BRITISH ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

ANNUAL MEETING, 1962 MANCHESTER, 29th August - 5th September.

Section A Date Tuesday, 4th September, 1962 Time: 11.15 a.m.

(Title of paper) NIMROD

(Author) Dr. T. G. Pickavance

Nimrod is a particle accelerator designed to accelerate protons, the nuclei of hydrogen atoms, to a maximum energy of 7000 million electron volts (7 GeV). It is the main equipment of the Rutherford High Energy Laboratory of the National Institute for Research in Nuclear Science. Construction was started in July 1957, and will be completed by August 1963. The N.I.R.N.S. was set up in 1957 with the principal object of providing and operating facilities for fundamental nuclear research, for use by the universities and other bodies in their own research programmes.

It is essential to the idea of a university that teaching and research should be combined in the same community. Among the teachers at university level must be those who are working at the frontiers of knowledge, but special provision must be made in those fields of fundamental research which require very expensive and complicated equipment. Research with high energy particles is particularly expensive, but is of great importance because it is concerned with the ultimate structure of matter. Nimrod will be used by teams of physicists from many universities, and also from the Atomic Energy Authority; small teams will be staffed by physicists of the N.I.R.N.S., but most of the research will be done by the visitors.

Like all other multi-GeV proton accelerators, Nimrod is a proton synchrotron. Hydrogen gas is ionised by an electrical discharge, and the protons produced are accelerated to 15 million volts in a linear accelerator. The focused beam of protons from this subsidiary machine are injected into a magnet ring, 150 feet in diameter and 7000 tons in weight, and are trapped in orbits. On each circulation the protons are electrically accelerated by a few thousand volts until, after a million orbits in less than a second, they have reached an energy of 7000 million volts and a velocity of 0.993 times the velocity of light. The magnetic field strength is increased during acceleration, to keep the protons in the ring, by passing currents through the magnet windings from a 100 megawatt power supply. The current through the magnet is reduced to zero, also in less than a second, and the whole process repeated 30 times a minute. The protons have to move in a vacuum and to be accurately focused to avoid excessive loss of beam intensity.

The proton beam strikes a target in the machine, and ejects the many kinds of elementary particles in collisions with the stationary particles of the target. The elementary particles are separated into their various types, and used to bombard other targets and detection apparatus in which their properties and interactions with each other can be studied in detail. Some of the particle detection apparatus uses electrical methods of identifying and counting the many types of events which have to be studied. In another technique, the bubble chamber, the tracks of the particles in a liquid are photographed and the pictures analysed afterwards with the help of automatic track-following machines and fast electronic computers.

Nimrod will be the biggest machine in Britain. There are several existing or under construction in the U.S.A., one of which at 32 GeV is the biggest operating machine in the world so far. A 28 GeV machine at C.E.R.N., Geneva, is the second biggest in the world. A 70 GeV machine is under construction in the U.S.S.R. All these machines, and others yet to be designed and built, will be needed if we are to unravel the secrets of nature in this fundamental and challenging field of physics. They differ in detail and complement each other, as well as serve scientists in many parts of the world.

Nimrod and a smaller 50 million volt machine, already operating at the Rutherford Laboratory and used by over 50 university physicists, will need the direct services of about 1000 staff for operation, maintenance, and the development and construction of the new research equipment which has to be devised to continue the experimental programme and to aid theoretical studies. Construction is well advanced and many of the most important components have been completed and tested. The design team have been supported by many British and a few foreign industrial firms, who have manufactured the parts to our specifications. A by-product of efforts of this kind is the development of technology which has more immediate application to practical problems; difficult technological problems covering a wide range have to be solved in producing a big accelerator.

The N.I.R.N.S. have had strong support from the United Kingdom Atomic Energy Authority; nearly half of the staff were originally employed by the Authority at A.E.R.E., Harwell.

<u>Biographical note</u>

Dr. T. G. Pickavance has been Director of the Rutherford High Energy Laboratory, N.I.R.N.S., since 1957. Previously he was at the Atomic Energy Research Establishment, Harwell. His special interests are in nuclear and high energy physics. He is a Liverpool graduate, a Fellow of the Physical Society and a member of the American Physical Society. He is 46, married with a daughter and two sons, and enjoys music, photography, and fast cars.

