British Journal of Applied Physics

INVITED ARTICLE

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To cite this article: T G Pickavance 1963 *Br. J. Appl. Phys.* **14** 643

BRIT. J. APPL. PHYS., 1963, VOL. 14

The work of the Rutherford Laboratory

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MS. received 2nd July 1963

The Rutherford Laboratory is principally concerned with two accelerators: a 50 MeV proton linear accelerator which has been operating since 1960, and a 7 GeV proton synchroton (NIMROD) completed in the autumn of 1963. Both machines are freely available to universities for use in their own research programmes. There is a great deal of activity in development of the associated research apparatus; this is done in collaboration between the universities and the Laboratory, and is financed by the Laboratory. Through the Rutherford Laboratory the National Institute for Research in Nuclear Science enables universities to make full use of expensive research facilities which can only be provided centrally.

1. Introduction

The Rutherford Laboratory is at Chilton, Berkshire, adjacent to the Atomic Energy Research Establishment of the United Kingdom Atomic Energy Authority, and belongs to the National Institute for Research in Nuclear Science. Its aim is to provide research facilities in nuclear and high energy physics for use by universities, the Authority and staff of the Institute.

There are two main research programmes, based on two accelerators: a 50 MeV proton linear accelerator which has been in use since 1960, and a 7 GeV proton synchrotron (NIMROD) completed in the autumn of 1963. Two other accelerators are being designed and constructed for other bodies: a variable energy cylcotron with azimuthally varying magnetic field for the Atomic Energy Authority, and a three-stage electrostatic generator for Oxford University (supported by a grant from the Department of Scientific and Industrial Research). A quite different type of activity, just starting, is assistance to universities in exploiting nuclear reactors for research in a number of fields including solid state physics. The Atlas Computer Laboratory, directed by Dr. J. Howlett and now under construction, is administratively a part of the Rutherford Laboratory although not exclusively concerned with nuclear research. A major Ferranti Atlas installation will enable the Institute to give a computing service to research workers in the universities, the Atomic Energy Authority, Government Departments and, of course, the Rutherford Laboratory itself. There are ancillary items on the programme, concerned with the main lines of work but on a small scale at present for budgetary reasons and also because of pressure of work against a time scale on NIMROD. Examples are studies of superconductivity applied to linear accelerators and of means of producing very high magnetic fields for nuclear research apparatus. The budget of the Laboratory, excluding the Atlas which at present is wholly construction expenditure, is currently about £6 million per annum, of which about half is non-capital. The total directly employed staff is just over 900, of whom about 100 are honours graduate physicists. About 100 university physicists, including research students, are basing some part of their work on the Laboratory and are therefore supported in part from the Laboratory budget, which provides their needs for apparatus and technical staff.

The Rutherford Laboratory, and the Electron Laboratory shortly to be built in Cheshire, have been established to enable the universities to remain fully active in fundamental research in branches of nuclear science which require extremely expensive and complicated apparatus. There is little doubt that fundamental research prospers most when associated with teaching, but there is no doubt that teaching at the most advanced level must be done in institutions actively engaged in research. The physics of elementary particles is currently, and promises to continue to be for the foreseeable future, one of the most important and challenging fields of fundamental research and cannot be denied to universities without very grave consequences. But there will be other important fields with similar problems of finance and organization, and the National Institute model may be a useful one to copy or adapt. It is still in an early stage, but there are some encouraging results.

2. The proton linear accelerator

The partly built linear accelerator was transferred to the N.I.R.N.S. by the Atomic Energy Authority in 1957 when the Institute came into being. The Authority also made available their Accelerator Division and an engineering team at Harwell, including the A.E.R.E. linear accelerator group and a design team working on the bigger machine. The staff remained for some years in the employment of the Authority, but most of them voluntarily transferred to the Institute's employment in 1961. The Institute accepted the linear accelerator, together with the responsibility for completing its construction, with the idea that it would be useful in establishing a preliminary service to universities some years before the completion of NIMROD. They also believed that it would enable them to solve, on a readily manageable scale, some of the human and technical problems involved in integrating a national laboratory with freely determined and directed university research programmes. Finally, they recognized that the proton linear accelerator would be a valuable research instrument in a rather neglected energy range. The success of the operation, in all these aspects, is very encouraging and has exceeded expectations.

The accelerator was completed by the Institute and first operated at full energy during 1959. It has been scheduled for nuclear research since April 1960, first at 30 MeV and, since the beginning of 1961, at the full energy of 50 MeV. Protons are injected from a Cockcroft–Walton generator, at an energy of 500 kev, into the three sections of the main accelerating structure (figure 1). These are cylindrical resonators,

