Chapter 2
Small Accelerators Grow

Contents

U. Amaldi, *Particle Accelerators: From Big Bang Physics to Hadron Therapy*,
DOI 10.1007/978-3-319-08870-9_2

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In 1960 the architecture of the first few CERN buildings was harmonious but rather spartan. A good forty years would pass before two well-designed buildings were constructed and called, in defiance of the disorderly numbering system typical of CERN, Building 40 and Building 39.

The physicists of the huge international collaborations working at the LHC occupy the first one, while the second is one of the hostels where some of the eight thousand physicists and engineers, who come from laboratories and universities all over the world to participate in the experiments carried out with CERN accelerators, stay for short periods. A large lawn and a road separate the two buildings from the main restaurant; and the area is traversed at all hours by many young researchers and, from time to time, also by some white-haired ones.

The square between Building 39 and 40 is dedicated to Edoardo Amaldi, who was one of the founding fathers of CERN and its Secretary-General between 1952 and 1954, in the years when the laboratory was created. As a young man Amaldi was part of the illustrious group of researchers gathered around Enrico Fermi in Rome, in the 1930s; they were famed as 'the boys of Via Panisperna', so named after the street where the Physics Institute was located. Other members of the group were Franco Rasetti, Emilio Segrè and Bruno Pontecorvo, whom we have either already met or shall encounter in later chapters.

Amaldi had an important role in the deliberations of May 1951, in which it was decided to propose to the CERN member states the construction of two accelerators, one intended for the present and the other for the future: a 600 MeV synchrocyclotron (which, after the entry of the Lawrence 184 inch machine into operation, was considered a sure success) and a much more challenging 10 GeV proton synchrotron, to whose story a section of this chapter is dedicated.

The Comeback of Linear Accelerators

After the invention of repeated acceleration, applied in the cyclotron of Ernest Lawrence, all the experts of the period were convinced that Wideröe's idea of the linear accelerator (Fig. 1.10) no longer had a future. All except one: Luis Alvarez, who was one of the most inventive scientists of the twentieth century. After the war he convinced himself that, at a sufficiently high energy, the cost of the circular accelerator would become prohibitive and therefore decided to use the new techniques of radiofrequency circuits to construct the first proton linear accelerator; after many highs and lows, in 1947 he succeeded to make it work.

Alvarez – who everyone called 'Louie' – was of Cuban-Spanish origin on his father's side and Irish from his mother. He had studied physics in Chicago after his father, a notable physician and medical researcher, left San Francisco in 1926 for the famous Mayo Clinic in Rochester, New York. Walter Alvarez had a great influence on the young Luis, including recommending him, as Luis recounts in his autobiography, "*to sit every few months in my reading chair for an entire evening, close my eyes, and try to think of new problems to solve. I took his advice very seriously and have been glad ever since that I did*" (Alvarez 1987).

During the Second World War Alvarez left Berkeley – where he had worked since 1936 – to contribute to the military development of radar at the MIT Radiation Laboratory in Boston. Among other things, there he invented and demonstrated the Ground-Controlled Approach system (GCA) which allowed landings of aircrafts at night and in conditions of low visibility, and the Vixen system which, mounted in a fighter aircraft, deceived the detection equipment installed on enemy submarines by creating the impression that the plane was receding while, instead, it was approaching. Having returned to Berkeley, he thought of using the thousands of radiofrequency components, of which the military had no further need, for the construction of his linear accelerator – the 'linac'.

Learning of this new idea, Lawrence, with his habitual enthusiasm, said: "*Alvarez has gotten the idea of putting obsolete radar equipment and incorporating it in a* *very interesting way in a Linear Accelerator which may make it possible to go to hundreds of millions of volts of all kinds of particles, not only electrons and protons but many ions as well. It is wonderful and in the Alvarez style – something that is out of the ordinary. It is bound to lead to very important physics in the future. The schemes of Alvarez and McMillan in my judgment is [sic] the outstanding event of their generation.*" (Lawrence 1945)

The original idea of Alvarez had enthused Lawrence but did not work. The final one, which is still known as the 'Alvarez linac' is illustrated in Fig. 2.1a; in a copper tube – more than a metre wide and fifteen metres in length – are inserted large hollow cylinders of increasing length. As in the Wideröe linear accelerator, the proton bunches move at high speed inside the cylinders, receiving an accelerating kick at each gap between them and thus travelling increasing distances in each equal interval of time in which the electric field oscillates. However, the Alvarez accelerator tubes were not connected by cables to a source of oscillating high voltage, as in Fig. 1.10; instead a source of radio waves with 1.5 m wavelength created an electromagnetic field which oscillated 200,000 times a second along the entire length of the tube.

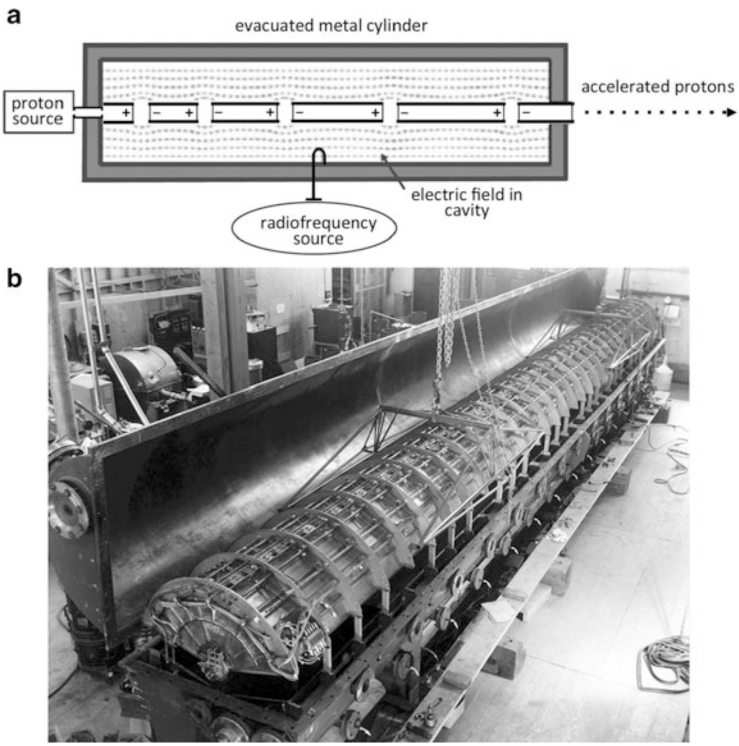

Fig. 2.1 (**a**) The principle of operation of an 'Alvarez'; the oscillating electric field produced in the cylinder by a radiofrequency (RF) source accelerates bunches of protons (electrically positive) when the left sides of the electrodes are positive. (**b**) The first proton linac under construction in the Berkeley Radiation Laboratory (Emilio Segrè Visual Archives/American Institute of Physics/ Science Photo Library)

Fig. 2.2 (**a**) The Alvarez linac accelerated protons with a 200 MHz oscillating electromagnetic field (Courtesy Lawrence Berkeley National Laboratory). (**b**) The electron linac of Bill Hansen used an oscillating field with a frequency 15 times larger: 3,000 MHz or 3 GHz (William Webster Hansen Papers (SC0126), Courtesy Stanford University Archives)

This field produces an electric force, in the *gaps* between two successive tube sections, which accelerates the proton bunches – provided they traverse them at the right moment – and impels them to travel (with increased energy) along the length of the next section, within which they feel no force.

