field conditions at injection; the magnet which must provide the field of the required strength and spatial distribution; the radio frequency accelerator which must accelerate the beam so as to maintain it in the centre of the vacuum chamber as the magnet field increases; the vacuum system; the pulsed power supply and the control system. After injection the protons will revolve about a million times in their orbit before being extracted from the machine or being brought to bear on an internal target; thereafter the secondary radiation produced is absorbed in shielding. Fig. 1 shows a model of the plant.

INJECTOR

The injector is a 15 MeV proton linear accelerator, a diagrammatic layout of which is shown on page 7. The equipment for accelerating the protons initially comprises a direct current proton gun which is fed from a 600 kV revolving drum electrostatic generator. The direct current gun incorporates a pulsed radio frequency ion source, with its power unit, oscillator, and controls mounted on a high tension platform maintained at the electrostatic generator potential. Because of the large difference of potential between the platform and earth, mechanical drives are insulated, and all switching uses compressed air links.

Die Entwurfsarbeit ist von Harwell durchgeführt worden. Mr. Bowles bringt im zweiten Artikel genauere Angaben über solche Teile der Maschine, die bereits endgültig festgelegt sind—einige Teile sind noch im ersten Reissbrett Stadium—und diskutiert die besonderen Probleme, die mit dem Aufrechterhalten der Stabilität des Strahles und mit der Beherrschung der sehr grossen Kräfte, die stossweise auftreten, verbunden sind.

Für den Bau der Maschine mussten eine Reihe neuer bautechnischer Verfahren entwickelt werden, und der dritte Artikel beschreibt die Hauptmerkmale dieser Verfahren mit Einschluss der vielfach vorgesehenen Möglichkeiten experimentelle Untersuchungen durchzuführen.

Sincrotono de Protones 7 GeV.

Bajo construcción en el Laboratorio de Alta Energía Rutherford en Harwell, cuyo personal ha provisto grande del esfuerzo relacionado con diseño, el sincrotono de protones 7 GeV representa la mayor actividad del Instituto Nacional de Investigación en Ciencias Nucleares.

En el primero, el Dr. Pickavance bosqueja el fondo histórico del proyecto, las razones que respaldan la selección de energía y también el tipo de máquina, y concluye con una descripción general del acelerador del Laboratorio Rutherford y una comparación con los aceleradores de alta energía en otras partes del mundo.

La labor de diseñar ha sido emprendida por Harwell. En el segundo artículo, el Sr. Bowles da, en detalle, el diseño de aquellas partes de la máquina que han sido finalizadas—ciertos componentes todavía están en la fase del tablero de dibujo solamente—y discute los problemas especificos asociados con e mantenimiento de estabilidad de haz y en manejar de una manera pulsada, las muy grandes cantidades de fuerza comprometidas.

La construcción de la máquina envuelve cierto número de técnicas novísimas de ingeniería civil, y en el tercer artículo de la serie, se describen las características principales, incluyendo la provisión de facilidades experimentales versátiles.

The design of the linear accelerator beyond the source, shown in Fig. 2, comprises a radio frequency liner and drift tube assembly supported in a vacuum vessel 46 ft in length and 8 ft in diameter. The vessel will be exhausted to a pressure of 10^{-6} mm Hg by four liquid-cooled mercury diffusion pumps, each of 2,000 l/sec capacity. The vessel will be heavily ribbed to withstand atmospheric pressure and weighs 26 tons. To provide adjustment of the beam height the vessel will be mounted on four adjustable outrigger supports.

Removal of the D shaped cover will enable easy inspection of liner and its controls. The liner, a large resonant cavity which will be tuned to 115 Mc/s is 44 ft long and $5\frac{1}{2}$ ft in diameter. It will have an array of 48 drift tubes of increasing length and spacing mounted along its axis. To produce the necessary radio frequency electric field between the drift tubes, large RF currents have to circulate on the surface of the liner and drift tubes supports, which calls for a high standard of surface finish. The liner, provided with pumping slots, will be fabricated from high conductivity copper, only 1/8 in. thick but will be reinforced by non-magnetic stainless steel rings and longerons to support the liner weight and that of the drift tubes. Thermal stresses will be minimized by the design of the supporting feet. At certain places along the length of the liner it will be necessary to make periodic adjustments to the electrical constants of the resonant circuit. This will be done by deflecting part of the surface which has been designed sufficiently flexible in a radial direction. Access will be gained to the interior of the liner through end hatches, the covers of which have garter springs between the joint faces to ensure a good RF joint.

Each drift tube assembly will comprise basically a four pole focusing magnet enclosed in an evacuated copper shell. The focusing magnet winding will be water cooled as heat dissipation in vacuum is difficult. The drift tube assemblies will be supported from the liner by two limbs at right angles, which are designed to permit adjustment in all directions to within 0.001 in. to obtain symmetry with the beam, and the correct position relative to the liner. Although similar in design, the 48 assemblies are different in dimension, the lengths varying from 3 in. to 13 in. and the bore from 0.8 to 2.0 in.

Cooling of the drift tubes and liner will be effected by circulating distilled water through tubes which will be soft soldered to non-working faces of the drift tubes and liner. In the latter case the temperature will be maintained at all parts of the liner to within ± 3°C by the water circulating contraflow in alternate tubes. This precise temperature control is necessary to prevent changes in dimension affecting the resonant frequency of the liner.

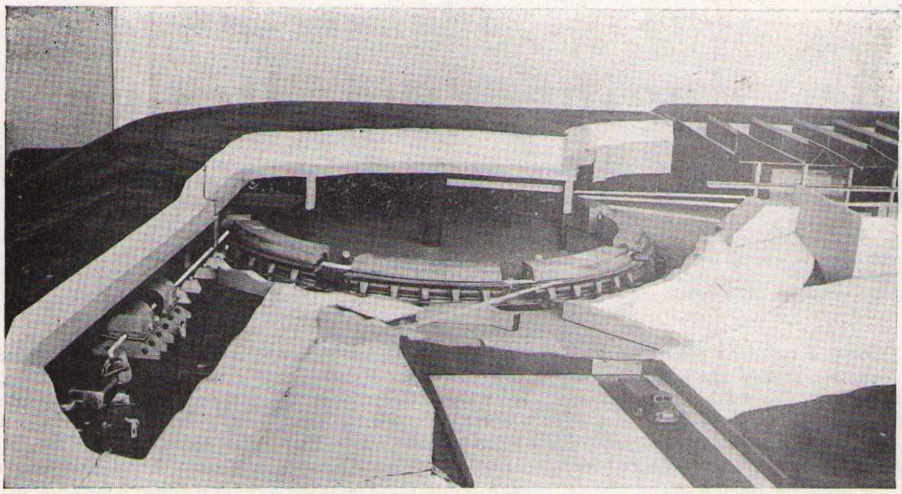


Fig. 1.—Sectioned model showing general arrangement of the plant and buildings. The path of the proton beam is indicated by the white line.

The RF power from a valve source will enter via a feed line through the base of the vessel and will be connected to the mid point of the liner. Similarly the base will be used for supporting the pumps and as a bulkhead for services.

THE MAGNET

The main factors affecting the design of the magnet for the proton synchrotron are the proton energy to be achieved, the mean radius of the orbit, the maximum values of the required flux density, and the air gap. Several secondary factors may affect the choice of magnetic circuit and other details of design, not the least important being access to the vacuum chamber, the shape of the required flux pulse, and the cost of steel.

For this machine a C shaped magnet was selected, with an orbital radius of 77.5 ft, a designed flux density (for 7 GeV) of approximately 14 kilogauss, and a magnet gap of 9 in. extending 45 in. radially. To establish 14,000 gauss in the gap, some 350,000 ampere-turns will be required and the stored energy in the magnet field will be of the order of 40 megajoules. The magnet is designed in eight units or octants separated by straight field free spaces which will accommodate the RF accelerating cavity, the injection equipment, the beam extraction equipment, targets and other experimental equipment. Each octant comprises 42 sectors, the whole 336 sectors weighing 7,000 tons.

Magnet Steel

In choosing steel for the magnet it is essential to give the correct relative weighting to the magnetic properties, viz. cost of the steel, cost of the power plant, and the recurring cost of the losses in the iron and copper. An exact judgment of the correct steel is most difficult, but final choice fell on a low silicon electrical quality steel, with the analysis given in Table 1.

