NUCLEAR PARTICLE ACCELERATORS

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NUCLEAR PARTICLE ACCELERATORS

1. Introduction

In addressing you this evening, on an occasion devoted to the memory of Walther Bothe, I have chosen a subject, nuclear particle accelerators, which, although necessary for research into the fundamental structure of matter, is only a means to this end.

Nuclear particle accelerators started from very humble origins as instruments which could conveniently be placed on an ordinary laboratory bench and were built by the physicists carrying out the research as a part-time activity. Just recently we have embarked at CERN on a proton accelerator which is 2.2 km in diameter and is being built by an expert team of scientists who will not, in general, engage in the research which this accelerator will make possible. Whereas 40 years ago an accelerator could be built for a few thousand D.M. in a university laboratory, the most recent machines cost many hundreds of millions of D.M. and require national and international laboratories to be established for their construction and operation.

All this has happened over a period of about 40 years, much of it during the life time of the man whose memory we are celebrating today, and in thinking about Walther Bothe and his work one cannot help but remark the very great changes which have taken place in experimental apparatus, in research method and style and in the organization of research, all of which have resulted from the development of the giant nuclear particle accelerators.

The first accelerators were built and used for nuclear research in the early 1930s. Before that time only natural sources of nuclear particles were available; the naturally radioactive elements and the cosmic rays. Rutherford in his research work in 1919, which led to the discovery of the atomic nucleus, used alpha particles from radium or thorium sources. It is worth noting that the energy of the alpha particles released from such sources is between 5 and 8 MeV, and it was not until about 1935, that is 16 years later, that particle accelerators could reach these energies.

Thus the first particle accelerators were developed with the aim of replacing the natural radioactive sources by machines which could produce beams of particles, more powerful, better collimated and of similar or higher energies. The research which could be done with such machines was already tentatively explored using the natural radioactive sources, and this theme of early exploration with natural sources followed by detailed studies using particle accelerators runs throughout the whole history of this research.

Cecil Powell in his Walther Bothe memorial lecture in 1969 spoke about the nature of the primary cosmic radiation and traced the course of this research from the observation by Coulomb in 1785 that the electric charge on a metal sphere suspended by a long silk thread slowly leaks away, to the demonstration by Bothe and Köhler in 1929 that part of this leakage was caused by penetrating material particles coming from outer space. As Powell described, these cosmic rays provided the nuclear physicist with a weak but very high energy source of particles for the experimental study of nuclear reactions.

Thus, even before particle accelerators had been developed sufficiently to replace the natural radioactive sources another much more formidable challenge was presented to the accelerator builders - to replace the cosmic rays by man-made machines - and from about the 1940s onwards it has been this challenge which, amongst other things, has inspired accelerator development. As I shall describe later, it is only in recent years that the accelerator builders have seen a way of producing in the laboratory nuclear events comparable in reaction energy to those produced by the incoming cosmic rays.

To round off this introduction to my subject I should perhaps add that not all physicists have welcomed the success of accelerator development. There were certain cosmic-ray physicists who found a real physical and mental satisfaction in working in laboratories untop of the highest mountains and in constructing and launching large balloons. Curiously enough the mountains and launching sites always seemed to be selected in very pleasant parts of Europe. Cecil Powell himself used deliberately to annoy the accelerator users in his lectures by producing from his pocket a small tin box of photographic plates and explained, with becoming modesty, that this was all he needed as experimental apparatus - the rest was supplied by nature and could be obtained by a healthy climb up a high mountain. Of course, he was only teasing. Nobody was stronger or more active than he in supporting the building of accelerator laboratories in Europe when it became clear that these were necessary for the continuation of the research. Nevertheless, the giant particle accelerators and their huge laboratories have altered the style of nuclear particle physics research beyond all recognition and a certain wistfulness for the early days is perhaps appropriate on an occasion like this.

2. The early accelerators

Early ideas of machines to accelerate nuclear particles all took the form of a high voltage source coupled to a long evacuate tube made of an insulating material with the particle source at the high voltage end and the target to be bombarded at

the zero potential end. The diversity in these early machines lay in the various types high-voltage sources employed and in the ways of making and evacuating the accelerating tubes.

Around the year 1900, just after the discovery of X-rays by Röntgen, which in many ways can be regarded as the beginning of modern physics, the most popular high voltage source was the induction coil, generally known as the Ruhmkorff coil, which was capable of producing a few hundred thousand volts. It consisted of a core of straight iron wires wound with a few layers of thick insulated wire, called the primary coil, on top of which were wound thousands of turns of fine insulated wire to make a secondary coil. An automatic switch made and broke the current in the primary and hence induced a high potential across the secondary. The accelerating tube in those days was usually made of glass, for example the Röntgen or X-ray tubes, and the air from this tube was evacuated either by Sprengel or Toepler mercury pumps and, later on, by the Geryk cylinder pump. Electric currents were supplied by galvanic cells or by accumulators.

An advertisement in 1897 by an English firm for this sort of equipment is shown in the first slide. Some idea of the attitude of experimentators towards their equipment can be learned from a leading article in a scientific journal of 1898 which said: "The possessor of a good induction coil made by our leading instrument-maker should cherish it as a violin player cherishes his Stradivarius". I am afraid modern research physicists have no such tender feelings towards their apparatus but regard the giant accelerators more as something to exploit than to cherish.

The induction coil gave pulses of high voltage at the frequency of the make and break contact but there also existed machines giving continuous high voltage. These were the separation of charge machines, called the Toepler-Holtz or Wimshurst machines, invented between 1870 and 1890. Such machines, whose operation, by the way, is quite complicated, used counter rotating discs 40-50 cm in diameter and could develop about 100 kV and deliver currents of several milliamperes.