The dimensions of the first linac, which accelerated protons from 4 MeV up to 32 MeV, were impressive (Fig. 2.2a), and the number of particles accelerated each second was much larger than it was possible to extract from cyclotrons of the era, and for many applications this feature was extremely advantageous.

In the same years, just a short distance from Berkeley, at Stanford University, Bill Hansen – Luis Alvarez's teacher at MIT – built the first electron linear accelerator, which was based on a similar principle but, because an electron is two thousand times less massive than a proton, could use wavelengths about ten times smaller. Therefore the linac had a much smaller diameter, ten centimetres instead of about a metre. In the ever lively competition between Stanford and Berkeley, to poke fun at the picture of the Alvarez linac (Fig. 2.2a), Hansen had himself and three students photographed as they carried a section of his linac, which accelerated electrons up to 4.5 MeV (Fig. 2.2b).

Fig. 2.3 Seven Nobel laureates from the University of California, Berkeley, pose in front of the magnet from the 37 in. cyclotron (Courtesy Lawrence Berkeley National Laboratory, 1969)

The Hansen linac was immediately used for cancer therapy with X-rays and its story is told in Chap, 8, dedicated to medical uses of accelerators. However, before closing the interlude, let us return to Luis Alvarez, who was truly an eclectic genius (Fig. 2.3). Let three examples suffice.

First of all, as will be explained in the fourth chapter, in 1953 he launched the construction of a new type of detector, called 'bubble chamber', with which so many new particles were discovered that he earned the Nobel Prize. Secondly, in 1965 Alvarez proposed the use of cosmic ray detectors installed in the pyramid of Chephren in Egypt to make, essentially, a 'radiograph' of the upper part of the pyramid to seek any hidden chambers. The result – announced in 1969 – was negative but the method worked perfectly and was then applied to other pyramids.

Finally, Alvarez was seventy when his son Walter, a well-known geologist, showed him a sample of clay extracted in Gubbio (Italy), dating back 65 million years, the period in which the dinosaurs disappeared. Luis had the idea of analysing the sample to measure the concentration of iridium, a very rare element in the Earth's crust, but abundant in asteroids. Analysis using nuclear techniques revealed the presence of much iridium, not only in the Gubbio clay, but also in samples of rocks from the same period originating throughout the world. The conclusion was what is known today as the 'Alvarez hypothesis'; the iridium is of extraterrestrial origin and was spread across the globe 65 million years ago following the impact of an enormous meteorite. The residue from the impact darkened the skies for years, causing the extinction of dinosaurs and many other living species.

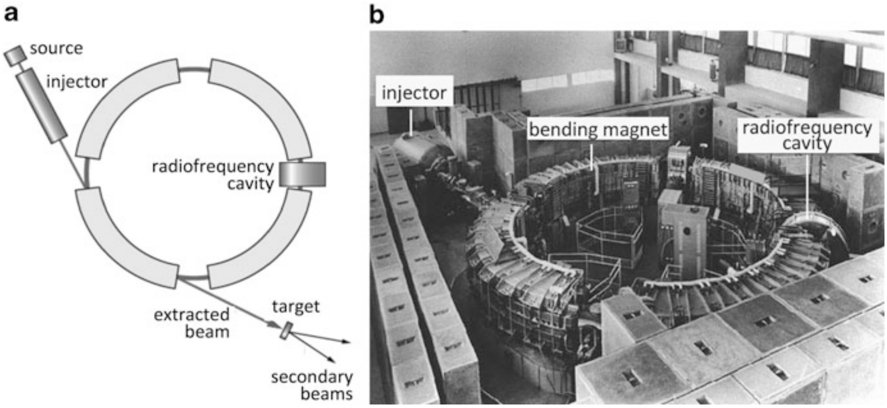

Fig. 2.4 Schematic diagram of a synchrotron and a photo of the electron synchrotron which began operation in 1959 at the Frascati laboratory of the Italian Institute for Nuclear Physics (INFN) ((**b**) Courtesy Physics Museum – Department Of Physics, University of Rome La Sapienza)

The First Synchrotrons

In a synchrocyclotron the spiral form of the orbits requires the deflecting magnetic field to be uniform over a large area, with the consequence that the weight and cost of the magnet which bends the trajectories increases greatly with the growth of the energy to be reached. In contrast, in place of a single large magnet, a *synchrotron* uses several smaller magnets placed around a circular 'doughnut', or hollow 'chamber' evacuated of air, in which the particles circulate.

As Fig. 2.4a shows, the principal components of this accelerating machine are the particle *source*; the *injector* – which gives the first acceleration to the particles and 'injects' them into the ring; the *bending magnets* – which steer the trajectories of particle bunches to keep them inside the ring; the *radiofrequency cavity* – made of two hollow electrodes which impart a small energy increment to the proton bunches, as they pass through them on each turn; the *extraction system* – which ejects the bunches of protons circulating in the ring when they have reached the desired energy, at the end of the acceleration cycle – and the vacuum chamber for the *extracted beam*.

In a synchrotron the weight of the deflecting magnets is much less than the weight of the single magnet of a cyclotron of equal energy and so, for the same cost and construction difficulty, much higher energy beams can be obtained. There are, however, two complications.

First of all, during the acceleration the magnetic field of the bending magnets must grow *in synchronism* with the increase in energy, so that the bunches of particles of steadily growing energy continue to follow, not a spiral orbit, but a *constant* circular path at the centre of the vacuum chamber. The growth of the magnetic field is obtained by increasing, during the acceleration, the current that circulates in the windings around the metal core, as in every electromagnet.

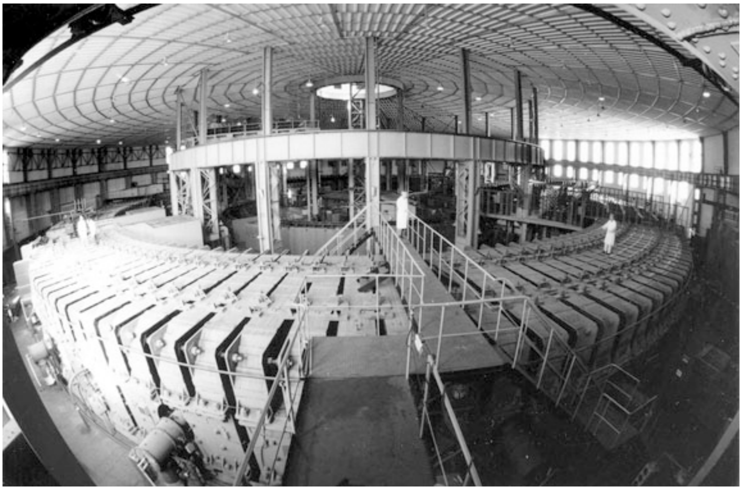

Fig. 2.5 At the International laboratory Joint Institute for Nuclear Research (JINR) in Dubna (Russian Federation) the Veksler Synchrophasotron operated until 2003 (Courtesy of JINR, Dubna)

In the second place, since the circulation time of the particles decreases with their increasing speed, the oscillation period of the voltage applied to the accelerating cavity must also diminish, *in synchronism*, with the energy increase, and therefore with the magnetic field; hence the name *synchrotron*. But, as in a synchrocyclotron, the synchronisation precision would not be sufficient were it not for the principle of phase stability, which guarantees that particles which are not exactly in time with the oscillation of the voltage on the cavity are also accelerated.