TABLE 1.—Composition of Magnet Steel

Element	Min. conc.:%	Max. conc.:%
Carbon	0·04	0·06
Manganese		0·40
Phosphorus		0·03
Silicon	0·80	1·00
Sulphur		0·04

After annealing to obtain the optimum magnetic properties the steel has an ultimate tensile stress not less than 18 tons/in^2. Each magnet sector is built up of 1/8 in., 1/4 in. and 1/2 in. hot rolled steel plates, the greatest attention being paid to minimizing the crowning effect of the rolls. As sheets 11 ft by 10 ft were not available, two sheets of approximately half this size are welded together to form a sheet of adequate size. The general shape of the magnet is illustrated in Fig. 6, and the following manufacturing process illustrates the care taken to achieve high

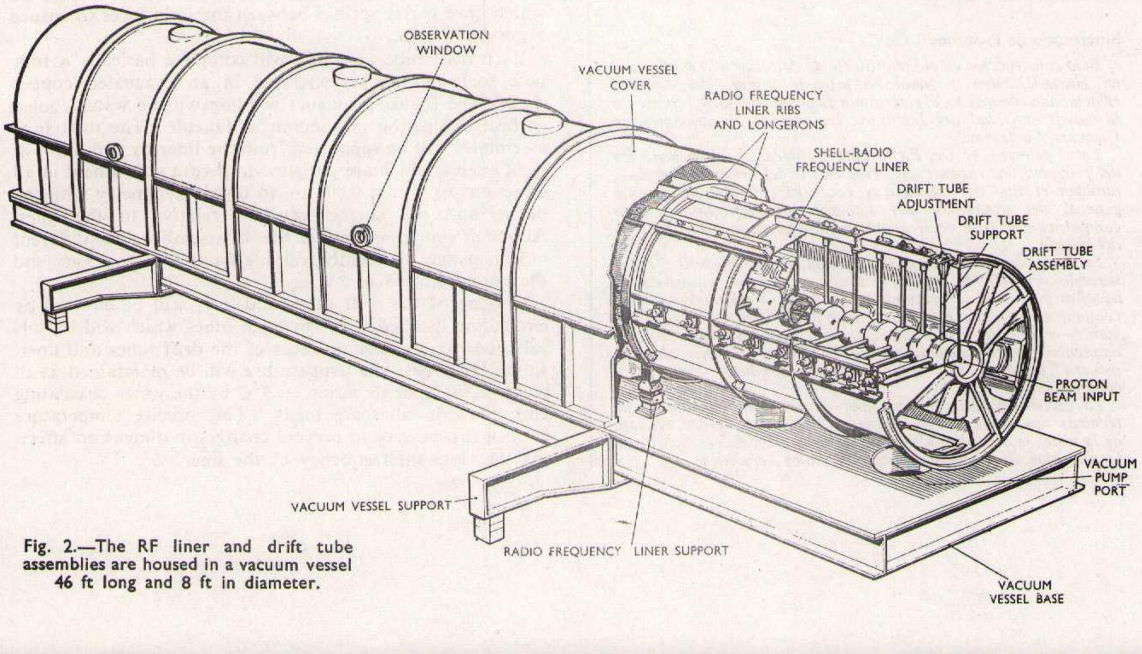


Fig. 2.—The RF liner and drift tube assemblies are housed in a vacuum vessel 46 ft long and 8 ft in diameter.

dimensional standards and magnetic uniformity of the 336 sectors.

The two plates forming one larger plate are matched to ensure that each piece not only comes from the same cast but from the same relative position in the ingot. Next each half plate is prepared for welding and a rough profile of the throat is cut by torch. The two sheets are then welded by a fusion process using CO_2 protection. The stacks of plates so produced pass to an annealing process and to final assembly via randomizing beds, where by particular selection it is ensured that the steel for each magnet is a random sample of the steel available at that time. About 75 tons of steel per batch is annealed in an inert atmosphere by a process cycle which takes about one month. The steel sheet so treated has optimum magnetic properties and skilful technology has produced flat plates.

After setting up a full sector, all the laminations are jig drilled at one setting, and taken apart for descaling and deburring. One side of each lamination is sprayed with an insulating coating, and after drying the laminations are assembled into a sector, each lamination being further insulated from its neighbour by phenolic paper. Specially hard resin sheet is inserted around the throat, this process being necessary to ensure clean machining of the edges, to prevent short circuiting of the laminations. After clamping the laminations with a uniform load of 50 tons, the side straps and back plates are welded in position to prevent distortion, and after tightening the lateral tie bolts the 50 tons load is removed. The welds will not introduce great circulating currents during operation of the magnet as the straps will not be linked by any appreciable flux. The sector weighing approximately 20 tons is next mounted vertically on the milling machine and in two operations the throat is machined to the final dimension. Upon delivery to site the sectors are checked dimensionally and the critical magnetic qualities measured in a rig; afterwards the magnet sectors will be erected on the magnet ring in specific positions determined by their quality. Forty-two sectors adjacent to each other form an octant which will be spanned by two symmetrically spaced magnetizing coils, as shown in Fig. 6.

The final design of the pole pieces has not yet been concluded but it is established that each one will comprise a stack of about 400 thin steel laminations of very accurate profile. The alternate laminations will be of different thickness and material, and will be bonded together to resist the severe disruptive forces. The laminations will be electrically insulated from each other and no bolting is permissible. It will be necessary to produce the pole pieces in matched pairs to preserve magnetic symmetry.

Magnet Winding

In a highly inductive circuit of low resistance the number of turns required for a given current and a given rate of change, is dependent upon the applied voltage. In the case of the synchrotron described the coils have 42 turns and the applied voltage will be approximately 14 kV. The coils sides are being formed into the required radius from 50-ft lengths of extruded copper of section 1.375 in. × 2.625 in. The front conductors which are carried on the lips of the sectors will be connected to those conductors in the throat, by means of separately shaped end connections of the same section. The conductors will be cooled by demineralized water which is pumped through the 0.2 sq. in. hole in the centre. In this way the 3 MW of heat is dissipated, and scale deposits are avoided. The weight of copper in the coils will be approximately 350 tons.

The peak current for a standard pulse is 9,150 amp but under special conditions it is planned to increase this appreciably. The normal pulse rate will be 28 pulses/min and as the force on the coils is of the order of several tons per foot run the mechanical integrity of the coil and its clamps becomes a very difficult engineering problem.

The normal working voltage will be 4 kV d.c. to earth and 100 V between turns. This presents no difficulty but the problem of selecting an insulation to withstand the destructive mechanical forces is not so easy. It is proposed to use an insulation with some resilience as the continued application of the above forces could cause cracking of a hard material. On the other hand continued plastic flow could cause slackening of the clamps and loosening of the coils. The insulation chosen is turbobar insulation which is basically a mica silk tape, compounded with bitumen varnish. This insulation will bear extreme pressure without breaking down. After applying the tape to each formed bar, it is vacuum dried. Seven such conductors are then assembled so as to prevent voids, and the whole is bound together with tape. The pack is then pressed to size and the mica tape belt applied; the outer surface is finished with terylene tape, which is brushed with graphite compound to produce a low friction surface and so minimize abrasion of the insulation.

Under normal operating conditions the changes in temperature of the copper conductor could produce appreciable expansion or severe temperature stresses and an attempt has been made to minimize this by designing the system so that the temperature of the circulating water will be controlled to limit copper temperature variations to ±4°C.

In concluding the brief picture of the magnet it should be appreciated that it is necessary to maintain the plane of rotation of the beam in the main vacuum chamber correct relative to the injection and experimental apparatus. This accuracy can be affected by sinking or tilting of the foundation monolith, or distortion of the monolith during curing. In addition it is necessary to locate to extreme accuracy not only the angular and radial position of each sector, but

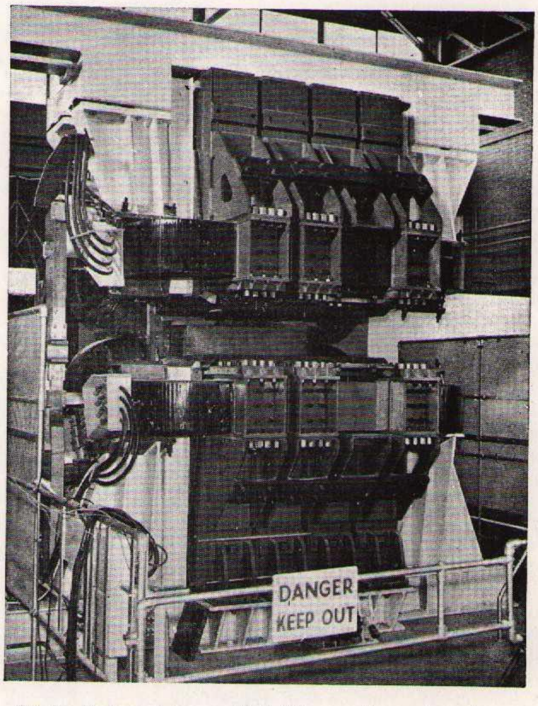


Fig. 3.—Each magnet assembly is fully tested on a rig similar to that shown above.