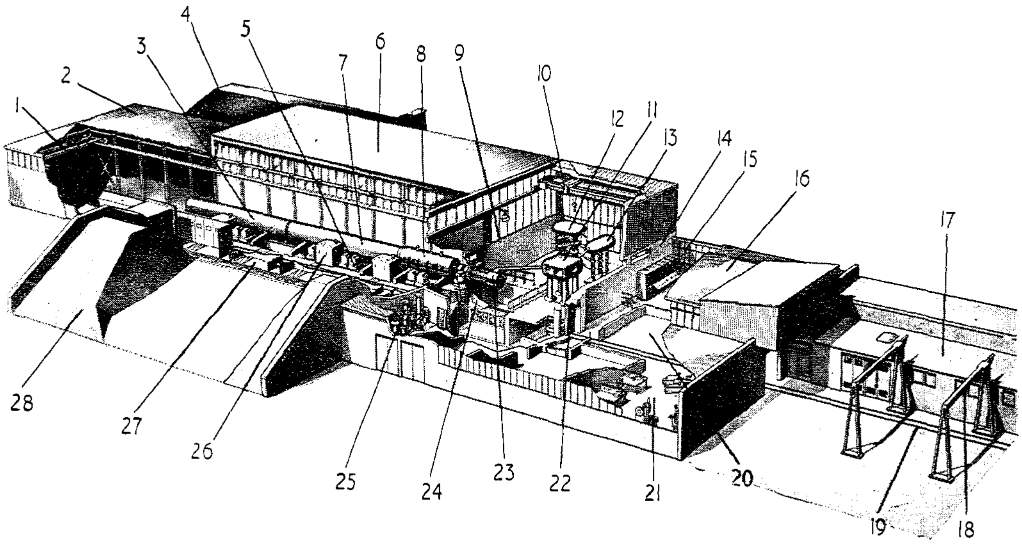

Figure 1. 50 MeV proton linear accelerator.

1, Travelling crane; 2, experimental area; 3, tank 3; 4, earth banking shield; 5, vacuum pump; 6, klystron hall; 7, tank 2; 8, tank 1; 9, injector room; 10, travelling crane; 11, high-voltage control; 12, h.t. set; 13, filter stack; 14, concrete shielding wall; 15, control room; 16, counting room; 17, laboratory and office block; 18, unloading gantry; 19, railway; 20, fitting bay; 21, workshop; 22, concrete doors; 23, injector column and ion source; 24, injector stand; 25, water softening plant; 26, r.f. valve cubicle; 27, modulators and drive stages; 28, earth bank shielding.

enclosed in separate vacuum envelopes, excited in the 'E_{010}' mode at their resonant frequency of 202·5 Mc/s. Drift tubes are spaced along the axis of the resonators, to shield the protons from decelerating electric fields during the 'wrong' parts of the radio-frequency cycle, in such a way that the particles travel from the centre of one gap to the centre of the next during one cycle. This is the so-called zero-mode of standing-wave operation which is usual for slow particles in a linear accelerator and follows the practice first established by Alvarez. The tanks are excited in pulses by demountable grounded grid triodes of unusual design (one for the first tank and two each for the second and third), developed for the purpose at A.E.R.E. because no suitable valves were available commercially at the time. Another triode drives these five, and is itself driven by a multi-stage power amplifier. Automatic phase-sensing and tuning devices keep the three resonators in the correct relative phase, as required by the stability conditions of the proton beam. The beam is focused electrically in the first tank (0·5–10 MeV) with the help of grids across the entrances of the drift tubes. This is a very simple method, because the grids distort the electric field between drift tubes so that the radial component of the field is always inwards, towards the axis. It is also very wasteful because those protons which strike the grid wires are lost from the beam. In the second (10–30 MeV) and third (30–50 MeV) tanks this trouble is avoided by enclosing quadrupole electromagnets inside the drift tubes, thus giving the well-known alternating-gradient focusing and avoiding obstructions across the axis. It is planned to replace the grids in the first tank by quadrupole magnets; the problem is technically difficult with the high duty cycle of this particular machine. This change will increase the beam current by at least a factor 5.

The more important parameters of the linear accelerator are listed in table 1.

The proton beam pulse has a fine structure, the protons being concentrated in bunches of 0·3 nsec duration during each radio-frequency cycle. This property, which can be a nuisance in experiments using electronic counting techniques,

Table 1

Ion source	Pulsed r.f. type, 10 mA peak current		
Main accel. structure:	Tank I	Tank II	Tank III
Length (ft)	18	39	37
Diam. (in.)	42	36	32
No. of drift tubes	41 + 2 halves (at ends)	40 + 2 halves	26 + 2 halves
Q values of resonators (with drift tubes in place)	85000	57000	47000
R.F. power (peak)	620 kW	1·25 MW	1·35 MW
(mean)	12·4 kW	25 kW	27 kW
Input energy (MeV)	0·520	9·95	30·56
Output energy (MeV)	9·95	30·56	49·95
Pulse repetition rate	50 pulses per sec		
Pulse duration (r.f. including build-up time)	400 μsec		
Pulse duration (proton beam)	200 μsec		
Mean proton current	up to 5 μA (1% duty cycle)		
Peak proton current	up to 500 μA		

has been exploited in time-of-flight experiments. Two out of three, eight out of nine, seventeen out of eighteen or thirty-five out of thirty-six of the proton bunches can be suppressed at the input to the machine to provide time intervals of 15, 45, 90 and 180 nsec between bursts. Accurate measurements can be made of the velocity of particles taking part in nuclear reactions by timing their flight over a few metres during the intervals between bursts. In particular, neutron spectroscopy can be carried out in this way with greater energy precision than has previously been possible at these energies.