Both the induction coil and the separation of charge machines were developed in the early 1930s to act as high-voltage sources for nuclear experiments. For example, a variant of the induction coil, called the Tesla coil, was developed in 1930 to give about 1 MV and a Holtz type generator built by Dahl in 1935 gave a current of 10 mA at 200 kV. The Wimshurst machine has been subject to quite recent development in the form of dielectric cylinders rotating in a hydrogen atmosphere by the French firm of SAMES who now produce very reliable machines giving d.c. currents of a few milliamperes at voltages between 50 kV and 1 MV. These machines are often used to preaccelerate protons for injection into the most modern and largest nuclear particle accelerators.

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Figure 1: Advertisement in 1897 for apparatus suitable for X-ray photography. The type of X-ray tube then in use is illustrated together with mention of induction coils and batteries or accumulators to supply electric currents.

Another important offspring of the separation of charge machines was the modern electrostatic generator, using an endless belt to transfer the electric charge, whose development was started in 1930 by Van de Graaff. The voltage of the first machine built was about 1 MV. Two recent machines of this type, one at MIT and the other at Los Alamos, have achieved 9 and 8 MV respectively and tandem versions of these electrostatic generators operate at about 20 MeV effectively, by using the applied voltage twice.

The other early types of high-voltage generators aimed at the multiplication of voltage in stages to reach higher voltage levels. For example, the surge generators using the "Marx" circuit store electrical energy in capacitors charged in parallel and then discharge this energy by means of spark gaps which connected the capacitors in series. One of the highest voltage surge generators was built by General Electric at Pittsfield in 1932 and produced surges of over 6 MV. The pulse duration of these machines is, however, only a few microseconds, during which time they are capable of delivering currents of the order of 1000 A.

Many other ingenious circuits were invented and built to achieve voltage multiplication such as the cascade transformer machines and the transformer rectifiers but the most well-known system, which by common consent is usually regarded as the first nuclear particle accelerator used for research, was the voltage multiplier built by Cockcroft and Walton at Cambridge University in 1932 and used by them in a series of experimental studies of nuclear reactions.

A historic photograph of this machine is shown in slide 2, in which the young Cockcroft can be seen adjusting something. Incidentally, about 10,000 DM was spent building this machine. The first machine gave about 500 kV but later on Cockcroft and Walton installed a 1.25 MV voltage multiplier which was engineered and built by the Philips Company at Eindhoven. This firm became specialized in the construction of these machines and many of the largest particle accelerators now operating in the world use Philips machines of about 500 kV potential as preaccelerators in their injection systems.

All the early accelerators, whatever type of voltage source they used, involved the development of evacuated accelerating tubes and this development raised a number of technical problems which were very difficult to solve in those days. Very early on it was realized that the accelerating tube had to be divided into sections in order to withstand the high voltages without electrical breakdown. Each section consisted of an insulating cylinder, usually glass or porcelain, and a hollow metal electrode through which the particle beam could pass. Thus, the voltage was divided down the length of the accelerating tube and by carefully shaping the metal electrodes the beam of particles could be focussed electrostatically during acceleration. Cockcroft and Walton, for example, used glass cylinders made for the petrol pumps common in those days and stuck these to the metal electrodes with plasticene. Later on techniques became more sophisticated as glass-to-metal seals were developed and oil and mercury diffusion pumps became available. Electrical breakdown, which originally occurred inside the accelerating tube due to poor vacuum and contamination was transferred to the outside of the tube and in place of air outside, it became common to use various gases, such as freon or sulphur hexafluoride at relatively high pressures.

But despite all the technological improvements it became clear even in the 1930s that the way to higher particle energies was unlikely to be through the development of higher voltage sources and longer accelerator tubes, and indeed this has proved to be the case. Such devices can accelerate particles to a few tens of MeV but for higher energies entirely different machines proved far more effective.

Figure 2: Photograph of the voltage multiplier set built by Cockcroft and Walton in 1932 at Cambridge University.

3. The resonant accelerators

At the time that Cockcroft and Walton were building their accelerator in Cambridge, England, Ernest Lawrence at the University of California was developing an entirely new principle of accelerating particles - the principle of resonant acceleration - and building a new type of machine which he called the cyclotron incorporating this principle.

Lawrence proposed the cyclotron principle in 1930 having conceived the idea in the summer of 1929 while looking through a paper which Wideröe had published in 1928 in the Archiv für Elektrotechnik. The idea was simply to circulate the particles round and round in a magnetic field so that on each revolution they could be accelerated by an electric field set up at two points on their circumference. Thus the same electric field would be used over and over again as the particles gained energy and the difficulties of high-voltage breakdown in accelerator tubes would be avoided.

Starting from a source at the centre of a magnetic field, particles in a cyclotron steadily gain energy on each revolution as they traversed the electric field and as they gained energy they spiral out in radius. At each turn of the spiral the radius of curvature of the charged particle is such that its centrifugal force exactly balances the magnetic force. The important point about the cyclotron is that, in a time-constant magnetic field, the frequency of revolution of the particle is constant, independent of the energy of the particle, so long as the particle mass remains constant.