It is not surprising that the first synchrotron capable of beating the record energy of Lawrence's 184 in. synchrocyclotron should have been built by one of the discoverers of this principle. Between 1945 and 1948, under the direction of Ed McMillan – who had invented the names 'synchrocyclotron' and 'synchrotron' – a 340 MeV electron synchrotron was constructed at Berkeley. With it a particle never before observed in cosmic rays was discovered: the *neutral pion*.

In 1949 the 250 MeV electron synchrotron designed by the other discoverer of the phase stability principle, Vladimir Veksler, began operation in the Soviet Union. In the same year he planned a proton synchrotron with a 200 m circumference, the '*Synchrophasotron*', which in 1957 reached 10 GeV energy (Fig. 2.5).

In Europe the first electron synchrotron was demonstrated in 1946 by F.G. Goward and D.E. Barnes at Woolwich Arsenal Research Laboratory in England, and the first proton synchrotron, constructed at the University of Birmingham by M. Oliphant and his team, accelerated protons up to 1 GeV of energy in 1953.

For many years the race towards ever higher energies was dominated by the United States. In particular, in 1946 nine large universities (Columbia, Cornell, Harvard, Johns Hopkins, Massachusetts Institute of Technology, Princeton, University of Pennsylvania, University of Rochester and Yale) created a non-profit organisation with the role of fundamental research into nuclear sciences, encompassing physics, engineering, chemistry and biology, and the construction (on the site of the former Camp Upton military base) of large facilities – specifically an accelerator and a nuclear reactor – that no single university could afford to develop alone. The laboratory took the name of Brookhaven National Laboratory (BNL) and its creation has been described by the American Nobel laureate Norman Ramsey:

> *The idea that grew into Associated Universities Inc. (AUI) and Brookhaven National Laboratory (BNL) arose in discussions between Isidor Rabi and myself at Columbia University during the period from October to December of 1945, shortly after Rabi returned to Columbia from the MIT Radiation Laboratory and I returned from Los Alamos. I wish I could claim that these discussions originated in a flash of genius and in a vision of AUI and Brookhaven as the important institutions they are today. Instead, I must admit that the idea grew from a mood of discouragement, jealousy and frustration. In particular, Rabi and I both felt that physics at Columbia University was coming out in this period with little scientific benefit in return. In particular, the earliest United States work on fission and nuclear reactors was that done at Columbia by Fermi, Szilard, Zinn, Dunning, and others. However, during the course of the war this activity had been transferred to other locations. As a result many universities emerged from the war with strong nearby nuclear science research laboratories, whereas Columbia did not.* (Ramsey 1966)

The BNL synchrotron – which became operational in 1952 and later accelerated protons up to 3.3 GeV – was dubbed the ‘Cosmotron’ to indicate that the machine would deliver beams of particles having energies as large as those of the cosmic rays which, at that time, were the means of discovery of new particles. The protons were kept in a circular orbit by 2,000 t of deflecting magnets, less than half the weight of the magnet of the 184 in. synchrocyclotron, which reached only 0.2 GeV.

Only 1 year after, at Berkeley, the ‘Bevatron’ accelerated protons up to 6.3 GeV, the energy chosen because, in the collision with target nucleons, the protons would liberate the 2 GeV which are necessary to create a proton-antiproton pair.

The magazine ‘Popular Science’ described the technical marvels of the Bevatron in an article entitled “A 10,000-ton Cracker for Invisible Nuts”:

> *In a hollow in a California hillside a large but unpretentious building covers one of the biggest and strangest of all machines. It is 135 feet across, cost 9,500,000 dollars and contains more than 9,500 tons of iron, 225 miles of wire and 2,400 vacuum tubes. Its 31 vacuum pumps evacuate the equivalent of a seven-room house. What it makes cannot be seen or felt, let alone be sold. This is the Bevatron, just completed, the most powerful atom-smasher yet built.* (Huff 1954)

As expected, the existence of antiprotons was proven in the collisions of 6.3 GeV protons with the nuclei of a solid target by a group of physicists led by the Italian Emilio Segrè (who had trained under Enrico Fermi in the 1930s as one of the ‘boys of Via Panisperna’) and made up of Owen Chamberlain, Clyde Wiegand and Tom Ypsilantis, a brilliant young doctoral student of Greek origin born in the United States. The discovery was rewarded by a Nobel Prize in 1959, shared by Chamberlain and Segrè (Fig. 2.3).

In Italy, things moved much more slowly because after the war the country was in ruins and funding was not available for science until the years of the post-war economic boom. In the reconstruction surge of the 1950s, physicists from Rome, Florence, Turin and Padua, who were mostly occupied with cosmic ray research, founded the Italian National Institute of Nuclear Physics (INFN) in 1951, whose first president was Gilberto Bernardini and whose second was Edoardo Amaldi.

At the beginning of 1959 a 1 GeV electron synchrotron started operating in the new Laboratory built by INFN in Frascati, close to Rome (Fig. 2.4b). It was a late development and the energy was not particularly high for the times, but I mention it here because this machine was instrumental in initiating my long-term involvement with particle accelerators.

The Invention of Strong Focusing

When the Cosmotron began operation at Brookhaven National Laboratory it was calculated that to reach an energy ten times larger (30 GeV) it would be necessary to employ a hundred times more iron (200,000 t).

During the acceleration, trajectories of particles, which circulate for a million turns inside the vacuum chamber of a synchrotron, do not remain constantly at the centre of the bending magnets, but oscillate vertically and radially about the central orbit. In order that the protons were not lost by collisions with the walls of the chamber, the cross-section of the Cosmotron ring was very large, around 20 cm vertically and 60 cm horizontally. To produce the necessary magnetic field on a ring of these dimensions, 2,000 t of iron were required. At higher energies the oscillation amplitudes increase further and so it becomes necessary to increase the chamber dimensions, and consequently, the amount of iron used.

In the summer of 1952 a delegation of accelerator experts from the newly created CERN (*Conseil Européen pour la Recherche Nucléaire*) laboratory went to Brookhaven to visit the Cosmotron and discuss with their American colleagues the properties of the European accelerator under construction. While preparing for this visit, Stanley Livingston (a former student of Lawrence), Ernest Courant and Hartland Snyder from Brookhaven had a brilliant idea for reducing the oscillation amplitudes and thus the cost of the magnets. The visitors brought this new concept back to Europe that, as I shall explain later, had a great impact on the CERN programme and on the building of the first European synchrotron. Meanwhile, the three authors published a scientific paper in 'Physical Review', the most important US physics journal, entitled "The Strong Focusing Synchrotron – A New High Energy Accelerator". In essence, the three suggested the use of a *transverse* magnetic field in addition to the *vertical* magnetic field which maintained the particles in their circular orbit.