Another attachment to the machine, which has proved to be extremely valuable, is a polarized ion source. This was developed and built in the Laboratory, and was installed on the machine in 1961. Polarized protons are produced by the ionization of hydrogen atoms which have been partially polarized in passing through a strong inhomogeneous magnetic field. The 2 tons of equipment in this source are mounted on a platform insulated for 500 kv, and the polarized protons are accelerated through the Cockcroft–Walton generator and into the main accelerator tanks. Changes from normal (unpolarized) to polarized ion sources can be made quickly and easily. The performance of the polarized source has been very reliable, and 10^7 to 10^8 protons per second, 30–35% polarized, have been regularly accelerated when needed. This device has enabled experiments to be done on spin-dependent aspects of scattering phenomena and nuclear reactions which would not otherwise have been feasible in this energy range. Other accelerators have been provided with polarized ion sources, but so far as is known the Rutherford Laboratory P.L.A. gives the best performance yet obtained in its energy range.

From the beginning of 1962 the P.L.A. has been operated on a two-shift, 24 hours per day schedule, with 5 days for experiments followed by 2 days for planned maintenance and changeover of experimental arrangements. About 4000 hours of operation for experiments were achieved during 1962, of which 1500 hours were with the polarized beam. The reliability, expressed as the fraction of scheduled time actually used, averaged 72% and has recently been increasing with the installation of improved components. For example, the working lives of the grounded grid triodes were improved when oil diffusion pumps were replaced by vac–ion pumps, and modulator reliability was improved when ignitrons were replaced by deuterium thyratrons. Proton linear accelerators are complicated machines, and it has been found necessary to keep a strong team pf physicists and engineers on machine development.

About 50 physicists have been conducting experiments with the help of the P.L.A., 40 of them from five universities. The other ten are staff of the Rutherford Laboratory and visitors from A.E.R.E. The research has been on the following topics:

- Polarization effects in proton–proton scattering at 30 MeV and 50 MeV
- Polarization in proton–helium nucleus scattering
- Polarization in the scattering of protons by complex nuclei
- Elastic scattering of protons by nuclei
- Study of the reaction $p + d \rightarrow p + p + n$ at 50 MeV
- Shell structure in direct interactions at the nuclear surface
- Neutron energy spectra from elements bombarded by 30 and 50 MeV protons
- Polarization effects in certain nuclear reactions
- Activation studies of proton capture reactions
- Study of (p–d), (p–t), (p–^{3}He), (p–α) reactions at 30 MeV
- Proton nucleus interactions and the optical model of nuclei
- Study of capture gamma rays from nuclei bombarded by protons
- Excitation functions for inelastic proton scattering.

This list is included to illustrate the range of problems which it has been found profitable to attack with the P.L.A. in this short time. The energy range of the machine is a relatively neglected one—it is well above the energy so far obtained with the much more precise electrostatic generator (which has no competitor at lower energies), and has been left out in the race for higher energies for the study of elementary particles. The fields for the P.L.A. are the study of processes involving a few nucleons, the mechanism of nuclear reactions and some aspects of nuclear structure. The machine has very good characteristics of beam quality, intensity and low background which will enable it to provide badly needed data for a considerable time ahead. Its possibilities for postgraduate education are very promising indeed, and several doctorates have already been awarded to students whose theses have been based entirely on its use. It is, in fact, far more useful than was thought when the Institute took it over.

The P.L.A. can be developed much further. It was originally intended to be the first stage of a 'pion factory', in which intense beams of π-mesons would be produced at targets bombarded by protons of 600 MeV or more. Space is being kept free for extension to such energies, although there are no plans for a start on such a major project in the near future. In the meantime, studies are continuing of the problems of radio-frequency accelerating structures for protons in these energy regions. Other accelerator research at the Laboratory has shown that a superconducting P.L.A. is fundamentally feasible, although there would be severe practical problems. Such a machine would limit the radio-frequency power requirements to those of the beam—the I^2R losses in the structure would be negligible. Continuous working would be possible, with very great advantages for the nuclear physicist, and it seems likely that the cost of the cryogenic equipment would be little if any more than that of the modulators which it would replace.