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"Nimrod" is the name we have given to a large particle accelerator which we have been building at the Rutherford High Energy Laboratory, Harwell, since the summer of 1957. The Rutherford Laboratory belongs to the National Institute for Research in Nuclear Science, whose object is to construct and operate the large and costly equipment now needed for fundamental nuclear research, for use by the universities and other bodies in their own research programmes. We have a 50 million volt accelerator, which is already being used by teams from several universities and by our own research staff, but Nimrod is a much bigger machine and will not be ready until the autumn of 1963.

Research with particle accelerators is often loosely described as "nuclear physics", but high energy machines such as Nimrod are used in a different field more correctly described as "elementary particle physics". Particles must be accelerated to energies of the order of a million electron volts (MeV) to break up the nucleus of an atom, and accelerators in the MeV range are used in studies of nuclear structure. To break up the nucleons (protons and neutrons) of which nuclei are composed, and thereby to probe more deeply into the structure of matter, we must use energies in the thousand million electron volt range (GeV). Nimrod will accelerate protons to an energy of 7 GeV; collisions of these protons with nucleons in a target will lead to the production of all the thirty-odd kinds of elementary particles now known. Elementary particle physics is the detailed study of the modes of production of these particles, of their decay for most of them are unstable, and of their interactions with each other, and to try to understand what it all means. This is the central problem of physics today; we can describe the elementary particle phenomena, but we cannot explain them.

Although most of the elementary particles were first discovered in experiments with cosmic rays, which have a maximum energy greatly exceeding that of the biggest accelerators, cosmic rays are far too weak in intensity to provide the prolific sources needed for detailed study. The big accelerators have enabled rapid progress to be made, and have also posed new questions and opened new fields of enquiry. Nearly all of them are in the U.S.A., the U.S.S.R., and Western Europe. The two biggest at present are the 28 and 32 GeV machines at CERN, Geneva, and Brookhaven, U.S.A. A 3 GeV machine at Brookhaven, the Cosmotron, has a counterpart in Saturne, in Paris. Nimrod will fit between the Bevatron, in California, and a new 12 GeV machine under construction near Chicago. The Soviet Union has 7 GeV and 10 GeV machines, and is building a 70 GeV one. There is already talk of 300 and even 1000 GeV, but only in design studies so far.

All the GeV proton accelerators are proton synchrotrons, with minor differences of principle but considerable differences in detail. An electric field accelerates the protons in small steps at one or more points on nearly circular closed orbits, in a vacuum chamber between the poles of a magnet ring. The strength of the magnetic field is increased gradually during the acceleration, to keep the orbits in the ring. An injector outside the magnet ring gives a preliminary acceleration, in order to begin the main acceleration process at a practicable value of the magnetic field. The attainable value of the magnetic field and the diameter of the magnet ring determine the upper limit of energy. As with all accelerators, and also nuclear reactors, shielding has to be provided to protect the laboratory staff and the public from the harmful effects of radiation, and the machine and much of the experimental equipment have to be remotely controlled.