To explain how *strong focusing* works it is helpful to refer to the focusing of a beam of particles, which, in the absence of a vertical magnetic field, propagates

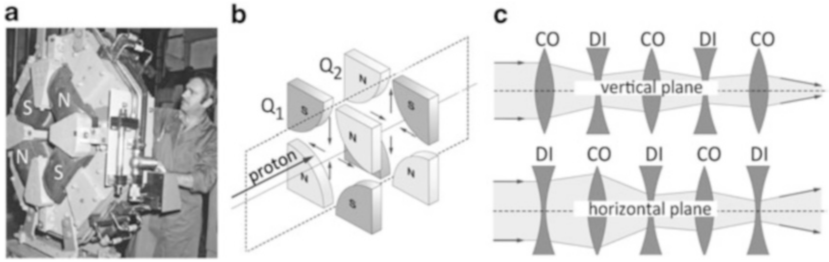

Fig. 2.6 The currents circulate in the copper windings of the 'quadrupole' in such a way that it has two South poles and two North poles facing each other, which produce magnetic fields – at the centre of the quadrupole – transverse to the direction of motion of the particles (Courtesy CERN)

horizontally in a straight line. The photograph of Fig. 2.6 shows a 'quadrupole', a magnet that has two North (N) poles and two South (S) poles.

Two quadrupoles on the same central axis produce transverse magnetic fields which run from South to North poles. These fields give rise to forces in quadrupole Q1, as shown by the arrows in the drawing of Fig. 2.6, which are directed towards the axis in the vertical plane and away from the axis in the horizontal plane.

The drawing on the right shows how the vertical and horizontal dimensions of a parallel particle beam are reduced under the effect of a series of quadrupoles which alternate between converging (CO) and diverging (DI), and so on, in the vertical plane. The focusing *also* takes place in the horizontal plane, where the first quadrupole is diverging (DI).

It may seem surprising that an alternating sequence of converging and diverging 'magnetic lenses' always has an overall convergent effect. This is the brilliance of the idea, which Courant, Livingston and Snyder confirmed with the many equations of their Physical Review article. A similar focusing effect can be obtained with beams of light by using an alternating series of optical lenses.

To illustrate the advantages of this new approach to particle acceleration, Fig. 2.7 compares a modern strong focusing synchrotron with a normal synchrotron, henceforth referred to as 'weak focusing'.

In the strong focusing synchrotron the more numerous bending magnets alternate with quadrupoles to keep the proton bunches well focused during each acceleration cycle. The protons are not lost, despite the vacuum chamber of the ring being much narrower than in a weak focusing synchrotron, typically 5 cm vertically and 15 cm horizontally (Fig. 2.8).

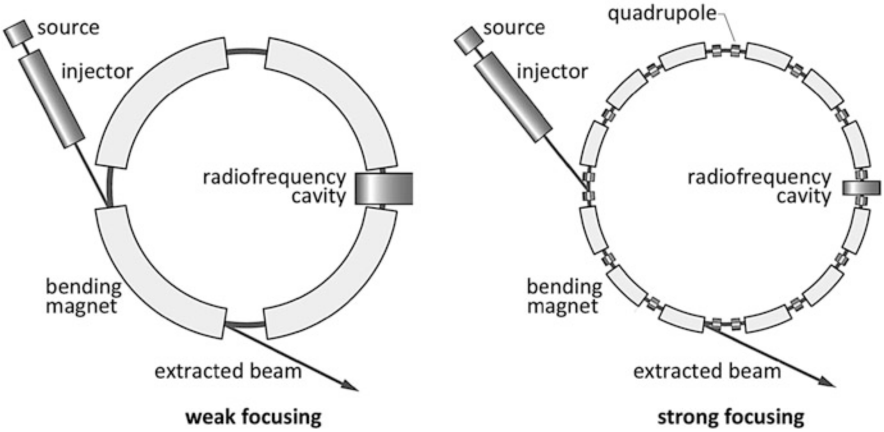

Fig. 2.7 Schematic comparison between a weak focusing synchrotron (like the one in Fig. 2.4) and a strong focusing machine which achieves the same energy

Fig. 2.8 Snyder, Livingston and Courant (from *right* to *left*) are pictured in front of the mock-up of a strong focusing bending magnet (From Panofsky) (Courtesy of Brookhaven National Laboratory)

Phase stability and strong focusing are the ideas on which all high-energy accelerators are now based. They are of very different degrees of sophistication, as remarked by McMillan (Fig. 2.3).

> *In the case of phase stability, it is easy to approach this in an intuitive, elementary way. When I first started telling people at Los Alamos about it, I found that I hardly needed to finish the explanation before they understood, and at least one said to me that he felt stupid in not having thought of it himself. But strong focusing is not the kind of thing that one thinks of in an elementary way.*
>
> *The team that did this in the United States was Stan Livingston, Ernie Courant and Hartland Snyder. But there was an independent inventor. He was working entirely isolated from contact with anybody, in Greece, and was somewhat earlier than these three. That was Nick Christofilos, one of the real geniuses of our time.* (McMillan 1973)

Interwoven Histories

The article by Courant, Livingston and Snyder was enthusiastically welcomed by the physics community, which was eager to exceed the 10 GeV barrier without recourse to the 40,000 t of iron needed by the Synchrophasotron. Everyone was convinced that the three inventors would soon share a Nobel Prize, but that did not happen because the idea had already been patented 2 years earlier by the Greek engineer Nicholas Christofilos.

Born in the USA in 1916, Christofilos had returned to Athens with his parents at the age of seven. He graduated from the National Technical University of Athens in electrical and mechanical engineering, later working as a lift engineer and repairing German lorries during the Nazi occupation. In his free time, he studied the physics textbooks he was able to find and, completely self-taught on the subject of particle accelerators, at the age of thirty he filed a patent, which essentially applied the phase stability principle to devise independently the idea of the synchrotron. While he built up his own lift maintenance company he learned, reading scientific magazines, that the synchrotron had already been invented. Instead of discouraging him, it drove him to search for a means of focusing protons accelerated in synchrotrons.

In 1948 Nick Christofilos wrote a long letter to scientists at Berkeley in which he described his own concept, which proved to be flawed. Having received a detailed answer explaining his mistakes, he continued to think about the problem, and while doing so discovered strong focusing. Therefore, the next year, he wrote another letter to Berkeley describing his latest ideas; this time, however, no one paid attention to the contents, even though correct, because the mathematics was complicated. Not receiving an answer, in 1950 Christofilos filed a second patent.

Three years later, while visiting the United States, he read the Physical Review article of Courant, Livingston and Snyder in the Brooklyn Public Library and became convinced his idea had been stolen. He rushed to Brookhaven where he learned that the Americans had arrived at the same conclusion without knowing of his patent. He was immediately offered a position, obtained recognition of his priority and $10,000 from the Atomic Energy Commission (*AEC*) for exploitation of the patent in the new Brookhaven synchrotron.

In Greece he had developed another idea in a field that at that time was just emerging: a new type of reactor that he called 'Astron' for the production of energy from nuclear fusion processes. This time the AEC listened attentively to him, even more because Astron seemed to solve problems that were being encountered in the implementation of two American-conceived reactors, the 'stellarator' and the 'magnetic mirror'. Astron was built in the Livermore Laboratories, in California, and to realise it Nick Christofilos invented a new type of linear induction accelerator, which is still in use today.

In Livermore he also worked on national defence, proposing the creation of an artificial belt of electrons around the earth produced by a nuclear detonation.