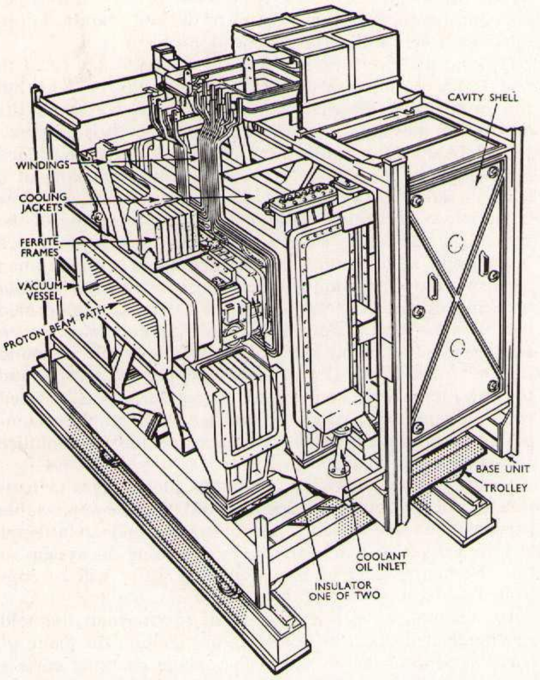


Fig. 4.—The RF cavity which accelerates the proton beam.

the height and tilt of each one relative to any other. The problem is doubly complicated since the erection has to be carried out to a scheduled programme and a bare minimum of time is available for the curing and drying of the concrete monolith. Furthermore once the magnet is set up and the coil and vacuum are installed no realignment of the magnets is contemplated unless there is a significant loss of beam current.

THE RF ACCELERATOR UNIT

Approximately every two seconds the proton linear accelerator will inject a proton beam tangentially into the main vacuum chamber and under the influence of the magnet the beam will be deflected along a circular path. At injection the protons will have a velocity of about 18% that of light and if the machine performs as designed the protons extracted for experiment will be travelling at 99% of the speed of light. A fresh beam will be injected every two seconds, and the accelerating period is 0.7 sec, during which time the protons go round the orbit about a million times. The accelerating device is known collectively as the radio frequency system, and comprises a primary frequency generator, a bias supply, a beam control unit and an accelerator unit. The last-named component produces the acceleration by means of a radio-frequency electric field.

The accelerator unit is fundamentally part of the main vacuum system, the flanges of the vacuum vessel located within the RF unit actually acting as electrodes for beam acceleration purposes. The insulators between the electrode flanges form a special design problem, as the choice of material is limited by radio-frequency loss characteristics; epoxy resin, porcelain and glass are all being tested. The bolts clamping the insulators must similarly be of low loss material.

The cavity, illustrated in Fig. 4 will be excited by a variable frequency oscillator whose frequency must vary from 1.4 to 8 Mc/s between beam injection and extraction. The peak voltage across each insulator will rise to 7 kV. The frequency control of the cavity is obtained by magnetically biasing the ferrite cores by a direct current, which changes the incremental inductance of the circuit. These cores are of picture frame type and are produced by bonding sintered blocks with an epoxy resin cement. Some 12,000 lb of ferrite will be used.

The bias winding requires 6,000 ampere turns. Initially a 600 amp, 10 turn arrangement will be used as this, on the basis of present knowledge, simplifies the control circuit, but it is anticipated that later a single turn 6,000 amp bias circuit will be used. The design permits conversion by simple reconnection.

In order to maintain the ferrite at 25°C working temperature oil cooling has been selected and some 45 kW will be removed under test conditions. The chilling of the oil will be effected by a Freon 12 refrigerator which has water cooled condensers. An oil dumping system is provided as a safety precaution.

VACUUM SYSTEM

Not only must the vacuum chamber be capable of being evacuated to a pressure of better than 10^{-6} mm Hg but the shell of the chamber must occupy a very minimum of gap length, be non-magnetic and circulating currents in its skin must not produce field distortion. It is equally necessary if non-metallic materials be used that there should be no accumulation of electrostatic charge on the surface, the material should have long life, and possess maximum resistance to any degrading effects produced by beam irradiation. Whilst satisfying these conditions the chamber should need a minimum external anchorage to prevent collapse, should be easily installed, and the inside should be freely accessible for experimental apparatus.

The vacuum chamber will comprise eight curved sections which correspond to the magnet octants and eight straight sections in the field free regions. The straight sections will be connected to the vacuum chamber by expansion bellows, and large vacuum valves will enable the chamber to be sectionalized to minimize pump down time after installing experimental apparatus.

Many designs of vacuum chambers can be evolved, and selected lines of approach depend upon opinion, cost, but more often upon decisions which may have been already taken for other components of the machine. The main contestants for the present machine were:—

(1) A partially self supporting chamber of insulating material.

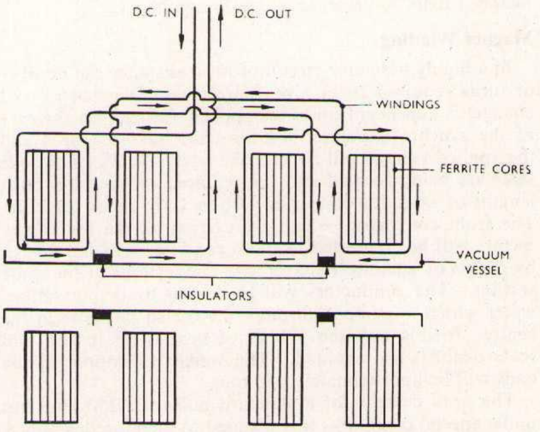


Fig. 5.—Bias winding of the ferrite cores, used for frequency control.

(2) A plastic chamber with metal skeleton to give mechanical strength.
(3) A stainless steel chamber, comprising thin metallic slats.
(4) A double-walled chamber of insulating material.

Selected Design

For the 7 GeV proton synchrotron, the last alternative has been selected; it is not an ideal solution but an optimum choice. The details of construction are not complete but the pattern is defined in Fig. 6 and the following description outlines the features. A complete section of the chamber will comprise three major components which join together at an almost common radius. This construction gives easy access to the inner chamber and enables the three parts to be more easily designed to satisfy their principal duty.

The preferred material is a resin laminate, probably epoxy resin and glass, but the design is such that the stresses are low in those parts of the chamber which suffer irradiation, and the parts most affected are removable for repair or replacement. The main feature of the design of the double-walled chamber is that if the interspace is pumped to approximately the same pressure as the inner chamber there are negligible stresses on the inner chamber, and the material for its construction can be selected mainly for its vacuum properties. Similarly the degrading of the mechanical characteristics by radiation will not be as serious as if the chamber were highly stressed. It will be noted that the outer chamber is a sandwich between the magnet sector and the pole pieces, so that the requisite strength against collapse can be obtained. The presence of the pole pieces and auxiliary windings in the interspace is of no serious consequence since any outgassing does not enter the inner vacuum chamber.

In order to remove charge from the inner chamber wall the plastics will be bonded to non-magnetic stainless steel sheet which will be of strip-ply construction so that not only are the circulating currents minimized, but a minimum area of plastic surface is presented to the high vacuum.

To evacuate and maintain the vacuum chamber at 10^{-6} mm Hg is a major vacuum pumping problem as the mean diameter is 155 ft and the chamber is approximately 7½ ft wide. This will be accomplished by a combined system of roughing and diffusion pumps. On evacuating the chamber the roughing pumps will take both the inner and outer vacuum spaces down to a pressure of 10^{-2} mm Hg, when the high vacuum pumping will be brought in to take the inner chamber down to the best obtainable vacuum. The roughing pumps will continue to maintain the outer vessel at a pressure better than 10^{-2} mm Hg. The high vacuum pumping equipment comprises forty 24-in. diameter oil diffusion pumps, with refrigerated chevron baffles and sliding gate valves. The overall pumping speed is 232,000 l/sec.