Having sketched the background of my subject, I can now describe the more important features of Nimrod, following the path of the protons as they are accelerated. The protons are produced in an ion source, by an electrical discharge through hydrogen gas at a low pressure, and are then accelerated along an evacuated, insulating tube by a high voltage of 600,000 volts applied between metal electrodes in the tube. Focusing devices ensure that the 600 KeV protons so produced emerge in a narrow beam. This ion gun is the same in principle as the first accelerator, built by Cockcroft and Walton 30 years ago. The beam is further accelerated to 15 MeV by the injector proper, a proton linear accelerator the main part of which is a cylindrical copper tank, 45 feet long and 5 feet in diameter. The tank is coupled to a high power radiofrequency generator operating at 110 megacycles per second, in the same frequency band as the B.B.C.'s V.H.F. broadcasting service, and is tuned so that an oscillating electric field is developed along the axis to accelerate the protons. The protons travel only a few inches during one cycle of the oscillations, and are shielded from the electric field during those times when the field has the wrong direction by a series of metal drift tubes suitably spaced out along the axis and surrounding the protons. Acceleration therefore takes place in the gaps between the drift tubes. Each drift tube contains a four-pole magnet to keep the beam in focus - otherwise all the particles would be lost to the walls. The highest standards of precision engineering are required in these components. The accelerating tank is contained in a steel vessel which is continuously evacuated to a pressure of 10^{-6} mm of mercury. Although the accelerating system is constructed of high conductivity copper, and losses have been minimised by careful design, a power of 1 megawatt is required to produce the necessary acceleration. The power source is therefore pulsed, at a rate to match the operating cycle of the Nimrod magnet, to conserve power and to avoid overheating. Nevertheless, the accelerating system has to be water-cooled. The injector has been operating satisfactorily for about a year.

The 15 MeV beam is transported into the gap of the Nimrod magnet with the help of focusing and deflecting magnets and electrodes. The magnet ring has a diameter of 150 feet and contains 7000 tons of special steel, built of insulated laminations like a transformer to reduce eddy-current effects as the magnetic field increases during acceleration. The space in the magnet gap available for particles is 36 inches radially and 9 inches vertically, and in order to ensure that the particles are focused into this space the pole pieces of the magnet had to be very accurately made to a specification developed in a long series of experiments. Very close quality control, and mixing of individual pieces of steel to smooth out unavoidable variations, were required throughout manufacture of the magnet components in industry and assembly at the Laboratory; errors outside the tolerances laid down by the design team would cause disastrous loss of particles. To relax the tolerances appreciably, and thereby to ease the problems, would demand uneconomical amounts of steel and magnet power and would also worsen the problems of structural engineering. I should mention at this point that Nimrod has a so-called "weak focusing" magnet; the 28 GeV machine at CERN has a "strong-focusing" magnet which required similar standards of precision but uses a much smaller magnet gap and thereby saves steel. This saving is economically essential for such a large machine, but the bigger gap of Nimrod gives the possibility of a higher beam intensity.

The Nimrod magnet is energised by an electric current flowing through water-cooled copper windings around its poles, and for convenience in this respect, and also to provide space to inject, accelerate, and extract the protons, we divided the magnet into eight sectors separated by straight sections. The magnet power supply is very large. Two motor-driven alternators, with a combined rating of 100 megawatts, feed the magnet windings through transformers and a network of 96 high-power rectifiers. During acceleration, the current through the windings and the magnetic field rise at a rate determined by the applied voltage and the inductance and resistance of the magnet. We arranged that acceleration to full energy takes 0.7 second, and is repeated 30 times per minute. At the end of acceleration the magnetic field has to be reduced to zero, and over 80% of the energy stored in the magnet is returned to the power supply to avoid excessive power consumption. This is achieved by electronically switching the rectifiers so that they reverse the magnet voltage. Two heavy flywheels are coupled to the motor-alternators to store energy; they slow down during the rise of magnet current, and speed up again as the energy is returned from the magnet. The magnet and power supply are complete, and have been successfully tested and adjusted in stages, except for one alternator which was delayed.

The vacuum vessel, in which the protons circulate, is intimately connected with the magnet. It has been the most difficult of all the many problems which we have had to tackle. The functional requirements are depressingly conflicting. The vessel has to withstand the atmospheric pressure of 15 lbs per square inch over an area of 4 feet by 55 feet, to consume as little of the costly magnet gap as possible, to be an insulator to avoid field distortion by eddy currents in the changing magnetic field, to resist damage from bombardment by stray particles, to be proof against air leaks, to have a very low evolution of gas and vapour, and to be capable of manufacture to close dimensional tolerances. We embarked on a programme of research and development, because no established and readily available material or technique was suitable for our needs, and finally adopted a double-walled chamber made of resin-bonded glass cloth. An outer vessel, made of material about $\frac{1}{4}$ inch thick, is fitted between the pole pieces and the remainder of the magnet, and is supported against atmospheric pressure by the pole pieces. An inner vessel, also about $\frac{1}{4}$-inch thick, sits between the pole pieces and contains the particles. Rough vacuum pumps reduce the pressure in the space between the vessels, occupied by the pole pieces, to about 1 mm mercury, thereby removing almost all the atmospheric load from the inner vessel which therefore supports only its own weight. A third vessel of much thicker material, external to the magnet, connects the inner vessel to 40 high vacuum pumps (5 per octant); this vessel and the inner vessel are evacuated to a pressure of 10^{-6} mm mercury, and are lined with very thin stainless steel foil to improve their vacuum properties. The 8 straight sections, between the magnet octants, are bridged by steel vacuum boxes.