The magnetic field for a cyclotron is provided by a large DC magnet with circular poles and a gap between them in which the charged particles circulate. An ion source is mounted at the centre of the cylindrical magnetic field and the electric accelerating field is established tangential to the particle orbits by hollow electrodes, called Dees. The particles cross the electric field twice per revolution and, since at each crossing the electric field must be in the correct direction to accelerate the particles, an alternating electric field is required. It works out that for protons the frequency of the electric field for a magnetic field of 13 kG is about 20 MHz. Thus a high frequency alternating electric field is required for acceleration in a cyclotron.

Since the particles circulate many hundreds of revolutions in these machines the beam of particles must be focused during their acceleration either by shaping the electric field or the magnetic field. In the latter case, which is the most usual, a slight gradient of the magnetic field gives the required focusing forces and it is customary to shim the magnetic field guiding the particles round their circular orbits so that the field decreases slightly from a maximum value at the centre

of the magnet to a value a few percent lower at the periphery of the pole tips. The curvature of the field lines due to this negative field gradient gives radial field components which return the circulating particles to the median plane of the magnetic field.

One of the early cyclotrons built by Lawrence and Livingston in 1931-32 is shown in slide 3, and its vacuum tank and accelerating electrode is shown in slide 4.

Figure 3: Photograph of one of the first cyclotrons built by Lawrence and Livingston in 1931. The electromagnet of the machine is in the background and the type of electrical equipment then used is illustrated.

Figure 4: Photograph of the vacuum tank and accelerating electrode of the cyclotron shown in Figure 3. Vacuum tightness depended on the use of wax. The beam ejection electrode is on the left and the accelerating electrode (called the 'Dee') is on the right of the photograph.

Cyclotrons of ever increasing size and particle energy were developed and built during the years 1932 up to the outbreak of the Second World War and what is now called the Lawrence Radiation Laboratory at the University of California, Berkeley, was the principal centre of this work. The team of physicists at Berkeley, led by the dynamic Ernest Lawrence, became world famous and a new breed of physicists - the accelerator physicists - evolved. A photograph of this team, taken in 1938, sitting inside

the magnet frame of the 60" cyclotron, is shown in slide 5. Several young men who became famous in accelerator building and in other branches of physics as well as nuclear physics can be noted.

Figure 5: Photograph of the team of physicists and engineers at the Berkeley Laboratory, California, taken in 1938. They are grouped inside the magnet yoke of the 60" cyclotron. Lawrence is seated in the middle of the first row. Other notables are Serber (second from left in front row), Alvarez (second from right in front row), McMillan (fourth from left, second row), Oppenheimer, Brobeck and Wilson (fifth, sixth and seventh from left back row).

By 1937 it was recognized that cyclotrons using the resonance principle were limited in the maximum energy to which they could accelerate particles. This limitation is inherent in the resonance principle and comes about because the mass of an accelerating particle does not remain constant at its rest mass but increases with its energy according to relativity theory. Thus as it gains energy a particle gradually slips in phase relative to the fixed frequency accelerating electric field and finally falls into the negative phase and is decelerated. In other words, above a certain maximum energy, the particle is no longer in resonance with the accelerating field. Several tricks were invented to alleviate this effect including the brute force method of increasing the voltage of the accelerating field to very high values so that a particle would carry out fewer revolutions in the machine and hence remain in resonance to higher energies. This limitation of fixed-frequency cyclotrons finally proved their downfall as the way to very high energies but not before many heroic attempts were made to build larger machines and to develop better technology. The most remarkable attempt was made by Lawrence himself with the 184" cyclotron which was started just before the war at Berkeley but was never completed as a fixed-frequency cyclotron. Fortunately, a new principle was discovered in 1945 which enabled this 184" cyclotron to be modified into a new type of cyclotron and thereafter it assumed a leading role as the highest energy particle accelerator in the world for several years.

4. The synchrocyclotrons

The new principle which opened the way to very high energy particle acceleration was announced almost simultaneously in 1945 by E.E. McMillan at Berkeley and V.V. Veksler in the USSR and is called the principle of phase stability.

The limitation of fixed-frequency cyclotrons, as has been explained, is that the particle's mass increases due to relativistic effects as it gains energy causing it finally to drop out the resonance with the accelerating electric field. Clearly, if the accelerating field could be varied in frequency to keep it in step with the particle rotation frequency, resonance could be extended to almost infinite energies at least for a few particles which consequently would be continuously accelerated. The important question was whether a substantial number of particles would be held together as a group during acceleration or whether the initial bunch of particles would disperse long before it reached high energies. The principle of phase stability showed that if a group or bunch of particles is centered around a certain phase of the accelerating voltage waveform all the particles in the bunch oscillate stably about this equilibrium phase and the whole bunch remains together up to the maximum energy that can be contained in the magnet of the machine.

The modification required to a fixed-frequency cyclotron to make it into this new type of cyclotron, called a synchrocyclotron, are only to the accelerating system. Instead of a fixed-frequency system a variable-frequency system is required. Usually a rotating capacitor is incorporated in the high-frequency circuit to vary its frequency.

Whereas the particle output of the fixed-frequency cyclotrons is continuous in time and modulated only at the frequency of the accelerating electric field (i.e. ~ 20 MHz) the particle output of synchrocyclotrons is pulsed and bunches of particles emerge, again modulated at the frequency of the accelerating field, at a rate of about 100 bunches per second determined by the rotation frequency of the capacitor.