POWER SUPPLIES

Associated with the proton synchrotron are many and varied types of power supplies but the principal one associated with the magnet presents the most interesting engineering problems. The machine will operate under a variety of conditions and the plant is being designed with a maximum flexibility. The characteristics of a standard pulse are shown in Fig. 7, where it can be seen that during each pulse, the magnet current will have to rise at approximately a constant rate to a maximum value of 9,150 amp and will subsequently fall to zero again. Facilities are required for maintaining the current at the maximum value for 0.125 sec, and for repeating the pulse at a rate of 26 pulses per minute.

KEY : (1) Magnet sector. (2) Magnet coils. (3) Pole tips. (4) Outer vacuum chamber (low vacuum). (5) Inner vacuum chamber (high vacuum). (6) Header chamber (high vacuum). (7) Pole face windings. (8) Pressure pads. (9) Pole tip jack. (10) Main pumping port. (11) Beam exit window.

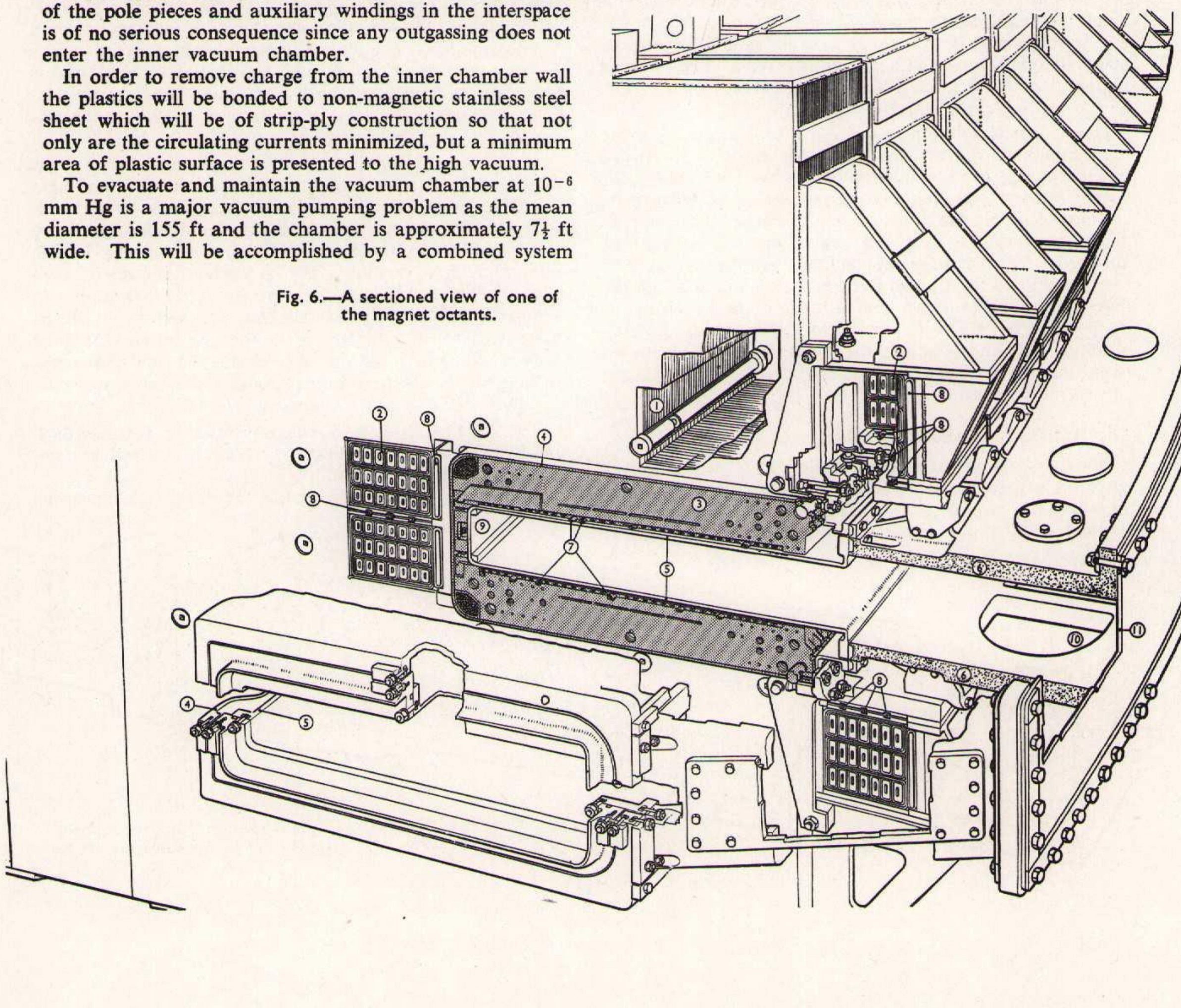


Fig. 6.—A sectioned view of one of the magnet octants.

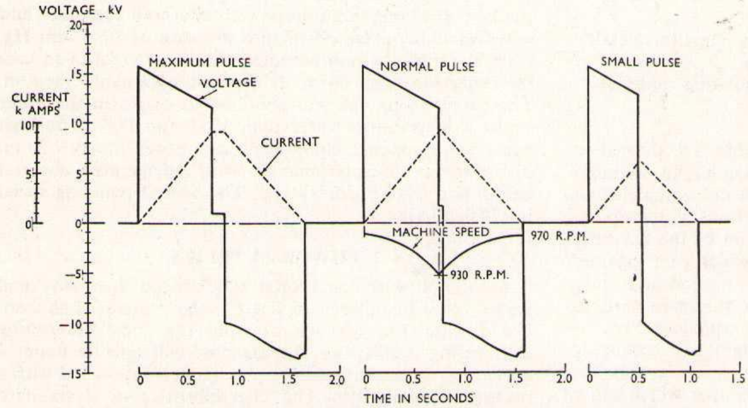


Fig. 7.—Characteristics of a standard pulse including fly-wheel speed cycle.

The energy stored in the magnetic field at maximum current is about 40 megajoules, and to take and return this energy once every two seconds to and from a public electricity supply network, would be impracticable as the surges of power would be of the order of 120 MVA; some form of energy storage, therefore, is required.

In order to produce the required current in the magnet winding during the rise time, an e.m.f. must act which can overcome the sum of the resistive and inductive voltage drops. During the flat top only a small fraction of this e.m.f. is required to maintain maximum current, and during the period when energy is being returned from the magnet to the source the e.m.f. must reverse. The voltages required for these three distinct phases are 13.9 kV, 1 kV, and −11.75 kV respectively.

One technical solution to the above problem is to isolate the demand of the machine from the electricity network by interposing a motor-alternator set with a flywheel for energy storage. The alternating current generated can be rectified to supply the direct current required by the magnet and control of the field will enable the rise time to be adjusted. By switching the rectifiers into inversion it is then possible to return energy from the magnet through the inverters so as to drive the alternators as synchronous motors and so return the energy to the flywheel. In such a circuit only the losses of the system have to be drawn from the supply network and the pulses of power are considerably reduced.

The Rutherford Laboratory Plant

The actual plant under construction for the proton synchrotron will comprise a motor, alternator, two flywheels, an alternator and a motor, arranged in that order for symmetry, reliability and to give an element of standby should one machine fail due to the exacting duty. A general impression of the plant is shown in Fig. 8. The similar halves will be mechanically coupled between the flywheels although provision is being made for the machines to be connected in electrical parallel should this prove desirable. The alternators ordered are 1,000 r.p.m., 3 ph, 50 c/s, 11.5 kV salient pole machines having a nominal rating of 60 MVA. The thermal rating of each is 46 MVA and the peak rating 79 MVA. The alternators are cooled by air in closed circuit, external fans having been selected for greater reliability under the duty of this machine. The stator frame is of fabricated construction, stayed and ribbed to form a structure of great strength. The rotor body and shaft are to be formed from a one-piece forging of high tensile nickel chrome molybdenum steel, bored through the length of its axial centre to permit inspection. The windings are specially wedged and braced not only to withstand the normally onerous conditions but severe stresses due to repeated fault conditions which could occur because of arc-back in the converter plant due to a defective excitron.

The motors ordered are of the wound rotor type each of 5,000 h.p. rating and operate at 11 kV from 3 ph 50 c/s mains. The rotors are connected to a rotor resistance to limit the power swing. The flywheel assembly has a stored energy of approximately 500,000 h.p., sec at 1,000 r.p.m., and is designed to limit the speed variation of the set to 4%. Eddy-current braking is being applied to the 40-ton flywheels to bring the set to rest.