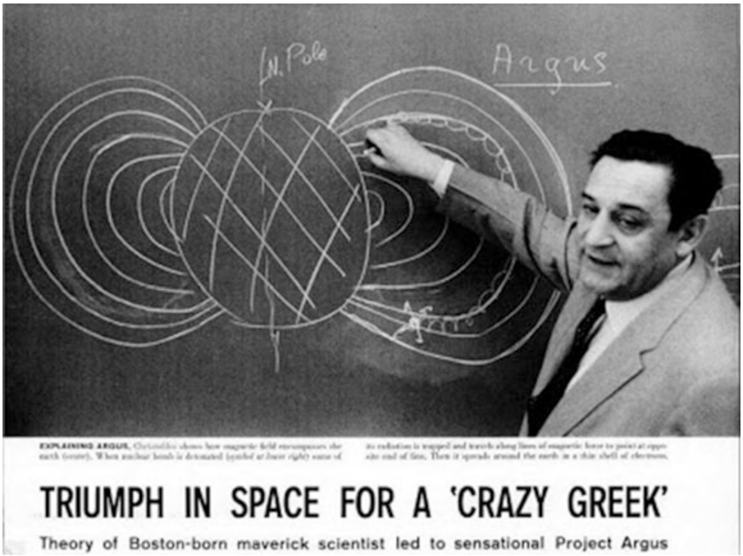

Fig. 2.9 This picture of Nicholas Christofilos explaining the Argus project appeared in the March 1959 issue of *Life* magazine (Trombley 1959)

In 1958, an exploratory experiment, called Argus, was carried out by exploding three small nuclear bombs above the South Atlantic Ocean (Fig. 2.9).

Despite all his efforts his pet project, Astron, never worked. He directed it with great determination, working day and night, defending it against detractors, arguing vigorously and drinking heavily, until a massive heart attack killed him in 1972 at the age of only 55. Shortly before he had met the head of the AEC, who had informed him of his project's cancellation. The life of this self-taught genius, often overlooked in the history of accelerator designers, has many aspects of a Greek tragedy.

How My Passion for Accelerators Started

The Courant, Livingston and Snyder article gave rise to the sequence of events just described and had many other consequences. The most important concerned the construction of the first CERN synchrotron, as we will see later. It also had an influence on me personally when, in 1957, Mario Ageno, head of the physics laboratory in the Italian National Health Institute (ISS), asked me – who had just arrived – to study its details, with the objective of designing and constructing a focusing system for the injector of the Frascati synchrotron, then under construction (Fig. 2.4).

It might seem odd that a group of researchers in a medical institute would be engaged in the construction of an accelerator. To understand the reasons, it is necessary to think back to the middle of the 1930s, when Enrico Fermi and the 'boys of via Panisperna' in Rome discovered that slow neutrons were more efficient than fast ones for the production of radioactive materials. Fermi, Franco Rasetti and Edoardo Amaldi therefore designed a 1 MeV energy Cockcroft-Walton accelerator to provide a very intense source of slow neutrons, and constructed it not at the University of Rome La Sapienza, but in the National Health Institute, which obtained the required funds from the Ministry of Health; indeed the newly abundant radioisotopes would be used for irradiating tumours. These developments were following the track opened by Ernest Lawrence in the States with the second generation of his cyclotrons.

In 1938 Fermi, whose wife was Jewish, left Italy for good in reaction to the racial laws to go to Columbia University in New York, and Edoardo Amaldi completed and operated, with the young Mario Ageno, the first Italian accelerator. Fifteen years later, when the Frascati synchrotron was launched, it was therefore natural that Ageno should lead a small group of researchers in the construction of an accelerator, similar to the one still then in operation at the ISS, which had the job of 'injecting' electrons into the, thousand times more powerful, second Italian accelerator.

In 1957, I had graduated a few months earlier and had decided to work at the ISS, because I did not want to participate in a research group in which my father Edoardo Amaldi, then already well known, was active. It was an excellent opportunity, given that Mario Ageno was an outstanding scientific personality from whom I learned a great deal.

I can still remember how much effort it took me to understand the strong focusing principle embodied in the equations of that famous article. Muddling through as best I could, in a couple of months I succeeded in converting some of the formulae into a mechanical design for two quadrupoles about ten centimetres long. Today I can say with satisfaction that those were the first quadrupoles built in Italy and that some examples have been working for many decades. Certainly their construction contributed to my deep interest in particle accelerators and these instruments have continued to fascinate me both for their use in fundamental physics and for their medical applications.

In the field of fundamental physics, I have had the good fortune to participate in, and sometimes to design and guide, experiments in nuclear and sub-nuclear physics carried out at several major accelerators: at Frascati the electron-synchrotron (Fig. 2.4); at CERN the Proton Synchrotron (PS), the Intersecting Storage Rings (ISR), the Super Proton Synchrotron (SPS) and the Large Electron Positron collider (LEP).

As far as medical applications are concerned, in the last 20 years I have worked on proton and carbon ion accelerators dedicated to the treatment of solid tumours; one of the accelerators, a synchrotron, which my research group and I designed, is now in operation at the National Centre for Hadron Cancer Therapy (CNAO), in Pavia, where patients have been treated since September 2011. The second accelerator we have been working at is a novel proton linac; the company A.D.A.M., spin-off of CERN, started its construction in 2014.

Accelerators for fundamental physics and medical treatments are based on the same principles of operation – in particular phase stability and strong focusing – and on the same techniques, but the objectives are different.

The first type of application targets the construction of what I call *beautiful physics*, driven by the innate need of comprehending and explaining the world around us, which provides the incomparable pleasure of understanding, and sometimes actually discovering, new natural phenomena.

The second falls instead into the category of what I call *useful physics*, meaning applied physics in general but, for me, specifically those applications which permit new methods of diagnosis and treatment of otherwise incurable illnesses. I am happy to have had the opportunity to dedicate my professional life to these two fascinating and interwoven branches of physics.

The Birth of CERN

In the years between 1945 and 1950, the idea of an international laboratory dedicated to physics using accelerators sprang into life more or less independently in several European circles. Many scientists and some politicians were worried by the conspicuous disparity which was developing between research in the United States and that in Europe. Moreover the flight of intellectuals resulting from the difficult pre-war and post-war conditions was rendering the recovery of top-level scientific research in Europe even more challenging.

The first seed was sown in 1945 by the American physicist Robert Oppenheimer, who had directed the Manhattan Project at Los Alamos, and who, in the course of work in the UN Commission for the Control of Nuclear Energy, formed a friendship with the French diplomat François de Rose, convincing him of the necessity for the European countries to work together towards the construction of the large and expensive instruments by then necessary to match research in the USA. This message was passed on to French physicists who participated in the work of the UN Commission – in particular to Pierre Auger, Francis Perrin and Lew Kowarski – and in October 1946 the French delegation submitted to the UN Economic and Social Council a proposal to create the 'United Nations Research Laboratories', dedicated especially to the peaceful development of nuclear energy.

In December 1949, the writer and philosopher Denis de Rougemont organised a European Conference of Culture at Lausanne. On this occasion, Raoul Dautry – Director General of the French Atomic Energy Commissariat– read out a letter from the great French theoretical physicist Louis de Broglie, the discoverer of the wave nature of the electron, who was unable to attend the conference in person:

> *At a time in which we speak of the union of the peoples of Europe, the problem arises of extending this new international unity by the creation of the laboratory or an institution where it would be possible to carry out scientific work, in some manner beyond the scope of the individual participating nations. As a result of the cooperation of a large number of European countries, this body could be endowed with resources beyond the level available to national laboratories.* (de Broglie 1949)

Among the objectives of the international laboratory, Dautry conjectured, on one side, research in astrophysics through the construction of powerful telescopes; on the other, research in the field of energy, given the growing concern about the steady reduction of natural resources, especially coal. The concluding motion therefore proposed the future Institute of Natural Science should be directed towards ‘applications useful for everyday life’. This, however, was not the general tendency of the initiatives which were developing in other European circles.