The operation of a synchrocyclotron is briefly as follows. At each rotation of the capacitor a bunch of particles is captured from the source into what is called a phase stable 'bucket', and the bunch is then accelerated to the maximum energy of the machine. Finally the particles are ejected from the machine onto external targets or allowed to hit targets mounted inside the machine. The particles during acceleration perform three motions at very different frequencies. Firstly, they slowly spiral out as they gain energy from the particle source at the centre of the machine to the maximum radius following the equilibrium orbit. Secondly, they oscillate rapidly about the equilibrium orbit due to the focusing forces provided by the radial decrease in the magnetic field at the 'free' or betatron oscillation frequency. Thirdly, they oscillate slowly about the equilibrium orbit radially and about the equilibrium phase angle azimuthally at the phase oscillation or synchrotron frequency.

The largest synchrocyclotrons built and operating are the modified 184" cyclotron at Berkeley giving a proton energy of 720 MeV, the machine at Dubna, near Moscow, giving 680 MeV protons and the machine at CERN, near Geneva, giving 600 MeV protons. The next slide shows the Russian synchrocyclotron. Larger machines could be built and the limitations are not so much in principle as in such practical considerations as the high magnet cost and its large electrical power consumption.

The next step in the evolution of high-energy accelerators clearly had to avoid these excessive costs and power consumptions and the way was found through the development of a new type of accelerator - the synchrotron.

5. The synchrotrons

Synchrotrons differ from cyclotrons in the respect that particle acceleration takes place at constant radius rather than following a spiral path. Since the particle momentum is proportional to the product of the magnetic field and the particle orbit radius, acceleration at constant radius is only possible in a magnetic field

Figure 6: Photograph of the 680 MeV synchrocyclotron at the Dubna Laboratory near Moscow. The size and weight of the magnet can be appreciated from the dimensions of the upper coil and the upper cross-member of the magnet yoke. The smaller cylindrical tank on the left is the radiofrequency coaxial line and contains the rotating condenser for frequency modulation.

which increases with particle energy and therefore with time. Because the particles circulate at constant radius the magnet can now take an annular form and hence, for a given maximum particle energy, it is less massive and much cheaper than the equivalent cyclotron magnet. Thus the synchrotron concept allowed machines to be built for particle energies very much higher than was possible economically using synchrocyclotrons and for the first time particle energies in excess of 1000 MeV or 1 GeV could be envisaged.

The requirement of a magnetic field increasing with time involved a new development in accelerators, namely the need to track the accelerating electric field frequency with the increasing magnetic field so as to preserve during the whole accelerating period a constant radius equilibrium orbit for the particles. Due to practical difficulties in making the magnetic field uniform around the equilibrium orbit at low magnetic fields it was found necessary to start with a field of a few 100 gauss. Consequently, particles have to be injected into a synchrotron at an energy corresponding to the equilibrium radius of the machine and its initial magnetic field and for this purpose another accelerator, called an injector, is required. For the larger proton synchrotrons giving output energies in the range 3 to 10 GeV the injectors used are either electrostatic machines or proton linear accelerators with output energies in the range 4 to 15 MeV. For the first time therefore, accelerators were joined in series and the particles, starting off in an ion source, were handed on from one accelerator to another until they reached their final energy.

Because the magnetic field in a synchrotron must increase with time from a few 100 G to 14 or 16 kG over a period of a few seconds the magnet core can no longer be made of solid blocks of steel as in the cyclotrons but must be constructed of steel laminations glued or welded together to form magnet units which are then arranged around the machine to provide an annular field.

The accelerating electric field in synchrotrons is usually provided by tunable resonant cavities, also distributed around the equilibrium orbit. The vacuum chamber enclosing the equilibrium orbit and mounted in the magnet gap, is also annular and the vacuum pumps, usually oil diffusion pumps, are distributed around the circumference of the machine.

The principle of phase stability used in synchrocyclotrons is equally necessary in synchrotrons. Also, as in cyclotrons and synchrocyclotrons, the particle bunches are held together in the vertical and horizontal planes as they circulate round the machine by focusing forces provided by the curvature of the magnetic field lines. The particles during their acceleration in a synchrotron, therefore, circulate round the machine at constant equilibrium orbit radius and oscillate about this equilibrium orbit in phase and energy in synchrotron oscillations and horizontally and vertically in betatron oscillations.

Amongst the largest machines of this type built for accelerating protons are the 3 GeV Cosmotron at Brookhaven National Laboratory completed in 1952, the 6 GeV Bevatron at Berkeley, completed in 1954, and the 10 GeV Synchrophasotron at Dubna near Moscow, completed in 1957. In Western Europe, the largest proton synchrotrons are the 2.5 GeV Saturne machine at Saclay, completed in 1958, and the 7 GeV Nimrod machine at

the Rutherford Laboratory near Oxford, completed in 1962. Slide 7 is a view of the Berkeley machine.

Higher energy synchrotrons than these were designed during the early 1950s, but economic problems arose due to the weight and cost of even annular magnets and the way to higher energies seemed once again blocked.

In 1952, however, a new principle was announced by Courant, Livingston and Snyder at Brookhaven for focusing the particles as they circulate round a synchrotron. This offered a way of reducing their amplitudes of oscillation about the equilibrium orbit so that once again the cross section dimensions of the magnet and hence its cost and power consumption could be reduced.

Figure 7: Photograph of the Berkeley Bevatron (6 GeV proton synchrotron). The annular magnet is most evident and its scale is given by the man standing on the right at the bottom of the photograph.