3. NIMROD

Most of the Laboratory's activity has so far been concentrated on the construction of NIMROD. As in all proton synchrotrons, protons are electrically accelerated in a time-varying magnetic field, in stable orbits of constant radius, after injection into the magnet ring at a low energy from a subsidiary accelerator. The original intention was to produce a proton intensity of at least 10^{11} particles per second at 7 GeV, to provide a strong source of all the elementary particles known at the time. The CERN and Brookhaven machines, the first large-scale applications of the alternating gradient focusing system, were then under construction for energies of 25 and 28 GeV respectively. These machines embodied a number of new and difficult problems, and estimates of their probable beam intensities varied from a few times 10^8 to a few times 10^9 protons per second. On the other hand, the biggest machine then operating, the Bevatron at Berkeley, California, was already producing about 10^{10} protons per pulse (every six seconds) and was clearly capable of considerable development along known lines. The Bevatron is a constant-gradient machine, with weak focusing of the beam which consequently needs a large magnet aperture. The large aperture of the weak-focusing machine is costly in magnet steel and power, but gives the advantage that particles can be injected over many orbits, spiralling inwards in a slowly rising magnetic field before acceleration begins. The alternating gradient machine with its very small aperture must use single turn injection (or a very few turns—only one has yet been used). For a given injected current, then, the weak-focusing magnet admits many more protons. The only sure way to get 10^{11} protons per second, in 1957, was with weak focusing. A weak-focusing machine was chosen, and an alternative proposal for a 12 GeV alternating gradient machine was rejected in discussions with the future users. With the knowledge of the time the decision was right. Now, when it has been found that the alternating gradient method is extraordinarily efficient and, in reality, quite simple, and has achieved 10^{11}

protons per second, no one would start to build a weak-focusing machine. NIMROD will be able to receive 10^{14} protons in each injected pulse, thanks to multiple turn injection, but the limit on accelerated intensity, as with all machines, will be set by space charge effects on beam stability. The limit is not accurately known, and has not yet been reached in any proton synchrotron. However, the target intensity of 10^{11} protons per second will certainly be exceeded, probably by a factor of at least 10. In absolute terms and in comparison with other machines NIMROD will be a formidable source of elementary particles.

Injection into the NIMROD magnet ring is from a 15 MeV linear accelerator, the design of which was based on experience with the 50 MeV machine (figure 2). Quadrupole focusing

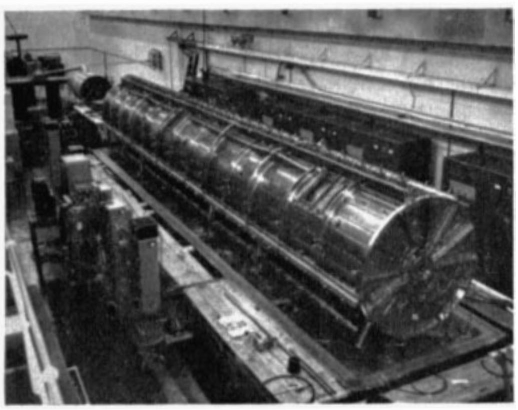

Figure 2. 15 MeV injector for NIMROD, under construction.

magnets are used in all the drift tubes, and there is only one tank. A low frequency, 110 Mc/s, was chosen to ensure that magnets could be placed in the drift tubes in a machine with the long pulses needed by multiturn injection. The 15 MeV proton beam is guided into the magnet ring through an achromatic system of electrostatic and magnetic deflectors, with quadrupole matching and focusing lenses to assist in transferring the maximum proton flux from the linear accelerator into the synchrotron magnet. The cross section of the magnet is of the open C-shaped type, so that no massive obstructions cross the outside of the proton orbits and particle beams may be extracted all around the machine. This is an important practical feature but it complicates magnet design. In particular, the unsymmetrical distribution of flux in the iron yoke changes the field gradient (from saturation effects) during the magnetization cycle. This is a serious nuisance, as the gradient has to be held within very close limits throughout acceleration, to preserve beam stability. The conventional solution is to energize correcting windings, near the pole tips, with programmed currents. This requires high power, and brings the usual cooling problems, unless the peak field is kept uneconomically low, thereby increasing the size and cost of the machine. A different solution was adopted for NIMROD, based on an idea of Bruch at Saclay which, however, came too late to be incorporated in the Saclay proton synchrotron. This is the so-called crenellated pole, in which alternate laminations of the poles are of different shape. The shapes can be arranged so that saturation in the poles produces a change of gradient opposite in sign to that caused by saturation in the yoke. Detailed work with models, finally on full scale, enabled the compensation to be exact, within the permitted tolerances for beam stability. The idea was further exploited to limit the volume of the magnetic field at high fields to that required by the particles. In a synchrotron the oscillations of the particles about their equilibrium orbits are damped at increasing field and kinetic energy, and the beam therefore occupies a smaller part of the magnet gap at high energy than it does at injection. This application of the crenellated poles enables a higher field to be obtained with a given magnet power.

NIMROD has one other unusual technical feature, which gave the greatest difficulty in development. This is the double-skinned vacuum vessel made of laminated reinforced plastics used in each of the eight curved sections of the machine. Epoxy resin, reinforced by woven glass cloth, is used. An outer vessel contains and is supported by the magnet poles, and an inner vessel sits in the gap between the poles (figure 3).