In Rome, at the end of the 1940s, Edoardo Amaldi had begun to discuss with some of his colleagues the need to create a European laboratory of fundamental physics, equipped with the accelerators which could compete with the best large American centres, in particular with Brookhaven National Laboratory, which was completing its Cosmotron.

As a high school student I had often heard my parents talk about these subjects and I took part, during our frugal daily meals, in animated discussions with notable European physicists. Among them, I remember the Frenchman Pierre Auger and the Englishman Cecil Powell, who had been awarded the Nobel Prize in 1950 for the discovery of the charged pion using nuclear emulsion techniques (Fig. 1.16).

In June 1950 the Nobel Laureate Isidor Rabi – one of the founding fathers of Brookhaven National Laboratory – participated as United States delegate in the General Assembly of UNESCO (United Nations Educational, Scientific and Cultural Organization) held in Florence. Having previously discussed the subject with the people mentioned above and having obtained the authorization of the American government, Rabi proposed that UNESCO should “*assist and encourage the formation of regional research laboratories in order to increase international scientific collaboration*” (UNESCO 1950). In the discussions in Florence there had been no mention of particle accelerators but three days later, during a press conference, Rabi spoke explicitly of this possibility.

To discuss Rabi’s proposal, in December Denis de Rougemont – who had become Director of the newly created European Cultural Centre – assembled in Geneva with Auger’s help a group of Belgian, French, Italian, Norwegian and Swiss physicists. The final document recommended “*the creation of an international laboratory centre based on the construction of an accelerator capable of producing particles of an energy superior to that foreseen for any other accelerator already under construction*” (Centre Européen de la culture 1950). The cost estimate (of 20–25 million dollars) was taken from the paper prepared by the Italian Bruno Ferretti, professor of theoretical physics in Rome.

This proposal was taken forward at the end of 1950 by Pierre Auger who – at the time – directed the Natural Science division of UNESCO. He could act because, immediately after the Florence assembly, about $10,000 were donated to UNESCO by Italy, France and Belgium for the organization of the first meetings of a group of consultants from eight European countries.

Auger was a master of experimental physics; among other things he had discovered that high-energy cosmic rays produced cascades of particles in the atmosphere, which had been named ‘extensive air showers’. It was impossible not to be impressed by Auger; he was tall, with a beard making him resemble a cartoon scientist, and came from a cultivated background, writing poetry in his spare time. He made me the present of a book, when I was a teenager passing a summer in his family holiday home in Brittany. The house was located in a village called, by physicists who knew of it, 'Sorbonne on Sea' ('Sorbonne plage') because it was frequented by the families of eminent Parisian professors, among whom – in the 1920s and 1930s – was Marie Curie.

In May 1951 in Paris, the seat of UNESCO, the 'Board of Consultants' met for the first time and two goals were established: the very ambitious project to build a proton synchrotron second to none in the world and, in addition, the construction of a 'standard' machine – a synchrocyclotron – which would allow an early start to experimentation. The government delegates met twice more under the auspices of UNESCO, which invited all its European members, including the countries of Eastern Europe; these, however, did not show up with the exception of Yugoslavia. Thus twelve countries from Western Europe were represented at the two conferences held in Paris at the end of 1951 and in Geneva at the beginning of 1952.

Auger and Amaldi wanted from the outset to create a truly international laboratory dedicated to particle accelerators, preferably in a neutral and geographically central location like Switzerland (Fig. 2.10). The physicists from northern Europe, gathered around the great Niels Bohr, preferred instead the idea of a decentralised organisation, which would exploit infrastructure and accelerators in already existing laboratories. There were discussions and exchanges of very heated letters but, in the end, the idea of a centralised structure prevailed, thanks to the speed with which the southern European physicists moved.

Eventually the agreement to create the 'Conseil Européen pour la Recherche Nucléaire' (CERN) was signed in Geneva in February 1952 and nominations made. Edoardo Amaldi became Secretary General of the provisional organisation; the Dutch Cornelis Jan Bakker was nominated director of the Synchrocyclotron group, the Norwegian Odd Dahl director of the Proton-Synchrotron group, the Frenchman Lew Kowarski director of the Laboratory group and Niels Bohr as director of the Theoretical group. On that occasion a telegram was sent to Isidor Rabi:

> *We have just signed the Agreement which constitutes the official birth of the project you fathered at Florence. Mother and child are doing well, and the Doctors send you their greetings.* (CERN Archives 1952)

The CERN Convention was established in July 1953 and signed by the 12 founding Member States: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom and Yugoslavia. The ratification process by the Parliaments was lengthy– at least in the mind of the promoters – so that only on 29 September 1954 was the required number of ratifications reached, and the European Organization for Nuclear Research then came officially into being. However the old acronym CERN was kept, even if it is now read 'European Laboratory for Particle Physics'.

Sixty years on, around ten thousand physicists and engineers, originating from almost every country in Europe and the world, work at CERN – the largest physics laboratory in the world – demonstrating that the original guidelines so determinedly

Fig. 2.10 Pierre Auger (on the *left*) with Edoardo Amaldi at the meeting of the CERN Council held in Paris in 1953 (Courtesy Edoardo Amaldi Archive – Department Of Physics, University of Rome La Sapienza)

upheld by Amaldi and Auger have proven successful. Carlo Rubbia – Nobel Prize for physics in 1984 and Director General of CERN from 1989 to 1994 – has written in a biography of Edoardo Amaldi, published by the Royal Society:

> *Amaldi was inspired by two clear principles. First he was convinced that science should not be pursued for military purposes. Secondly, Amaldi was a dedicated European. He realised very early that no single European nation could hope to hold its own scientifically and technologically. To compete they had to collaborate. The [CERN] laboratory has become the greatest physics centre in the world, where more than half the particle physicists on our planet work. The dream of Amaldi to re-establish a centre of excellence and to halt the 'brain drain' to the United States has been completely realised.* (Rubbia 1991)

It was actually in 1989, when the new LEP accelerator began operation, that the flow of scientists reversed, as shown in Fig. 2.11. Since then the number of American physicists who work in Europe has been larger than the number of European physicists who work in the USA.

Today the number of CERN member states is twenty-one, nine more than at the beginning. At the end of 2012 Israel and Serbia were appointed Associate Members in the pre-stage to membership; in 2014 Israel joined as full member. In addition the United States, Japan, the Russian Federation, India and Turkey participate with the status of 'observer states' in the meetings of CERN Council and have thousands of researchers performing experiments at CERN. All these countries contributed – with many others [1] – to the construction of the latest accelerator, the *Large Hadron Collider* or LHC, and its detectors.

[1] Non-member states with co-operation agreements with CERN include Algeria, Argentina, Armenia, Australia, Azerbaijan, Belarus, Bolivia, Brazil, Canada, Chile, China, Colombia, Croatia, Ecuador, Egypt, Estonia, Former Yugoslav Republic of Macedonia (FYROM), Georgia, Iceland, Iran, Jordan, Korea, Lithuania, Malta, Mexico, Montenegro, Morocco, New Zealand, Pakistan, Peru, Saudi Arabia, Slovenia, South Africa, Ukraine, United Arab Emirates and Vietnam.