6. The alternating-gradient synchrotrons

In both the cyclotrons and the synchrotrons the focusing of the accelerating beam of particles around the equilibrium orbit is achieved, as I have mentioned, by shaping the magnetic field lines so that the magnetic field all round the machine has a negative field gradient. Synchrotrons with this kind of focusing are often referred to as constant-gradient synchrotrons. The new idea for focusing was to using a magnetic field gradient which is alternatively positive and negative round the circumference of the machine. Large synchrotron magnets as I have said are usually composed of several magnet units placed round the circumference of the machine to form the required annular magnet. According to the alternating gradient idea there would be hundreds of such magnet units whose gradient would be positive and negative in successive units. Thus a beam of particles circulating round such a machine would be focused and defocused in alternate units and the theory showed that the overall effect on the particles could be arranged to be focusing. Indeed, the focusing forces work out to be very much stronger with alternating-gradient magnets than with constant-gradient magnets and consequently the amplitudes of both the betatron oscillations and the radial amplitudes of the synchrotron oscillations turned out to be very much smaller.

The first proton synchrotron to be completed using this new focusing principle was the 28 GeV machine at CERN which first operated in 1959. It was closely followed by the 33 GeV proton synchrotron at Brookhaven which came into operation in 1960. Some idea of the economic advantage of using alternating-gradient focusing can be seen from comparing the weight of the magnets of the two types of synchrotrons. The steel core of the Bevatron magnets weigh roughly 10,000 tons and that of the Russian synchrophasotron, 35,000 tons. Both these are constant-gradient machines. On the other hand, the magnet core of the CERN machine weighs 3,400 tons and that of the Brookhaven machine 4,000 tons. Since the CERN and Brookhaven machines give much higher proton energies than the Berkeley and Dubna machines the comparison is most striking if units of magnet core weight per GeV are used. In these units, the CERN and Brookhaven synchrotrons work out at 120 tons/GeV as against the 1500 tons/GeV of the Bevatron and the 3500 tons/GeV of the Russian machine. Thus the alternating-gradient idea gave reduction factors of 10 to 30 in tons/GeV of magnet steel over the constant gradient machines and a reduction of about 4 in total machine costs. The next slide of the CERN machine shows the relatively small cross section dimensions of the magnetic units.

However, these dramatic economic advantages were offset by certain technical problems. For example, the relatively small radial amplitudes of energy oscillation in alternating-gradient synchrotron produced a new phenomenon hitherto not encounter-

ed in other accelerators, namely a critical energy during the acceleration process, called the Transition Energy. The reason this comes about is as follows. The principle of phase stability requires that a particle with more or less energy than the equilibrium particle adjusts its phase relative to the equilibrium phase such that if it has excess energy it picks up less energy per revolution or if it lacks energy it picks up more energy per revolution. The direction in which a particle moves in phase depends

Figure 8: Photograph of part of the CERN 28 GeV proton synchrotron. The cross section dimensions of the annular magnet are much reduced compared with the Bevatron shown in Figure 7 due to using alternating-gradient focusing.

on two competing factors. If it has energy in excess of the equilibrium energy its velocity is greater than that of the equilibrium particle which causes it to gain in phase over the equilibrium particle. However, because of its excess energy, it follows an orbit of greater radius than the equilibrium orbit radius, takes longer to complete a revolution and therefore falls back in phase relative to the equilibrium particle. These two factors - the velocity factor and the radius factor - act in opposite directions. At the beginning of acceleration in an alternating-gradient synchrotron the velocity factor predominates and hence determines the stable phase angle of the bunch of particles. As the bunch of particles gain energy, the effect of the velocity factor decreases as the particle's velocity approaches that of light, and at the Transition Energy, the velocity and radius factors just cancel out. There is then no phase stability. After Transition Energy the radius factor predominates and phase stability is restored but with the stable phase angle on the other side of the accelerating field waveform. It is therefore necessary to introduce a phase jump of about 60° at Transition Energy and the great unknown when the CERN 28 GeV machine was being designed and built was whether the bunch of particles would remain together during the passage through Transition Energy when phase stability was lost. The problem is rather analogous to a man running along with a cup in his hand containing hundreds of small balls. At a certain moment he must remove the cup quickly leaving the balls in the air and then put it back again so that none of the balls are lost. Fortunately, the problem was eventually solved and no loss of particles occurred in practice but these worries resulted in many sleepless nights for the accelerator builders. The solution to this problem was greatly helped by the use of what is called a phase-lock system, invented by Ch. Schmeltzer, now at Heidelberg, who was then in charge of this work at CERN. In a phase-lock system, which, incidentally, was the first use of a cybernetic system in accelerators, the bunch of particles automatically determines its own phase angle.

Other problems raised by the alternating-gradient idea concerned the extreme accuracy required of the magnet field. As can be seen from the next slide (9) the magnet is composed of many units - in the example shown, the CERN 28 GeV accelerator, the number is 100. Small errors in the magnetic field of these units and in their physical lengths and position give rise to a set of resonances which throw the particles out of the machine. Also, errors in the magnetic field gradients of these units give rise to another set of resonances which have equally disastrous effects. It was therefore found essential to impose extremely tight tolerances on the permissible errors in the magnet units, to build very stable foundations for the machine and to position the units round the machine circumference with very high precision.

Nevertheless, despite the Transition Energy problem and the extreme accuracy required in the manufacture and installation of the component parts of the accelerator, the alternating-gradient synchrotron has proved the most flexible and most efficient type of machine for the acceleration of protons to very high energies and this design has now replaced all others in this field.

Consequently, when a new generation of machines of higher energy than the 30 GeV accelerators was required for research, they were based on the alternating-gradient principle. The first of these machines was the Russian 70 GeV proton synchrotron completed in 1967 at Serpukhov near Moscow. The second is the 400 GeV American machine at Batavia near Chicago which is expected to come into operation in 1972 and the third is the European 300 GeV machine, the construction of which was started this year at CERN, Geneva.