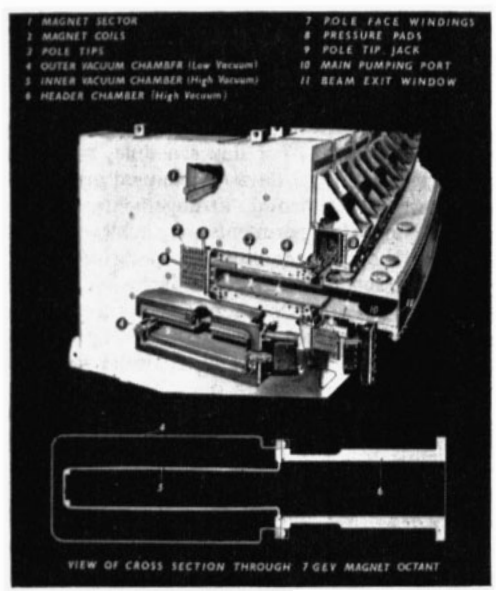

Figure 3. Section through NIMROD magnet.

The space between the vessels is evacuated to a rough vacuum, about 1 torr, and the interior of the inner vessel, which is lined with thin stainless-steel foil, to the working pressure of 1 μtorr. Thus neither vessel has to withstand the atmospheric pressure, and the walls of both can be thin—about a quarter of an inch. An unsupported single vessel would need to be several inches thick, for the 42-inch radial aperture of NIMROD. Solid metal cannot be used, because of eddy current effects. The choice of material is influenced by the conflicting requirements of low vapour pressure and permeability, high mechanical strength and resistance to damage by radiation, and ease of manufacture to close tolerances. Hundreds of samples of different resin formulations were tested before and after irradiation in nuclear reactors. In the material finally chosen, deterioration of mechanical strength begins to occur at a total dose of a few times 10^9 rads. This is expected to represent about a year's running at full intensity for the worst affected parts of the chamber. There are spare vessels, and a repair technique has been developed.

Although the NIMROD magnet is a monster at 7000 tons, the combined effects of the crenellated pole development and the double-walled vacuum vessel may be illustrated by the fact that a direct scale of earlier machines using C-type magnets, to NIMROD gap dimensions would have needed 15000 to 20000 tons of steel. Moreover, the beam intensity would have been lower, because the larger stored magnetic energy would have enforced a lower repetition rate.

The magnet is powered in the normal manner, by motor alternators coupled to the windings through banks of grid controlled converters which rectify during current rise and invert during decay, feeding the stored energy from the magnet back into the rotating machines. Flywheels store the energy mechanically. The system is unusually large, because the stored energy at peak field is 45 megajoules and the repetition rate is 30 pulses per minute. Two alternators, each with a peak rating of 79 MVA and a thermal rating of 46 MVA, are coupled together on one shaft with two flywheels and two 5000 h.p. motors. The machines are three-phase and run at 1000 rev min^{-1}, and are connected through phase-splitting transformers to 96 water-cooled single anode excitrons and thence to the magnet windings.

The protons are accelerated in one of the eight field-free sections of the magnet ring, by a frequency-modulated radio-frequency cavity tuned (by magnetically biased ferrite) to the fourth harmonic of the orbital frequency and fed by a broad-band drive chain from a primary frequency generator. The generator operates initially by converting information derived from the magnetic field and its time rate of change into a computed frequency law, to synchronize the accelerating electric field with the orbital motion sufficiently accurately to maintain phase stability of the beam. When a sufficiently intense beam has been accelerated, the system is switched to phase-lock on the motion of the particles themselves, so that the machine becomes self-synchronizing.

The proton beam may be extracted from the magnet by disturbing the orbits sufficiently to allow the protons to enter a pulsed deflecting magnet thrust hydraulically into a straight section during acceleration. For other experiments beams of secondary particles, produced in collisions of the circulating protons with internal targets, are led from the machine through quadrupole magnetic lenses and through crossed-field separators which separate particles into different momentum groups and different masses.

The machine is enclosed in heavy shielding, for protection from radiation, and the beams enter experimental halls through channels in the shielding walls (figure 4).

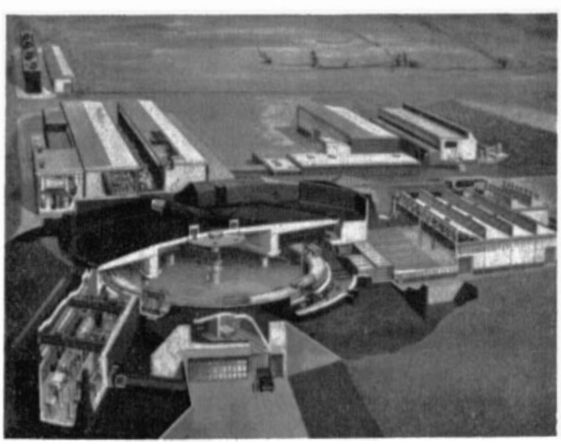

Figure 4. General view of NIMROD.