The severe difficulties of the vacuum vessels in development and manufacture took longer to overcome than was allowed in the original programme, drawn up in 1957. This has been the main cause of the delayed completion date of Nimrod; however, there were also delays on the alternators for the magnet power supply which were only just contained by the vacuum vessel delays. All the difficulties of vacuum vessel production have now been overcome; most of the vessels have been delivered and the remainder are flowing satisfactorily through the factory.

The accelerating system of Nimrod is a radiofrequency apparatus giving an average accelerating voltage of about 7000 volts on each orbital revolution of the protons; there are therefore about a million orbits in the acceleration to full energy. The oscillation frequency of this system has to be tuned very accurately to the changing orbital rate of the protons as they gain energy and speed; it is controlled by the motion of the protons themselves. All the equipment has been built and tested outside the machine, and is now being installed.

The design of the main Nimrod buildings is dominated by the needs for stable magnet foundations, because small movements of one part of the magnet relative to the rest can cause severe loss of particles, and for heavy radiation shielding. The foundation is a reinforced concrete cellular structure, 15 feet thick and 200 feet in diameter, resting on the chalk subsoil of the Berkshire Downs. This great thickness is necessary because the hard chalk is not homogeneous, but is in layers interleaved by soft material. Appreciable settlement was predicted and has occurred, but the civil engineering design was based on uniform loading of the subsoil to ensure uniform settlement. This has been successful. The building has a concrete roof about 6 feet thick and surmounted with 20 feet of earth; earth is mounded to greater thickness around the sides except for one section, about 200 feet in length, where a massive 30 feet thick concrete wall has been constructed. The lower portion of this wall is composed of removable 25-ton blocks of concrete, through holes in which beams of particles may be admitted into the experimental halls. There are two experimental halls and space for

the experimental halls. There are two experimental halls and space(?) for third if it should be required, with heavy concrete floors and several 30 ton cranes to handle the experimental apparatus which will be used to separate and transport the particles and detect the high energy events under study in the research programme.

The remaining buildings are fairly conventional, and consist of power houses, plant rooms, workshops, laboratories and offices. Most have been completed. Operational trials of the complete machine are due to start in September 1963, and if all goes well we should be able to begin serious research a few months later. We can test and adjust individual parts of the machine as they are installed, and have already done a great deal of this work.

The auxiliary equipment is no less complicated than the accelerator itself, and has to be continuously developed, adapted and redeployed to suit the changing needs of the research programme. A typical experiment in elementary particle physics, which I can outline as an illustration, might be to study the collisions between negative K-particles and protons. The negative K-particles, which are intimately concerned with nuclear binding forces, can only be produced in bombardment of a target in the accelerator by the high energy proton beam; they carry a negative electric charge and are unstable, with very short lifetime. Any serious experiment would have to use K-particles at a fixed energy, because the characteristics of the events under investigation vary with energy. Moreover, the K-particles are produced at the target in company with many other kinds of particles, some positive, some negative, and some uncharged. These mixed particles are emitted over a range of angles and with a range of energies. The first problem, therefore, is to focus and separate the wanted from the unwanted particles, and this is done with the help of deflecting magnets, focusing magnets, and separators using crossed electric and magnetic fields. With high energy particles such as Nimrod will produce, beam separation and transport is very difficult and demands complicated and expensive apparatus which has to be developed specially for the job. Several beam lines, for different particles or different energies, will be set up simultaneously in the experimental halls because they take a long time to adapt and change.