Figure 9: Plan of the CERN 28 GeV proton synchrotron showing its hundred magnet units and four experimental areas (S, N, E and NE).

7. Summary of accelerator development

In this talk so far I have tried in a rather superficial way to sketch the main developments of accelerators since their earliest days. I have not been able to mention all the developments which took place but rather I have followed the main line which eventually led to the highest energy machines. I have given a definite bias to proton accelerators and hence have done less than justice to electron machines, although the highest energy electron accelerators, with one exception, are of the same type as the proton machines, namely alternating-gradient synchrotrons. The Deutsches Elektronen-Synchrotron at Hamburg is the largest European electron accelerator of this type and a similar machine is in operation at the Daresbury Laboratory in England.

The exception which I just mentioned is the electron linear accelerator and its interest lies in overcoming a fundamental limitation of electron synchrotrons, namely the massive radiation of energy from high energy electrons circulating in orbits round a synchrotron. The energy radiated in this way increases as the fourth power of the electron energy and inversely with the radius of the machine, and hence it becomes uneconomic to build electron synchrotrons above about 10 GeV energy. The linear accelerator, in which electrons are accelerated along a straight line, is obviously not affected by this radiation loss, and for the highest energies becomes more attractive. The largest of these linear electron machines, over 3 km long, was completed at Stanford University, California, in 1967 and operates at the 20 GeV energy level although it is capable of being developed up to 45 GeV electron energy.

To summarize all this accelerator development from its early beginnings to the giant accelerators now being built at NAL and CERN it is convenient to display the energies reached by the different machine types as a function of the years. This is shown in the next slide (10). Here you can see the year of first operation of each type of machine and its subsequent development in energy. What is clear from this slide is that machine energy has increased exponentially over many decades and that the increase of energy with time has been achieved by replacing one machine type by another as time went on. I must point out that nearly all the machine types shown on the slide are still used today since they give outputs which are particularly suitable for low and medium energy physics research and they have been developed especially for these purposes.

8. New ideas and concepts for accelerators

It is tempting in a talk of this kind to proceed at this stage to hazard a guess at likely future developments of even higher energy accelerators despite the obvious danger of being proved a false prophet by future events.

Figure 10: Graph of accelerator energy against time, 1930 to 1960. The replacement of one type of accelerator by another has enabled machine energy to be steadily increased over 30 years at a rate of a factor of ten in energy every 6 years.

Before coming to the more advanced ideas I would like to describe two significant developments which are already under way.

One of the frustrations of accelerating a beam of particles to high energies and then letting it hit a target is that so much of the energy is, in a sense, wasted as far as nuclear reactions are concerned. A high energy proton from an accelerator striking a proton at rest in a target produces only a fraction of its energy in the centre of mass system. Most of the energy is wasted in projecting the reaction products - the secondary particles - along the direction of the incoming proton. For example, the proton-proton centre of mass energy using the 28 GeV CERN proton beam and a target is about 7 GeV and this energy only increases as the square root of the primary beam energy.

A more efficient system would be to bring together two beams of protons of equal energy from opposite directions since then the centre of mass energy would be just the sum of the energy of the two beams. Whereas a 28 GeV proton striking a proton at rest in a target gives 7 GeV centre of mass energy, two protons each of 28 GeV energy colliding together from opposite directions give 56 GeV centre of mass energy. To obtain 56 GeV centre of mass energy from a proton beam striking a target would require an incident beam energy of 1500 GeV.

The difficulty with this attractive way to very high reaction energies is the very low reaction rates which result from the collision of two beams of particles due to the relatively low density of particles in the beams. To overcome this difficulty it is necessary to build up several ampères of protons in each beam and even then the unwanted background reactions due to protons hitting gas atoms in a vacuum of say 10^{-7} torr, which is usual in accelerators, masks the proton-proton reactions. Until methods of accumulating dense beams of particles were developed and vacuum pressures could be lowered to 10^{-10} or 10^{-11} torr this idea therefore lay dormant in the minds of the accelerator builders.

In 1965 a very large machine of this type, called the Intersecting Storage Rings, was started construction at CERN and at the beginning of this year this machine came into research use.

The CERN Intersecting Storage Rings use the 28 GeV proton synchrotron to accelerate the protons which are then fed into each ring. The layout of these machines is shown in the next slide (11). In order to build up several ampères of protons in each ring it is necessary to store in each ring about a thousand output pulses from the 28 GeV machine and this takes about an hour of running time of the 28 GeV machine. Once the required current is built up in each ring the two proton beams can be brought together at several points round the circumference of the machine and in these regions the high energy proton-proton reactions take place. A view of the CERN storage rings showing the intersecting rings and magnet units is shown in slide 12.

Figure 11: Plan of the CERN Intersecting Storage Rings showing proton transport lines from the 28 GeV synchrotron and the two storage rings intersecting at 8 points.

I should also mention that storage rings are now being added to the DESY machine at Hamburg and electron storage ring devices already are in operation in France and Italy, so that in Europe we have both proton and electron storage rings.

It may be wondered why, if storage rings are so effective for reaching the very highest nuclear reaction energies, it is necessary to go on building high energy accelerators. The reasons are the following. In the first place the reaction rates are many orders of magnitude less using intersecting beams than using a single beam on a target even with beam intensities in the rings of many ampères. In the second place only proton-proton interactions can effectively be studied since the intensity of secondary particles from these reactions is very small indeed. Thirdly, if the aim is to get to the highest cosmic ray energies, it is necessary to start with an accelerator of energy much higher than 28 GeV to feed the rings.