The alternators will be connected to 96 water cooled single anode, grid-controlled mercury arc converters, via eight 12 MVA phase splitting transformers, single anode units having been selected as it was considered this would give the minimum arc-back rate. With no phase shift on the alternator shaft couplings the converters will act as a 24 phase rectifier and can deliver above 10,000 amp. In accordance with the pulse sequence the converters will be switched into inversion to enable the magnet current to be reduced to zero in the shortest permissible time thus minimizing the power loss, and increasing the repetition rate. A schematic diagram is shown in Fig. 9.

The magnet coils will be connected in two identical blocks, and the two identical converter units will be connected in alternate series.

In view of the exacting duty of these machines the

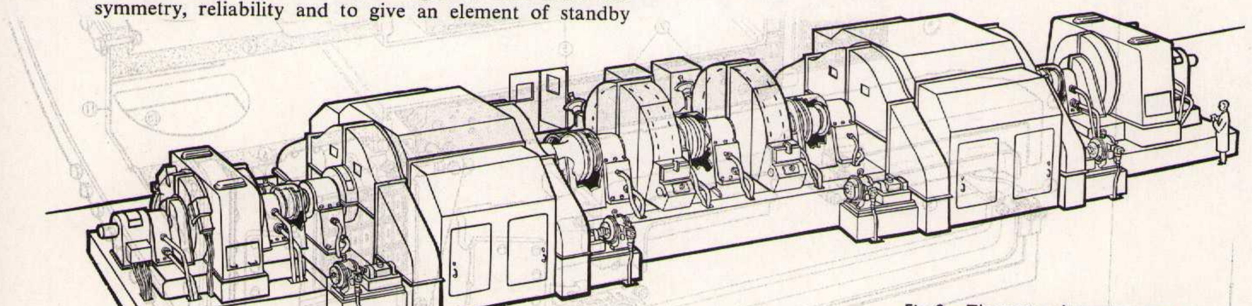


Fig. 8.—The motor alternator power supply and energy storage units for the magnet.

strictest attention is being paid to mechanical resonance on the shaft system and it is this feature which determined the choice of a 1,000 r.p.m. set. Similarly every care is being exercised in the choice of fastenings and features of mechanical construction. In view of the pulsating duty the whole is being mounted on a floating bed. This should ensure a minimum vibration to neighbouring buildings and reduce vibration stresses in machine components.

The set will be isolated from neighbouring supplies to some degree as it will be connected directly to the 132 kV grid lines via its own 20 MVA transformer. By using a flywheel set the power swing has been reduced to 10,000 kVA for a power swing of 120,000 kVA in the alternators, and the input voltage variation on the transformers due to the pulse is only ½% or 2% dependent on the number of power lines connected.

CONTROL SYSTEM AND INSTRUMENTS

The control system of the proton synchrotron has the duty of maintaining at the preselected value during successive pulses, all critical variables associated with the equipment described. It must also maintain the proper sequence of events and ensure the correct relative values of the variables during a pulse as acceleration takes place and be capable of extension to experimental apparatus. Fig. 10 gives diagrammatically the precise sequence of events.

In addition the control room will accommodate all the important instruments relative to the operation of the plant, and the control and protection of personnel. This decision to centralize controls and instruments has been taken principally because it will enable a single operator to determine quickly the operational status of the whole plant, and for him quickly to make adjustments on the basis of information. It will also permit the minimum number of staff to be engaged in machine operation and for the fault area to be quickly appreciated. Furthermore a great many components will be installed over such a large area—many in radiation areas; without an integrated control scheme it would be impossible for operators to oversee the whole project. The complete plant has therefore been interlocked in the interest of general and radiological safety and strict control will be maintained over traffic of personnel into areas of excessive radiation. As the control personnel will remain in the same situation for very long periods the control room has been located in a well screened area.

The controls for all the sections of the plant previously described will be grouped around the control room according to function, only the essential instruments and controls being located on the console. Such controls include the selection of the injection point and the peak energy, which will then operate automatically when the selected values of magnetic field are reached. The " flat top " period and pulse repetition rate which are precise time controls will also be selected. After injection, beam pick up electrodes by servo-action, control the frequency of RF acceleration required to keep the particle bunch on a stable orbit as the magnetic field and particle energy simultaneously increase.

Although centralized control has been adopted it will be necessary during the start up of the plant to carry out tests, section by section, and arrangements have therefore been made for local control panels, which can only operate when isolated completely from central control. To assist the operator an attempt has been made to follow the principle of every adjustment giving an indication on lamp or

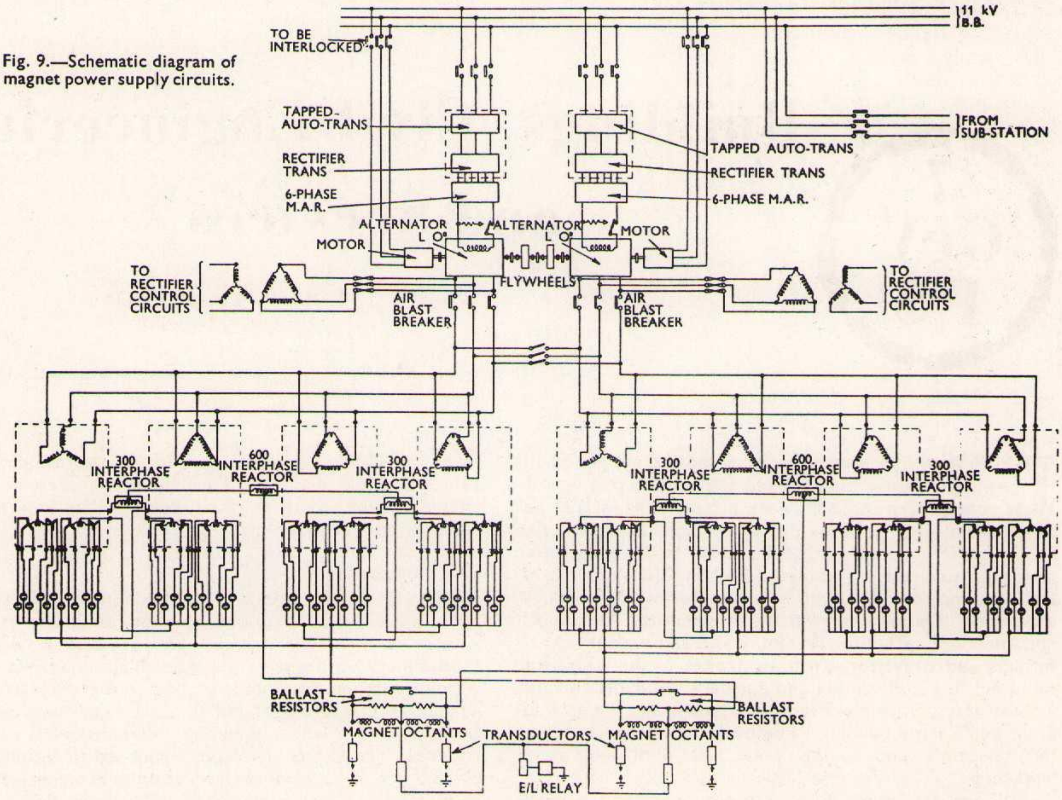
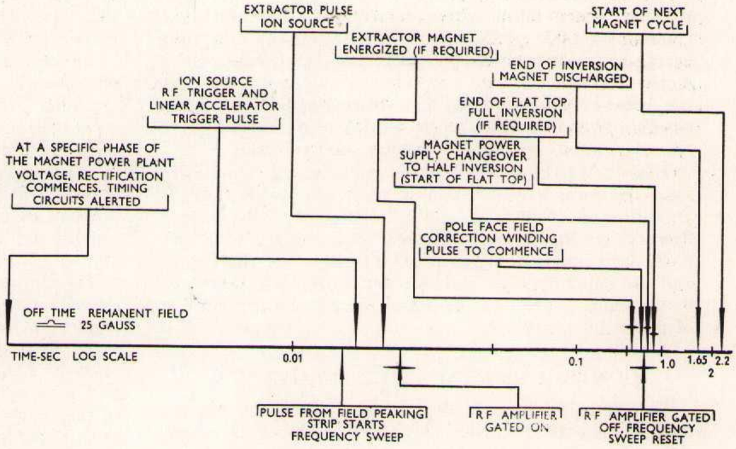


Fig. 9.—Schematic diagram of magnet power supply circuits.

Fig. 10.—Timing sequence for one complete pulse period plotted on a logarithmic time-scale.



meter. Similarly when a particular condition must exist for the safety of a piece of equipment it is provided with an interlock and will not depend upon memory or instruction.