In my example, the beam of negative K-particles produced in this way will then bombard a target containing protons, and equipment will be needed to detect and trace out the events occuring in collisions with the target protons. Such events will include the creation and subsequent decay of other particles, and it will be necessary to identify and count the product particles, to measure their energies and directions of emission, and, of course, to search for hitherto undiscovered phenomena. Protons are contained in the atomic nuclei of all matter, and therefore in principle any material may be used as a target. However, all substances except hydrogen contain neutrons as well as protons, and the neutrons confuse the events when we wish to isolate interactions with protons. Hydrogen is therefore the best target material with which to study interactions with protons, but it has to be used in liquid form in order to get as high a density of protons as possible.

One of the most powerful and elegant detection techniques is the liquid hydrogen bubble chamber, which acts as its own target. A tank contains liquid hydrogen raised just above its boiling point by a sudden expansion. When a charged particle passes through the liquid it creates pairs of ions in collision with hydrogen molecules. The ions form centres on which boiling begins, and a row of bubbles marks out the track of the ionising particle. A light flash and a camera enable the tracks to be photographed. Before boiling becomes general, the liquid is compressed and brought below its boiling point ready for the next picture. The chamber is fitted into a magnet, and the magnetic field curves the tracks of the charged particles and enables their momenta to be determined. Examination of the pictures, to extract the required data, is a tedious business which in the early days was done manually by research students and technicians. This is far too slow to match the great output of high energy accelerators and automatic track-following machines have been developed, and are used with fast electronic computers to calculate the data.

A group of physicists and engineers from several British universities have designed and built a large liquid hydrogen bubble chamber, for use initially at CERN and later on Nimrod, and we have built the auxiliary services for this chamber in collaboration with the university group. The chamber is 1.5 metres long, has its own hydrogen liquefier, and has a magnet weighing over 200 tons. Other liquids are also used, for different types of experiments, and we are building a heavy liquid chamber and a liquid helium chamber in collaboration with University College, London, and Oxford University. Automatic and manual track analysing machines have been developed by a team at Imperial College, London, and eight sets are being manufactured for use by seven university groups and the Rutherford Laboratory. In this way the experimental data can be studied in the universities, remote from the accelerator.

I have mentioned the bubble chamber as an example of the experimental techniques. In other techniques we identify events with the help of arrays of detectors which produce electrical pulses, and count them with electronics apparatus. The processing and analysis of the experimental data depend increasingly on fast digital computers, and a Ferranti Orion computer is being manufactured for the Rutherford Laboratory. Probably over half of the time of this computer will be used on data analysis for bubble chamber and counter experiments, and the remainder on theoretical studies, for example of elementary particle processes and the motion of particles in the accelerator and beam systems.

The components of Nimrod and its auxiliary apparatus have been manufactured to our specifications by a large number of firms in British industry and several foreign firms. Many difficult technological and engineering problems have to be overcome in producing a large accelerator. A by-product of efforts of this kind is the development of technology which has more immediate application to practical problems.

We now have a staff of just under 800 at the Rutherford Laboratory, of whom about 120 are physicists and engineers. Towards the end of next year, when Nimrod is expected to be operating, the total staff will have risen to about 900 and many will have transferred from construction and development to operation and research use of the machine. Just over 100 are directly engaged on the smaller accelerator, which is already serving about 50 university staff, fellows, and research students, 5 or 6 similarly qualified nuclear physicists on our own staff and a group from the A.E.R.E. The numbers basing their research on Nimrod will not be proportionately higher but will be of the order of 150, because at the higher energy the accelerator and the techniques are much more complicated. A bigger relative effort is therefore needed on the associated applied physics research, and the engineering and technological services. Eleven university physics departments are already using or preparing to use the facilities of the Rutherford Laboratory; most of them have no accelerators of their own. It is essential for universities to combine teaching with research, and we are trying to help them to do this in a very important and challenging field of fundamental study from which they must not be excluded but in which the apparatus is, of necessity, inconveniently complicated and costly.