The second innovation which I want to mention leads on from the evolution of high-energy accelerators and the recent addition of storage rings. This innovation concerns the idea of building up on one site a complex of accelerators coupled together to provide a wide variety of experimental facilities for nuclear particle physics research.

The idea of an accelerator complex was first born out of necessity. Towards the end of 1969, despite many hopes and much hard work, it became evident that the European 300 GeV Programme was unlikely to be realised in the form presented at that time. The planning had followed the conventional wisdom that for a new accelerator of much higher

energy than an existing one, a new laboratory is set up and equipped to carry out experiments with the new machine. Thus, for the European 300 GeV machine, sites for a new laboratory were sought in the Member States of CERN. When it became clear that this plan was unlikely to succeed the idea was put forward of building the new machine next to the existing laboratory of CERN, coupling it up with the other accelerators on the site and using the experimental facilities already constructed in that laboratory. By this means the original cost of the 300 GeV Programme was greatly reduced and at the same time the idea of an accelerator complex was born. Necessity is very often the mother of invention.

Figure 12: Photograph of an intersecting region of the CERN storage rings. The annular magnets of the two rings can be seen and the size of the magnet units is given by the man in the foreground. The intersection of the two vacuum chambers is now surrounded by nuclear experimental equipment.

To show you the advantages and flexibilities of the accelerator complex at CERN I refer to the next slide (13). Here you see a number of accelerators and facilities joined together. Let us start with the source of protons which feeds the complex.

CERN 300 GeV Layout

Figure 13: Plan of the CERN accelerator complex. The 28 GeV synchrotron and the intersecting storage rings are the small circles at the bottom. The large circle is the new 300 GeV machine. The West Experimental Area is to the left of the intersecting storage rings and the North Experimental Area extends to the top of the picture. Both these areas will be fed by protons from the 300 GeV machine.

The basic instrument is the existing CERN 28 GeV proton synchrotron. The protons feeding this machine are created in an ion source and first accelerated up to 500 keV energy using a high voltage generator similar to that used by Cockcroft and Walton. After acceleration to 500 keV, the protons enter a linear accelerator which takes them, in three stages, up to 50 MeV energy. At this point they are either injected directly into the proton synchrotron or, in the future, they will first pass into a smaller machine which subsequently injects them into the proton synchrotron. This smaller machine is called a booster synchrotron and its purpose is to increase the injected proton beam intensity by about a factor of ten. Once inside the proton synchrotron the protons are assembled into bunches and accelerated through the Transition Energy up to a maximum of 28 GeV. The output of the 28 GeV proton synchrotron will serve three purposes. Firstly, the protons can be used for research at about the 28 GeV energy level; secondly, they can be fed into the intersecting storage rings for research studies at about 50 GeV centre of mass energy and thirdly the protons can be injected into the 300 GeV machine. Those injected into the 300 GeV machine are again assembled into bunches and then accelerated through the Transition Energy of this machine to 300 GeV or higher energy. Thus to get to 300 GeV energy the protons are accelerated sequentially in not less than 5 machines in series.

However, these are really only the beginning stages of building up a European accelerator complex. We foresee in the future increasing the energy of the 300 GeV machine to about 1000 GeV by using pulsed superconducting magnets in place of the iron-cored magnets which we shall use at the start. We also wonder about using superconducting magnets in the existing intersecting storage rings which would allow nuclear reactions to be studied at over 200 GeV centre of mass energy. To produce such high centre of mass energies with a single beam and a target would require a beam energy of 20,000 GeV or $2 \cdot 10^{13}$ eV. Finally, new intersecting storage rings, using superconducting magnets, could be built on the site to store 1000 GeV protons from the accelerator which would enable 2000 GeV centre of mass energy reactions to be studied. The energy of a single beam striking a target to produce 2000 GeV in the centre of mass system would be $2 \cdot 10^{15}$ eV which is getting near to the highest energies observed in the cosmic rays.

This is why I said at the beginning of this talk that accelerator builders at last see a way of reaching with their machines nuclear reaction energies similar to those produced by the highest energies of the cosmic rays.

Of course, all these are ideas for the future. They are certainly not included in the 300 GeV Programme at present agreed and financed by the CERN Member States. Whether they are carried out or not depends on the needs of nuclear particle physics in the next decades and on the future financial support for this research by the Euro-

pean governments. The important thing is that the accelerator complex now being built up at CERN could be developed in this way in the future without having to move to a new site.

Turning, finally, to completely new ideas of accelerating particles one must admit that there are not many at this moment. Clearly, any new idea must in some way overcome problems and limitations presented by the existing accelerators and it is perhaps useful to note what these are.

For the circular machines using alternating-gradient focusing the energy is set by the radius of the machine and the maximum magnetic field. Remembering that the diameter of proton synchrotrons has now reached about 2 km, it is attractive to consider increasing magnetic fields above the 20 kG level set by iron-cored magnets rather than building even larger diameter machines. Pulsed superconducting magnets offer the possibility of reaching 40 - 60 kG and may prove an economic solution to this problem.

For the electron synchrotrons, radiation from the circulating electrons set an upper limit on energy and there seems no clever way out of this problem. Above about 10 GeV electron energy it seems that one must turn to linear accelerators.

Electron linear accelerators are already very long - the Stanford Linac is 3 km in length, and to go to higher energies and longer lengths without excessive radio-frequency power consumption, superconducting cavity linacs seem to offer a possible solution.

For very high centre of mass energies, as I have already mentioned, intersecting storage rings seem the only feasible solution but they are limited by the very low reaction rates produced with colliding beams. This problem could be alleviated by steadily pushing up the circulating beam currents above the few ampères now available.