The control room besides accommodating the equipment to control the machine as a whole will also be used for subsidiary control desks for radiation monitoring, beam marshalling and special experiments. Wherever possible the two types of circuit will be kept physically separate as the machine control wiring is likely to be of a more permanent nature than experimental apparatus which will require rapid installation and frequent modification.

A public address system with its microphone in the main control room will operate over the whole proton synchrotron area. In addition to normal duty arrangements the system will broadcast pre-recorded routines to ensure safety in confined areas. This audible announcement will be supplemented by visual signals, and turnstile checks.

The whole site and environs will be monitored by permanently installed radiation equipment, and the levels are to be relayed to the control room.

The operator will be assisted in his control function by being able to view the pulse shapes on oscilloscopes. He will also be able to watch the behaviour of plant in high radiation areas by the use of closed circuit television.

Acknowledgments

The author wishes to thank Dr. B. F. J. Schonland, Director of the A.E.R.E. and Dr. T. G. Pickavance, Director of the Rutherford High Energy Laboratory for their permission to publish this paper. In addition the co-operative efforts of the large team of engineers and physicists both in the U.K.AEA and industry are gratefully acknowledged as the foregoing article represents much of their collective contributions.

Buildings, Civil Engineering and Services

By G. W. DIXON, A.R.I.B.A.
(Chief Architect, A.E.R.E., Harwell)
and
A. G. ENTWISTLE, M.B.E., B.Sc.(Eng.), A.M.I.Mech.E., A.M.I.E.E.
(Merz and McLellan, Consulting Engineers)

THE Proton Synchrotron and its power supply plant require extensive building and civil engineering works. These comprise an injector room, a magnet room and an experimental area to house the accelerator and to provide facilities where equipment can be set up to study the properties of accelerated particles; a building housing control and counting rooms with an area attached where preparatory work in connection with experiments can be carried out; buildings to house the motor alternator plant, transformers and convertor plant; an annexe to the convertor room housing a substation and ancillary mechanical plant; a three-storey office block with laboratories on the ground floor, and a large building to be used initially for preparatory assembly and testing work and ultimately as a workshop.

With the exception of the injector room and magnet room, the buildings are of conventional steel-framed construction. The main buildings, however, present many unique features both in their construction and in the facilities provided therein.

Civil Engineering

When the synchrotron is in operation intense radiation is produced and it is, therefore, necessary to ensure that the injector and magnet rooms are adequately shielded. Furthermore, instruments must be shielded against background radiation. Semi-underground construction has been adopted for the main buildings and both concrete and earth are employed for shielding. Particle beams entering the experimental area are largely confined to a horizontal plane 6 ft 3 in. above floor level and the experimental area has, therefore, been arranged with a conventional north

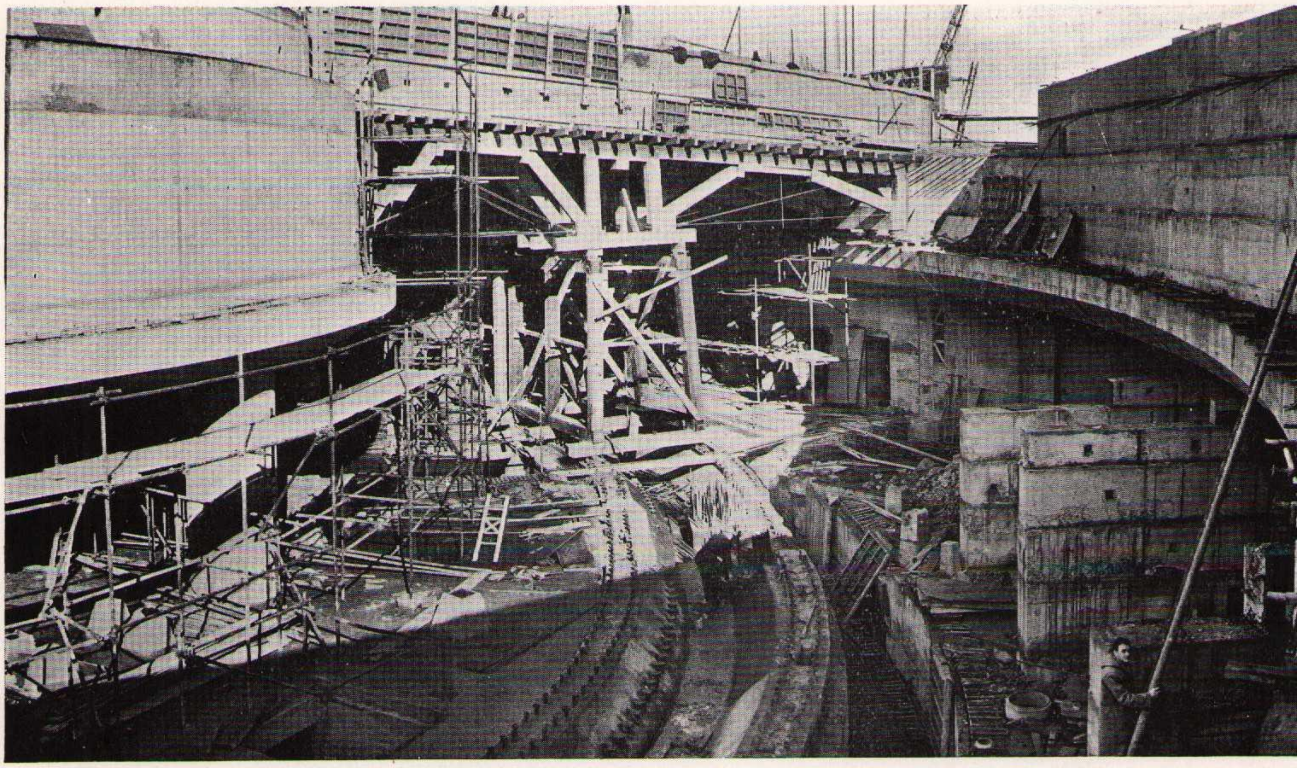


Fig. 1.—The foundations of the magnet annulus showing in the background the partially completed magnet room roof.

light truss roof so located that the path of experimental beams is directed towards an adjacent hillside.

Sub-soil. The sub-soil is fractured and weathered middle chalk to a depth of over 200 ft. The loads to be carried entail stressing the whole area of the magnet room and adjoining structures to about 2½ tons/ft^2. At this loading the weathered parts of the chalk yield plastically after the manner of an overloaded clay. Within 10 ft of the original ground surface the chalk is almost entirely decomposed but soon gives way to a mixture comprising about 75% lump chalk with irregular portions of the claylike decomposed chalk. The proportion of lump to decomposed chalk gradually increases with depth, but decomposed pockets were found as deep as 150 ft in boreholes.

Because of its mixed nature the sub-soil as a whole was not susceptible to laboratory experiments for strength. Tests were, however, made separately on the block chalk and on remoulded specimens of the decomposed chalk. No calculation of the behaviour of the mixed materials could be made from these but, as a matter of engineering judgment, an opinion was formed of the likely behaviour of the mixture under load.

Magnet Room. The magnet lies on an annulus of about 150 ft diameter in a room 200 ft in diameter and weighs some 7,000 tons. In order to maintain alignment of the vacuum chamber forming the accelerating orbit for protons it is required that the magnet foundation should neither hog nor sag and that it should tilt by no more than ±¼ in. across its diameter. A further requirement that the foundation as a whole should not settle in relation to adjacent buildings was relaxed in order to provide, with the sub-soil conditions obtaining, an economical building which could be built in a relatively short time. The magnet, its foundation and roof shielding impose heavy loads on the sub-soil and it was found to be uneconomical to divorce the support of the magnet itself from the ground affected by the structural loads. The foundations are, therefore, designed so as to load the sub-soil as uniformly as possible and thus minimize movement of one part at the expense of another. The foundations are divided into several units to simplify stress and load distributions and to localize horizontal thrusts from earth pressures.

The magnet itself is supported on a cellular disc foundation about 160 ft in diameter which also carries a central column and eight other columns located on a circle of 100 ft diameter. These columns transmit to the foundation a substantial portion of the weight of the magnet room roof and of the earth shielding on top of the roof. The foundation monolith self-weight is restricted by allowing substantial voids in the structure, which incidentally provide space for the accommodation of ancillary plant and for running cables and general services.

Immediately outside the magnet foundation disc, a substantial services trench is provided. The annulus of floor outside the trench is the toe of the magnet room outer wall, which is designed to take a load of 25 tons per lineal foot, being principally roof and shielding earth load.

Injector Room. The linear accelerator is housed in a reinforced concrete room 170 ft long arranged tangentially to the magnet circle. It is mounded over with earth in the same way as the magnet room and, although it is arranged on a separate foundation, connections are provided between the magnet room annular services trench and a longitudinal trench in the injector room.