Construction was started in July 1957, when the first sod was cut on the site. The injector first operated in August 1961, and magnet pulsing began on portions of the magnet early in 1962. By the end of 1962 the complete magnet had been installed and run up to maximum field, and the complicated field survey had been completed with satisfactory results for energies up to 7·5 GeV. Final commissioning of the magnet power supply, including extended overload tests, was finished by April 1963. By this time the radio-frequency system, in its final version, had been commissioned at full power. All the vacuum vessels had been delivered, tested and installed (figure 5)—a process which engaged a large team on leak detection and repairs to the many inevitable minor defects in the laminated plastic material. All major parts of the machine have been installed and tested at the time of writing (June 1963), and the injected beam has been steered through its complicated focusing and deflection system into the magnet ring. Installation of numerous minor details is due to be completed, and the machine closed for overall commissioning, by September 1963. This has been the programme date for the past two years, but is later by over a year than the date laid down at the beginning. There was considerable over-optimism in setting the original date, but substantial delays have occurred on some major components—notably the vacuum vessels and the magnet power supplies. Delays on the vacuum vessels and some other items were largely the result of difficulties which arose during development of very unusual equipment.

Table 2. Principal parameters of NIMROD

Maximum proton energy	7 GeV
Maximum magnetic field	14000 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	7000 tons
Magnet copper weight	250 tons
Useful magnet aperture, width	36 in.
Magnet aperture, height	9 in.
Pulse repetition rate	30 per min max.
Expected intensity	[illegible]·10^{12} protons per pulse
Acceleration system frequency	1·4–8·2 Mc/s
Acceleration time	0·7 sec
Vacuum pumps	40 × 24 in. oil diffusion type
Vacuum pumping speed	200000 l. sec^{-1}
Operating pressure	1 μtorr
Radiation shield thickness:	
overhead	6 ft concrete, 20 ft earth
main shield wall	30 ft reinforced concrete
elsewhere	concrete and earth equivalent to 30 ft concrete or more

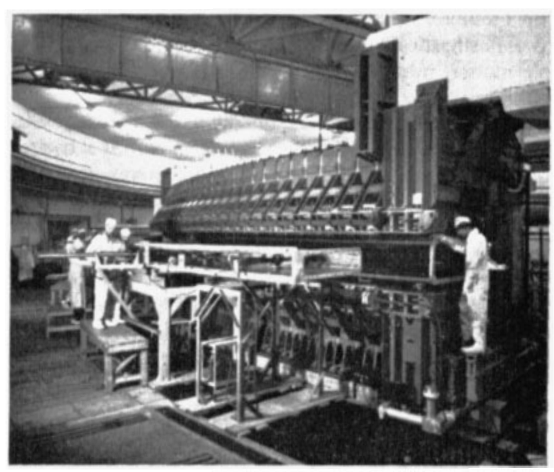

Figure 5. Installation of NIMROD inner vacuum vessel.

4. Experimental apparatus for NIMROD

The hardware required for high energy physics is formidable in cost and complexity, and needs considerable development effort by applied physicists and engineers. Broadly, it can be classified in three groups: beam equipment, particle detection equipment and data reduction equipment. Beam equipment depends upon the same expertise in particle optics and the technology of magnets, high electric fields and high vacua as the accelerator itself, and many of the physicists and engineers of the NIMROD design team have transferred progressively to work on the beams. They have been joined in this by the high energy physicists, because every beam is a part of an experiment. Nearly all the applied physicists are staff of the Institute, but the majority of the high energy physicists are from universities.

Bubble chamber experiments are more demanding of beam equipment than counter experiments because, unlike a counter system, the bubble chamber cannot be triggered by a predetermined type of event and records every ionizing particle which passes through it during its sensitive time. The desired incident particles, say K^- particles in a momentum band of a few per cent width, must therefore be separated from background very efficiently if the pictures are not to be fogged by irrelevant detail. Focused beams are momentum-analysed in bending magnets, velocity-selected in separators using crossed electric and magnetic fields, and refocused. On NIMROD, the standard separators are 10 ft long, with two parallel plates a few inches apart and carrying potentials up to $\pm$ 600 kV with respect to earth. Typically, four would be needed on a K-beam of 1 GeV c^{-1} momentum, for a degree of purity suitable for bubble chambers. There are already ten separator tanks, and large numbers of bending magnets and quadrupole magnetic lenses of 8 in. aperture. Pions are produced more profusely than K particles, and also have longer lifetime and therefore can be allowed longer flight paths. Purification of pion beams is therefore a relatively simple matter, mainly confined to focusing and momentum selection.

There are three large bubble chambers on the programme, all with 4 MW magnets. The 1·5 m British National hydrogen chamber (figures 6 and 7), with a 200 ton magnet, was built by a group drawn from four universities and has been shipped to Geneva, after preliminary operation at the Rutherford Laboratory, for use on the CERN proton synchrotron. It will return in about 18 months, for permanent installation on NIMROD. A heavy liquid chamber, roughly the same size, is being built in a collaboration between University College London and the Rutherford Laboratory. This chamber will be more effective than the hydrogen chamber for studying processes in which electromagnetic radiation is involved, because the materialization of radiation into positron-electron pairs is much more probable in heavy than in light materials, but less effective for studying simple interactions with nucleons. A third large chamber, using liquid helium, is being built in collaboration with Oxford University. The hydrogen and helium chambers incorporate their own refrigerators; they are too big to be economically supplied with liquid transported from external liquefiers. The heavy liquid chamber can use a variety of compounds, and is designed to operate at high pressure but normal temperatures.