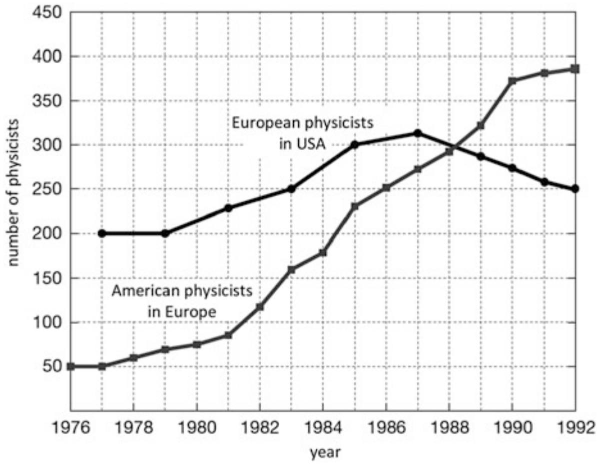

Fig. 2.11 The number of particle physicists originating in the USA who work in Europe between the second half of the 1970s and the beginning of the 1990s, compared to the number of Europeans who work in the United States. In 2012 about 1,000 American physicists and engineers were carrying out experiments at the CERN accelerators, mainly LHC

Choice of the Large Accelerator

In August 1952, awaiting the ratification of the international treaty by the parliaments of the twelve member states, which would formally approve the new organisation, a delegation of experts visited the then unfinished Brookhaven Cosmotron and learned about the recent invention of strong focusing. The visitors were prestigious: the Norwegian Rolf Wideröe, inventor of the linear accelerator which had inspired the young Lawrence, the Englishman Frank Goward, who had built the first European electron-synchrotron, and another Norwegian: Odd Dahl, leader of the delegation. Odd Dahl was a remarkable character, with a strong physique and adventurous spirit (Fig. 2.12). In 1922, at the age of 24, he decided to join the expedition to the North Pole organised by the great explorer Roald Amundsen, as the pilot of a small plane. On board the icebreaker *Maud*, aircraft and crew let themselves drift at the edge of the pack ice, so as to approach as close as possible to the Pole.

With the boat trapped by ice, the plane permitted exploration of the surrounding area; these were among the first polar flights to take off from a ship. The event which signified the start of Dahl's scientific career occurred a few months after the departure of the expedition; during a landing the plane broke up, forcing Dahl to remain on board the ship for more than 2 years as a prisoner of the ice, together with other members of the expedition. Despite lacking any scientific training, he used this time to study physics, constructing very sophisticated instruments and undertaking geophysical observations. He recounted that these were very productive years, completely dedicated to study and work, even if – being the youngest member of the team – he did not have the right to begin a conversation with his fellow adventurers.

On his return, he went to Washington to work on one of the first electrostatic accelerators and became a renowned expert at international level. Returning to

Fig. 2.12 In the Smithsonian Institution Archives one can find this picture of Odd and his wife Anne "Vesse" Dahl (Courtesy of Smithsonian Institution Archives)

Norway in 1936, he built three particle accelerators and later, after a few years working in CERN, he led the construction of the first nuclear reactor built by a small country.

Kjell Johnsen, Dahl's most brilliant pupil, described the impact of the invention of strong focusing on the construction of the CERN synchrotron in this way:

> *Dahl at once saw the implications and convinced his group that this was the way to go. All effort was immediately switched. That autumn, CERN's Council was also convinced, and one of the most important decisions in CERN history was made. Intuition governed the choice more than knowledge. It would have been much easier (as other laboratories did and later regretted) to have played safe. Had CERN gone for a 10–15 GeV scaled-up Cosmotron, its future would have been very different. It was also a very unselfish decision for Dahl, because the whole nature of the Proton Synchrotron Group work changed. Instead of being essentially an engineering group scaling up an existing machine based on well-established principles, it became a physics group studying the theory of accelerators, only later returning to engineering design. To lead this demanded full-time commitment, which Dahl could not give, and he returned to Norway.* (Johnsen 1994)

In October 1952, during the third session of the CERN Council meeting held in Amsterdam, the Council decided to construct – without increasing the cost – a 25 GeV synchrotron based on the new ideas, instead of the 10 GeV weak focusing synchrotron which was foreseen before the Brookhaven visit. A similar decision had been taken at Brookhaven for an increase to 30 GeV energy of the original 3 GeV Cosmotron and the construction work for the two synchrotrons – European and American – started at the same time. It is interesting to note that during the same Council meeting Geneva was chosen as site of the European laboratory.

The CERN Proton Synchrotron (PS), which has a circumference of more than 600 m, started operation in 1959, while the AGS (‘Alternating Gradient Synchrotron’) in Brookhaven, of about 800 m length, began to accelerate particles several months later.

Over more than 50 years of operation, the Proton Synchrotron, the historic first CERN machine, has accelerated all types of particle: electrons and positrons, protons and antiprotons, as well as heavy nuclei such as lead.

John Adams and the PS

The construction of the Proton Synchrotron was led by John Adams, a self-made man who – with a war invalid father – could not go to university and in 1939 had obtained a modest Higher National Certificate, at the age of nineteen, at a London technical college. After having worked during the war on radar development, in 1945 he was employed by the UK Atomic Energy Research Establishment (AERE) in Harwell, gaining the responsibility of lead engineer in charge of construction of the first large European accelerator, a 175 MeV synchrocyclotron which began operation in 1949. His success in this difficult challenge drew him to the attention of the Harwell director, Sir John Cockcroft, the Nobel Laureate who had built the first electrostatic accelerator with Walton.

Adams was recruited to CERN at the age of 33, following a meeting organised by Cockcroft with Amaldi, who was then 48 years old. Amaldi described the events of that day:

> *I met John Adams for the first time on 11 December 1952 in London at the Savile Club, where both of us were invited to lunch by John Cockcroft. On the telephone I had expressed to Sir John the desire to exploit my trip to London to meet some young British physicists and engineers who could be interested in participating in the construction of the European Laboratory. At lunch I was immediately impressed by the competence of John Adams in accelerators, his open mind on a variety of scientific and technical subjects, and his interest in the problem of creating a new European laboratory.*
>
> *In the early afternoon I was received, together with Ben Lockspeiser - Secretary of the Department of Scientific and Industrial Research (DSIR) - and Sir John, by Lord Cherwell, scientific adviser to the then Prime Minister, Winston Churchill. As soon as I was introduced to him in his office, he said that the European laboratory was to be one more of the many international bodies consuming money and producing a lot of papers of no practical use. I was annoyed, and I answered rather sharply that it was a great pity that the United Kingdom was not ready to join such a venture, which, without doubt, was destined for full success, and I went on by explaining the reason for my convictions. When we left the Ministry of Defence I was unhappy about my lack of self-control, but Sir John and Sir Ben were rather satisfied and tried to cheer me up.*

> *Shortly after 4 p.m. I left London for Harwell. The conversation during the three hour drive confirmed my first impression of John Adams; he was remarkable by any standard, and he was ready, incredibly ready, to come to work for CERN. I was also impressed by the other young people I met at Harwell. Contrary to the impression that I had got from Lord Cherwell early in the afternoon, they were not at all insularly minded.* (Amaldi 1986)

After a few weeks Sir Ben sent a letter requesting observer status for the UK in the provisional organisation and the DSIR (Department of Scientific and Industrial Research) began to contribute 'gifts', as they were called, which precisely corresponded to the fraction of the required investment, calculated according to the same rules applying to the other eleven countries.