Shielding Bridge. On the south side of the magnet room there is an opening 160 ft in arc length into the experimental area, but it is generally required that this opening shall be stemmed with concrete except for small apertures through which experimental beams will be guided. Up to a level of 12 ft 6 in. above the floor this shielding takes the form of a concrete wall 30 ft thick in the form of transportable blocks. The blocks are arranged in stacks of five, each block being 2 ft 6 in. deep, and their plan positions will be such that there will be no continuous straight paths between blocks permitting particles to stream from the magnet room to the experimental area. Above

Reprinted from "Nuclear Engineering," April, 1959

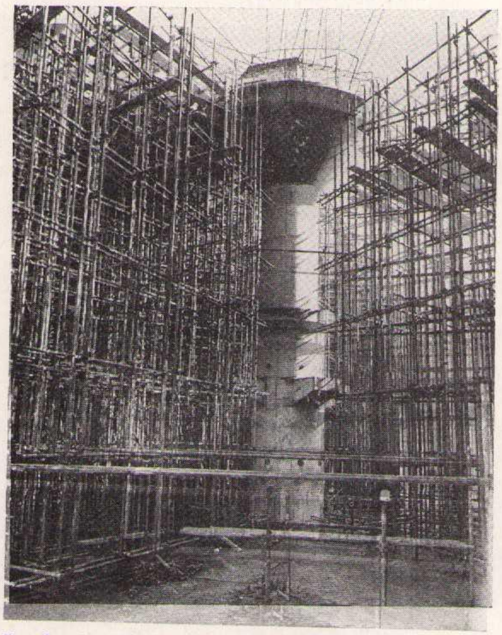


Fig. 2.—Central column, which together with eight other columns on a 100-ft circle transmits the bulk of the roof and earth shielding weight to the foundations.

the 12 ft 6 in. level a concrete shielding bridge spans the whole of the width of the opening into the experimental area. The bridge superstructure is 28 ft wide and 17 ft 6 in. high and is dog-legged in plan with supports only at each end and at the point of change of direction. A single monolith foundation supports the two abutments of the bridge and the central pier. Voids are left in this monolith and large cells are formed in the eastern abutment to achieve a balance of the complicated loadings.

If it could have been achieved economically it would have been desirable for the whole of the beam to span the opening with no central support, since this would increase the scope for beam paths available to experimenters. However, it was agreed that a central pier could be accepted provided that the projected width at beam height on a line from the magnet room to the experimental area was kept to a minimum. It proved possible to design a pier with a solid mild-steel shaft only 1 ft wide and 8 ft long with a height of 2 ft 6 in. The mid-height of the shaft is at the plane of the experimental beam and the shaft carries 7,500 tons. Above and below the mild-steel section are very heavy spreading blocks forming a cap and a pedestal, each of which comprises five heavy plate girders clad in concrete. The cap and pedestal are sized to match the module of the shielding blocks which will be placed alongside them and when necessary the open spaces around the steel shaft will be stemmed with small blocks which can be placed by a fork-lift truck or by hand.

Tunnels. The floor level of the main buildings is several feet below that of the adjacent ancillary buildings and services have, therefore, to be run in tunnels, which in some cases are taken down to such a level that they pass below the foot of the magnet room retaining wall. Separate tunnels are provided between the ancillary buildings and the magnet room for mechanical services, electric cables and conditioned air, while a tunnel from the control room branches to both magnet room and experimental area. The latter forms the normal personnel access to the magnet room from the control room and a passenger/goods lift is provided in the control building for easy access.

Electrical Services

The plant, when operating at full power, may consume as much as 20 MVA of electrical power. The main supply will be from the national grid through a 132/11-kV transformer, installed in the existing grid compound at Harwell and feeding an 11-kV switchboard located in the synchrotron substation in the annexe to the convertor room. The two motors of the motor-alternator set will be fed from this board, which will also supply, through an 11/3.3-kV transformer and a 3.3-kV switchboard, the larger items of ancillary plant.

General electrical services will be supplied through 11-kV/415-V transformers and 415-volt switchgear, but in this case the 11-kV supply will be derived from an existing substation located near to the synchrotron area. The general services will thus not be supplied from the same 11-kV input as the main plant and will *not* be unduly subject to the effects of the pulsed load on the latter circuit.

All services in the injector room, magnet room and experimental area are to be fed from the synchrotron 415-volt switchboard via local switch-fuseboards or direct from this board. Certain ancillary buildings will be fed at 415 volts from the existing substation already referred to, and distribution in these will be via switch-fusegear. Facilities will be provided for emergency tripping of supplies to experimental apparatus, while leaving energized the switchgear through which lighting, cranes and other non-experimental services are supplied.

Cabling. The magnet supply, with an r.m.s. current of 6,000 amp, will be taken from the excitrons in the convertor room to the coils of the magnet by means of 22-kV grade mass impregnated non-draining cables running through the electrical services tunnel and voids in the magnet foundation.

L.T. cabling will generally be of the mass-impregnated non-draining type, and multicore cabling of the Unipren type.

Lighting. The injector and magnet rooms will be lit by cold cathode fluorescent tubes, which incidentally permit economies in building costs by minimizing the clearance required between overhead cranes and the roof. Other areas of the workshop type will generally be lit by high bay fittings of the blended mercury arc-tungsten type. The control room lighting will be of the diffusing ceiling type with dimming control. Over-riding control of lighting in the magnet and injector rooms will be provided from the control room so that switching of lights can be used to indicate to personnel that start-up of the machine is imminent. This system will be backed up by sirens and flashing red warning lights. Emergency d.c. lighting will be provided in all operational and workshop areas and corridors.

Small Power Supplies. Throughout the operational and workshop areas busbar trunking is being provided, with 30 amp and 60 amp triple pole and neutral plug-in units, and special panels comprising one 15-amp and three 5-amp switched and fused outlets will be installed on walls at frequent intervals. Triple pole and neutral switch fuse units are being provided for special services at various locations in ratings up to 300 amp.

Plant Cooling

The majority of the 20 MVA of power fed into the plant must ultimately be removed by various cooling services and both water and air cooling systems will be provided for this purpose (Fig. 5).

The main heat losses in operation will be copper losses in the main magnet coils and in the ancillary plant. Demineralized water will flow through the hollow magnet coil conductors in order to dissipate losses of approximately 4 MW, the water supply being taken from ring mains accommodated in the mechanical services trench adjacent to the magnet and fed by pipelines in tunnels from the water plant house in the convertor room annexe. The demineralized water will be cooled in a pair of surface-type heat exchangers and provision will be made for heating the magnet coil water when the magnet is not energized, in order to limit to a narrow range the temperature of the copper. Other plant, such as the vacuum pumps and experimental gear in the experimental area, will be cooled by separate demineralized water circuits connected to heat exchangers in the water plant room, while other items of plant will be supplied with raw cooling water for use either direct or in local heat exchangers.

The heat in the raw water cooling the heat exchangers and other plant will be dissipated in a battery of induced draught cooling towers rated to cool 420,000 gallons of water per hour from 95° to 79°F with a wet bulb temperature of 72°F.

Air-conditioning Plant. In order to limit distortion of the magnet sectors, arrangements are being made for them to be kept at substantially constant temperature whether on or off load, dissipating iron losses or heating as appropriate by air flow over their surfaces. Conditioned air will be forced by fans installed in the air-conditioning plant room (annexed to the convertor room) into a duct forming a ring main under the magnet foundation. Outlets from this duct are provided under each gap between magnet sectors and air from these will pass over the magnet sector surfaces to be ultimately discharged from the magnet room at roof level into a return duct. Ducting equipped with fans and heaters will allow a certain amount of air to be drawn off from the main body of the magnet room and diffused through the injector room, before returning to the magnet room.