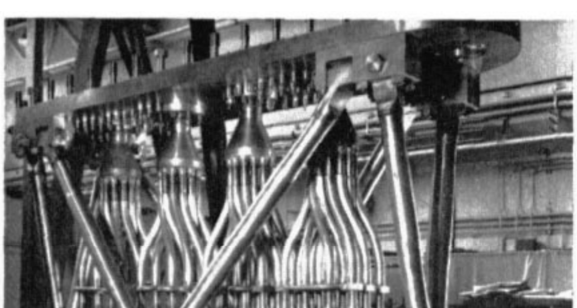

Figure 6. Body of National liquid hydrogen bubble chamber, showing part of expansion system.

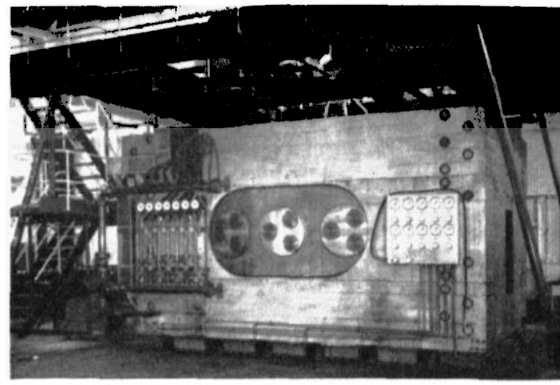

Figure 7. Liquid hydrogen bubble chamber, installed in its magnet.

The events photographed in bubble chambers are the tracks of ionizing particles, curved in the magnetic field and showing branches where collisions have occurred with nuclei in the liquid, resulting in the ejection or creation of other particles. Stereoscopic photography enables the events to be analysed in three dimensions. Observation of the coordinates of the tracks at suitably chosen intervals enables the kinematics of the events to be computed. Corrections have to be made for the inevitable non-uniformity of the magnetic field, possible distortion due to optical effects or turbulence in the liquid, and the effect of scattering and slowing down in the liquid on the curvature of the tracks. Very large numbers of events have to be scanned and suitable candidates analysed in detail in order to extract good statistical data on the elementary particle phenomena under investigation in a particular experiment—10^5 pictures is a typical number. Measuring machines have been developed to speed the extraction of data from the photographs. The output of these machines, on punched cards or tape, is fed to a digital computer; considerable effort has been put into the development of computer programmes for this work. There are seven British university groups, and one in the Rutherford Laboratory, working on the analysis of bubble chamber film, equipped with machines which have been developed by the universities with the help of grants from the Department of Scientific and Industrial Research. Attempts are being made to increase the efficiency of the automation in this work. A machine using a flying-spot scan of the pictures, coupled directly to a fast computer, has been developed in CERN and in U.S. laboratories, and more refined versions are now being built—one at the Rutherford Laboratory in collaboration with CERN. A second British machine of the more advanced type is being developed by colleges of London University and the Rutherford Laboratory.

These machines still need human intervention at a crucial and time-consuming stage—the selection of events by scanners for detailed measurement; also three coordinates must be measured on each track of the selected events before the 'on-line' machine is called into play. To eliminate this, and to increase efficiency still further, a machine is required which can be instructed to recognize track patterns of interest, and then to measure them and compute the data. All ideas so far put forward for this ultimate solution would consume vast computer resources, with present types of computers.

Experiments with counters are designed to select the desired events electronically and to trigger a recording device on the arrival of such an event. Some of the more usual elements in a counting system are: scintillation counters to define a direction, to be part of a time-of-flight selection or to veto a trigger on a charged particle entering a region where the desired event would give none; counters using the Čerenkov effect to define a particle velocity; multiple gap spark chambers in which the location and direction of a charged particle can be accurately recorded on a photograph. The spark chamber has become extremely valuable in high energy physics. It gives less complete information than a bubble chamber, but has the great advantage that it can be triggered. It is also comparatively simple and inexpensive, and can therefore be built for a particular experiment. The paraphernalia of track analysis, mentioned in connection with the bubble chamber, have to be used—but in rather simpler form at least so far as computer programmes are concerned. Work has been under way on counting systems for over a year in the Laboratory and, with N.I.R.N.S. support, in several universities.

The Rutherford Laboratory is equipped with a Ferranti Orion computer for the track analysis work and for reduction of experimental data from counting systems. The Orion has a direct-data channel, enabling it to be coupled directly to the flying-spot measuring machine or other data reduction devices. Some experiments with counters are beginning to be put on-line to a computer, either for selective monitoring of some part of the experiment or for direct reduction of the main experimental data. The Orion is also needed for general computing, for example, to aid the design of accelerators and of particle optical systems, and some of the larger computational problems will undoubtedly overflow on to the Atlas. Many of the universities involved in high energy physics research have computing resources of their own which are called into play but, as is usual in other work also, the expansion of computing facilities never seems to catch up with the needs.