Finally, for proton or heavy ion acceleration, there is the idea of using electron ring accelerators. The possible advantages of these machines can be explained as follows. A limitation of proton linacs is the long length required for high energy acceleration. Essentially the length is determined by voltage breakdown in the cavities and the present acceleration rate is about 10 MeV/m. The electron ring accelerator aims to overcome this problem by accelerating bunches of electrons in which protons are trapped in the potential well of the electron bunch. A stable form of electron bunch is a torroidal ring and hence the name sometimes given to this device is a Smokatron since the torroidal rings of electrons are accelerated along the length of the accelerator rather like smoke rings. The rate of acceleration of the electron rings would still be limited to about 10 MeV/m by voltage breakdown in the accelerating structure but the protons trapped in the rings, because of their heavier mass, gain more ener-

gy per metre than the electrons as the velocity of the rings approaches that of light. In the limit, the ratio of proton to electron energies in the accelerating rings is equal to the proton-electron mass ratio but ring stability and other problems limit the ratio to about 40 or 50. Nevertheless, the rate of acceleration of protons in this device might reach a few 100 GeV/m so that, for example, a 300 GeV proton linear accelerator might be only a few kilometres long.

This idea is still in the early stages of development and it is not yet possible to see clearly whether it will ever be a serious challenger to the alternating-gradient synchrotrons for very high energy machines. In Europe several research teams, for example, the group at Munich-Garching, are working on this idea and there are also powerful teams at work in America and the Soviet Union.

9. Conclusion

I would like to conclude this talk with some general comments about particle accelerators which have nothing to do with their technological development.

It is obvious that any research instrument which grows in size from a device which can be housed in a small room to something over 2 km in diameter is likely to have a very profound effect on the experimental research which is carried out with that instrument. I was looking the other day at a picture of Rutherford holding in his hand the apparatus he used in 1919 to discover the atomic nucleus. If one takes a photograph of one of the giant accelerators nowadays it is very difficult even to see a man standing beside it. For example, the next slide shows an aerial photograph of the CERN accelerator complex. Not only are the research physicists dwarfed by the accelerators, with all the psychological effects such a changed relationship can have, but the size of the machines has brought into the research, relationships which were totally absent in the early days.

For example, machines of this size and sophistication involve many industries which are called upon to manufacture their component parts. What stimulates industry to advance technology is not so much development contracts but substantial orders for the manufacture of technologically sophisticated equipment and these orders have been provided by the requirements of the particle accelerators and their experimental apparatus. Undoubtedly this stimulus is essential for industrial progress and good for the European economy, but it has taken the research physicist away from a personal relationship with his experimental apparatus. In fact the size of the accelerators is such nowadays that research physicists join only in their specification leaving it to others - the accelerator physicists - to design and build the giant machines.

Another relationship which has been much strained in recent years is that between teaching and research. In the old days one could give seminars in the morning and carry out research in one's laboratory in the afternoon since both activities took place in the same university building. The size of the accelerators has now taken the experiments out of the universities and into national and international laboratories and so has placed a serious strain on the teaching-research relationship which is essential in all scientific work. Solutions to these problems have been found in many of the European universities but the new ways of working do not easily accommodate to normal university life.

Figure 14: Aerial view of the CERN accelerator complex whose parts can be identified from Figure 13. Very little sign of the 300 GeV machine will be evident at ground level since it is built in a tunnel deep underground. The countryside will therefore hardly be changed by its construction.

Yet again, the need for national and international action has involved research physicists in quite new relationships with governments. Considering the cost of the accelerators and their laboratories this was inevitable and, on the whole, it has been beneficial to both of the parties concerned. For example, laboratories like CERN have been instrumental in helping to create a scientific Europe and in pioneering scientific collaboration between Europe and its neighbouring countries which may well in the years to come be judged just as important as the research carried out with the giant accelerators. Governments, on their side, have been able to use this experience to facilitate other international collaborations.

These new relationships between the research and the outside world have come about simply because of the ever increasing size of the particle accelerators. It is no longer possible for research physicists to live apart from the society which supports them and in many ways these new social relationships are a very healthy development for science as a whole. But, looking back to earlier days, one has the feeling that men like Bothe could concentrate on his research with far less distraction than can any research physicist these days.

In view of all these changes it is no wonder that the style of research today is so different from that of 40 or 50 years ago. Not only do the research physicists have to travel from their universities to a foreign country to carry out their experiments, but they also have to work in large teams in which individuality of thought is sometimes compromised by the necessity for common action. Furthermore, they have to present their experimental proposals to committees of physicists which decide whether or not their experiments are carried out with the accelerators and at which hour of the day or night. On top of all this the size and complexity of the equipment they use can easily lead them to mistake technical virtuosity for profundity of thought.

It is indeed a hard life being a nuclear particle physicist these days and the problems they face are much easier to define than to solve.

However, if first-rate research is to continue - if creative genius and originality is not to be dulled or distracted by all that using the giant accelerators involves, then some way must be found to free the minds of the young Bothes of today so that they can bring the full power of their intellects to bear on the real research problems. We must not forget that the purpose of building accelerators is to carry out research into the fundamental constituents of matter.

So, if I have succeeded today in interesting you in the history of the development of these extraordinary machines and perhaps conveyed to you some of the excitement they bring to the hearts and minds of the accelerator builders, I hope I have also fairly pointed out to you at the end of my talk some of the problems they raise for the physicists who use them and for this discipline of scientific research.