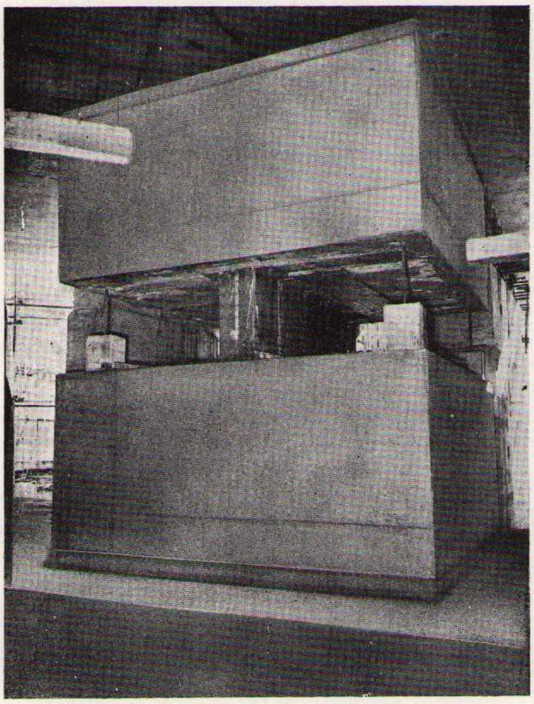


Fig. 3.—Pier with steel shaft carrying 7,500 tons.

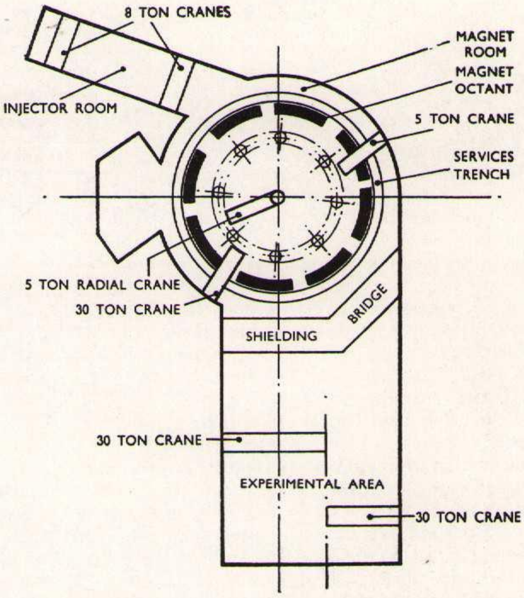


Fig. 4.—General arrangement of the lifting facilities.

At the air-conditioning plant room the return duct will be equipped with two extract fans and provision made for a normal discharge of 10% of the air circulation to atmosphere and corresponding make-up with fresh air. Full-flow air filters will be installed and the heat picked up in the magnet room will be extracted by refrigerating plant. Provision will be made for moisture extraction and subsequent reheating to ensure that there shall be no deposition of moisture on the magnet surfaces. The steam air heaters will also be capable of making good the losses from the magnet room when the plant is not operating.

Recooled water from the cooling towers will be supplied to the motor alternator house for coolers associated with the motor alternator plant and also to the phase-splitting transformers and to the excitrons in the convertor room.

Water Treatment. The clean water circuits are to be filled with water from three mixed-bed demineralizing plants which will operate in conjunction with ion exchange units for the removal of residual oxygen. Each plant is capable of treating 180 gallons per hour of raw water or 480 gallons per hour of water bled from the cooling system.

The raw water make-up for the cooling towers will be treated in a starvation base-exchange plant.

Handling Facilities

In the main buildings, two major handling problems arise, namely the setting of the magnet sectors on their foundations and the movement of concrete shielding blocks. The magnet sectors weighing approximately 20 tons will be handled in the magnet room by an overhead

Reprinted from "Nuclear Engineering," April, 1959

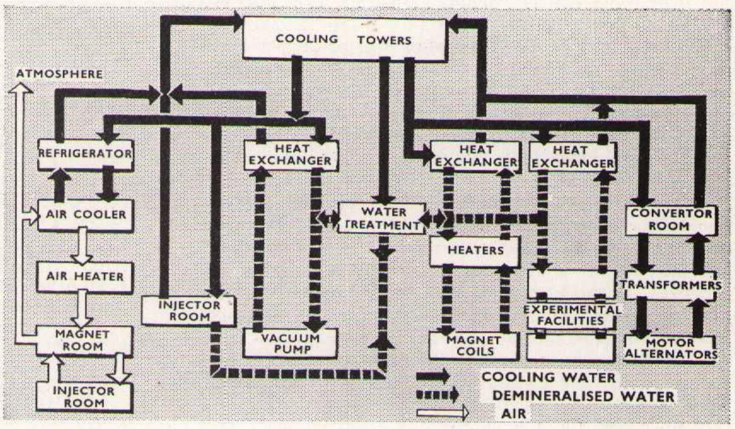


Fig. 5.—Schematic diagram of the site services.

crane of 30 tons capacity running on an annular track as indicated in Fig. 4. Also running on this track will be a separate 5-ton overhead crane, while the inner section of the magnet room will be served by a 5-ton crane operating radially around the centre column.

Concrete shielding blocks may be used to stem the opening under the shielding bridge or for building shielded enclosures, known as "igloos," in either the magnet room or the experimental area. It is, therefore, necessary to be able to move stacks of shielding blocks into position under the shielding bridge and also to turn the blocks, the largest of which measures 15 ft by 10 ft by 2 ft 6 in. and weighs 25 tons, on to any of their faces. Furthermore, since the experimental area is divided into two parts by a row of stanchions along its length, provision must be made for handling shielding blocks from one side of the stanchions to the other. Each side of the experimental area will be equipped with a 30-ton overhead crane and special handling gear provided for turning and transporting the blocks.

Block Handling Gear. To turn a block from the horizontal position on to an end or a long side it will be placed by an overhead crane on to a cradle pivoted about a horizontal axis at one end. The crane will then be attached to a bracket mounted on the free end of the block, which is slowly hoisted and traversed so that it is brought into an erect position. The cradle will be locked and the block removed by a further lift from the crane. In order to take a block from one side of the experimental area to the other, the two cranes will be used in tandem, supporting a long fabricated beam from which the block is suspended.

Trolleys and Tractors. Since the shielding blocks when in position under the shielding bridge will almost completely fill the vertical space available they cannot be put into position by any form of overhead lifting equipment. It was, therefore, necessary to devise a method of moving a stack of five shielding blocks across the floor into position with a minimum clearance lift, and it was decided to employ jacking trolleys propelled by a tractor. The lowest block of each stack will have two longitudinal slots 1 ft 6 in. wide and 1 ft 1 in. high pitched at 5 ft centres through the whole length of the block. Into each slot a pair of eight-wheeled bogies will be run on rails built into the floor and extending from the mechanical services trench in the magnet room, under the shielding bridge, and well into the experimental area. Each trolley will incorporate a hydraulic jack capable of lifting a load of $62\frac{1}{2}$ tons through a vertical range of $1\frac{1}{2}$ in. An independent tractor, incorporating the hydraulic pumping equipment and control gear and its own electric travelling gear, will be linked to the bogies. The tractor, whose wheels will be fitted with tyres of solid rubber, will run on the same rails as the trolleys and be able to move a complete stack of blocks weighing 125 tons at 2 ft/min. The design of equipment and the operating procedure ensure that, while the gap between adjacent blocks is kept to an absolute minimum, it will be possible to move stacks of blocks without fouling adjacent blocks. To this end, the control of the individual hydraulic jacks is arranged so that the operator can correct any tilt which may develop while the stack is being moved.

Cranes. In addition to the cranes already mentioned two 8-ton overhead travelling cranes are installed in the injector room where they will handle the parts of the linear accelerator and its associated equipment. In the preparation area adjacent to the control room is a 25-ton overhead travelling crane, which handles magnet sectors which undergo their initial testing in this area. The motor-alternator house and convertor room will have cranes of 80 tons and 10 tons capacity respectively, the former being used for erection of the motor-alternator set and for maintenance work on the phase-splitting transformers. Other ancillary buildings contain one 8-ton overhead electric travelling crane and one 5-ton and one 3-ton hand-operated overhead cranes. Of the overhead electric cranes only those in the motor-alternator house and convertor room will be cab controlled, the remainder having pendant controls for operation from floor level. The magnet room and experimental area crane pendant controllers are arranged so that they can be moved along the crane girder by the operator, thus enabling him to circumvent obstructions.

General Services

Supplies of mains water, compressed air, gas and steam, together with a condensate return system, will be provided from the existing main supplies to the Atomic Energy Research Establishment nearby.

In all buildings, gas, compressed air and cold water service points will be provided on a liberal scale so that full facilities shall be available for work in connection with the setting up and operation of experiments. A special compressed-air supply will be available in the magnet room for use in conjunction with the vacuum pumps, and in the event of failure of the main site supply this system will be automatically changed over to a stand-by air compressor.

Heating of the injector and magnet rooms will be carried out by the air-conditioning plant already described. Other buildings are heated by low-pressure hot water or steam, employing unit heaters, convectors and radiators to suit the individual requirements of the various areas. Hot water is supplied from storage-type steam-heated calorifiers or electric storage heaters.