5. Preparation for experiments on NIMROD

Counter experiments are being prepared by seven groups of physicists from nine university physics departments (including four colleges of London University), the Rutherford Laboratory, and the A.E.R.E. Some of the experiments are in an early stage, and in any case could not be run in the first six months of machine operation because of the limitation of running time during early development of the accelerator. But preparations take a long time, and it is necessary to plan well ahead. Preparation of several of the experiments is sufficiently advanced to justify mentioning them here.

High energy scattering of protons by protons (A.E.R.E. and Queen Mary College, London)

This will be a continuation of experiments done last year at CERN, in which the phenomenon of the shrinking diffraction peak was discovered. It is intended to pursue a more detailed investigation, and in particular to examine resonances in the 'near-elastic' scattering.

A low intensity proton beam, defined in position and momentum by bending magnets, scintillation counters and spark chambers, will be incident on a liquid hydrogen target. The forward-scattered protons will be similarly defined.

Polarization in scattering of π^- mesons by protons near 1 GeV c^{-1} momentum (Rutherford Laboratory)

The purpose of the experiment is to determine the parity of the resonance at 1030 MeV c^{-1}. It is hoped to build a target containing polarized protons for this experiment. Asymmetries would be measured in the scattering from this target.

Charge exchange scattering of neutrons by protons (A.E.R.E., Birmingham University and Bristol University)

A neutron beam, produced at a beryllium target placed inside NIMROD, will be incident on a liquid hydrogen target. The full-energy protons ejected from the hydrogen will be detected, and their angular distribution determined, over an angular range 0–6° using a magnetic spectrometer. Present experimental evidence is conflicting. Experiments of this type give information on the role of pions in the neutron–proton interaction.

Accurate determination of the width of the ω^0 resonance (Imperial College, London, and Manchester University)

A beam of K^- particles will be incident on a liquid hydrogen target, producing in some of the collisions a Λ^0 particle and the ω^0 resonance or particle. By measuring the incident momentum with an accuracy to $0 \cdot 1\%$ and the momentum of the Λ^0 particle to 1% it is possible to determine the mass of the ω^0 to a precision of 1 MeV c^{-2}. From a series of such measurements the 'width', or the equivalent lifetime, of the ω^0 state can be determined. The 'instrumental width' can be determined in a calibration experiment using a state of known (and infinitesimal) width. Errors on existing measurements are very much higher; more accurate knowledge is needed on this and other properties of the new resonances.

Bending magnets and spark chambers will be used for accurate momentum measurements.

Differential cross section of elastic scattering of π mesons by protons near 2 GeV (University College and Westfield College, London)

A detailed study of angular distribution near resonances, recently observed, will give information about the spins and parities of the resonances. π mesons will be scattered in a liquid hydrogen target and detected in spark chambers. Counters depending on time-of-flight will reject protons and admit pions, in the incoming beam, in triggering the spark chambers.

Not all these experiments may be run in their present form. Technical difficulties, and results obtained elsewhere, as the subject develops, can cause changes. But all are the first stages of developing programmes, and the beams and particle detection equipment in each case form the basic equipment for such programmes. Apparatus is being prepared in the Laboratory and in the Universities.

Bubble chamber work has already been mentioned. Here, unlike the counter work, the experiment is carried out after operation, on the film. The experimental decision affecting accelerator operation is simply on the nature and energy of particle beams to be admitted into each particular bubble chamber. Beams are being designed, and the university groups are collaborating in this. But all their film is still coming from CERN, and, in some cases, from American laboratories. Bubble chamber operation at the Rutherford Laboratory is expected to start some time in 1964.

It is quite clear already that NIMROD will be fully used by physicists, of whom the majority will be from universities, and that its place in elementary particle research is assured for as far ahead as one can never see in pure research. There is no lack of important problems to suit the characteristics of the machine, and there is no need to tempt physicists to desert other fields in order to staff the research teams; too many physicists, eager and able to work in the subject, are chasing too few machines. In such an expensive field it is better to have too few machines than too many—so long as there are enough to do a reasonable job in an expert and rapidly moving field. There are probably enough in the GeV range in this country for some time to come, and the next development in this field should be international. But it will be important to support the home laboratories properly; the work is rapidly becoming more expensive in men and money as the techniques become more sophisticated. The resources available to universities from their normal income are pitifully inadequate for this type of work, and the N.I.R.N.S. have to provide far more than the accelerators, their operating staff and scientific colleagues to give the Laboratory a suitable intellectual flavour.

Acknowledgments

The construction of the buildings and accelerators and other apparatus at the Rutherford Laboratory has depended on the co-operation of large numbers of British firms and some abroad. They have had to tackle many difficult engineering problems, and they are too munerous to mention individually here, but many are referred to in publications describing particular aspects of the work of the Laboratory. It is a pleasure to acknowledge the help and co-operation of the United Kingdom Atomic Energy Authority, particularly the Atomic Energy Research Establishment, Harwell, the Engineering Group, Risley and Tadley, and the London Office of the Authority.