In September 1953 John Adams became a CERN staff member and was made responsible for construction of the PS when, in March 1954, Frank Goward died suddenly after succeeding Odd Dahl in leading the acceleration group.

Before arriving in CERN Adams had already made a great contribution to the planning of the PS when, in winter 1952, it was discovered that the application of strong focusing, adopted in the first design, introduced such instability that the proton beams would have been lost during the acceleration. The magnet design was changed, such that the focusing was made much less strong, and the weight of the magnets increased from 800 to 3400 tons. In this, and in many other difficult decisions that became necessary, Adams demonstrated all his qualities as an engineer and a manager, maintaining his calm even in the most stressful moments and identifying – with the contributions of all – the most appropriate engineering solution.

The CERN accelerator experts have always been of very high standard, but I do not think I exaggerate in claiming that the success of all the accelerators built by CERN, and especially the LHC, have their roots in the quality of the work carried out under the guidance of John Adams, during the 5 years of the PS construction (Fig. 2.13).

The PS began operation on 24 November 1959 while the AGS (Alternating Gradient Synchrotron), constructed in parallel at Brookhaven, accelerated a beam of protons to 33 GeV 6 months later. Despite the sophistication of the theory of strong focusing synchrotrons, at that time many aspects of the behaviour of proton bunches during the acceleration were still very obscure, so that in the first Quarterly PS Report one can read a sentence, possibly written by Adams (Fig. 2.14): "*The situation in December 1959 was that the synchrotron had worked successfully to its design energy, and already beyond its design current, but with its builders and operators in a state of almost complete ignorance on all the details of what was happening at all stages of the acceleration process*." (CERN PS 1960)

At this point I want to stress that, the PS would never have been built so efficiently and in such a short time without the active help and presence at CERN of Brookhaven specialists; in the relations between the two laboratories the collaboration was more important than the competition.

Today, the PS is still the beating heart of the research centre, because it supplies the first accelerating push to the particles which are injected into the LHC ring.

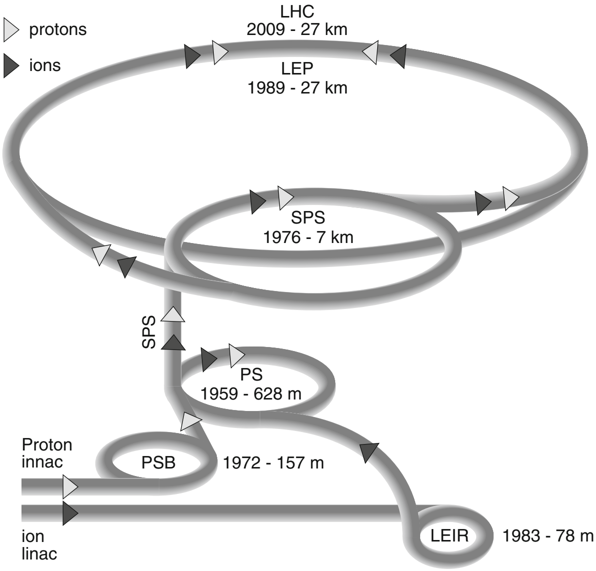

Fig. 2.13 The CERN accelerator complex

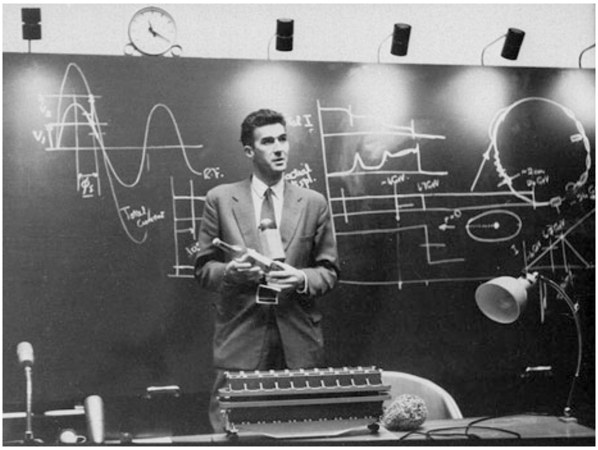

Fig. 2.14 In the CERN Auditorium John Adams announces that the night before the PS accelerated protons up to 25 GeV (Courtesy CERN)

The particles accelerated by the PS first enter the SPS and then are directed into the LHC ring with an energy of 450 GeV, as the diagram of Fig. 2.13 shows.

To add a personal story, at this point I should say that I arrived in CERN for the first time a few months later. I also visited the Proton Synchrotron, that I knew from the outset, and the enormous, completely empty, experimental halls where I saw a few experimenters carrying particle detectors in their arms, which were then arranged – it seemed to me with great uncertainty – around the few 'targets' then available. In fact, the PS had functioned much earlier than foreseen, taking the CERN scientists by surprise. Among other things, they did not have the expertise of their Brookhaven colleagues, trained in the USA on many working accelerators of the time. Precisely because of this difference in background, the physics results obtained at the AGS were superior to those from the PS for more than 10 years.

In those few exciting days I decided to apply for a scholarship with the intention of taking an absence from the ISS laboratory for a couple of years. Thus I joined a CERN research group and I worked on a series of experiments mainly dedicated to understanding the properties of antiprotons, the antiparticles of the protons that had been discovered 5 years before with the Berkeley Bevatron.

The 25 GeV protons extracted from the PS were guided by a 'transport line', built of bending magnets and of quadrupoles, and they struck a fixed target, which could be a piece of carbon or a container with a specific fluid inside. In some experiments the creation of new particles caused by the collisions of the protons with the target was studied; among them were antiprotons. In others the collision products were themselves formed into 'secondary beams' of particles, which would normally not occur in nature; these were antiprotons, pions and muons. Their properties could then be studied bombarding other fixed targets with these secondary beams.

In 1962 I returned to Rome with my family but I continued to go back periodically to Geneva to take part in another series of experiments, in which nuclear emulsions and cloud chambers were replaced by a new kind of particle detector: the 'bubble chamber' – developed by Luis Alvarez – which had a very important role in the development of sub-nuclear physics.

In a bubble chamber (Fig. 2.15a) the tracks of charged particles are visualised by means of small bubbles that form in a liquid that is 'superheated', i.e. held at a temperature and pressure such that – at the instant the photo is taken – it is just at the boiling point. In these unstable conditions, the energy of the electric charges freed in the liquid by the passage of a charged particle causes local vaporisation of the liquid and thus the formation of micro-bubbles.

Figure 2.15 shows two photos taken by a camera in a hydrogen bubble chamber. The liquid, held at 250° below zero, is at the same time the fixed target and the means of displaying the trajectories travelled by the particles.

In the figure, the charged particle tracks are slightly curved, due to a magnetic field, which is orthogonal to the plane of the paper; from the curvature of each one it is possible to estimate the energy of the particles, and thus calculate their masses applying the law of conservation of energy. The masses of the new particles created in the second collision between a pion and a proton from the hydrogen are computed to be 0.5 GeV (for the kaon K^0) and 1.1 GeV (for the lambda Λ^0).

The Limits of Fixed Target Accelerator Experiments

When a fast pion strikes a proton at rest in a bubble chamber (Fig. 2.15b), not all the total energy it carries is useful for producing the mass of new particles. In fact, a non-negligible part of the incident particle energy is 'wasted' because, after the

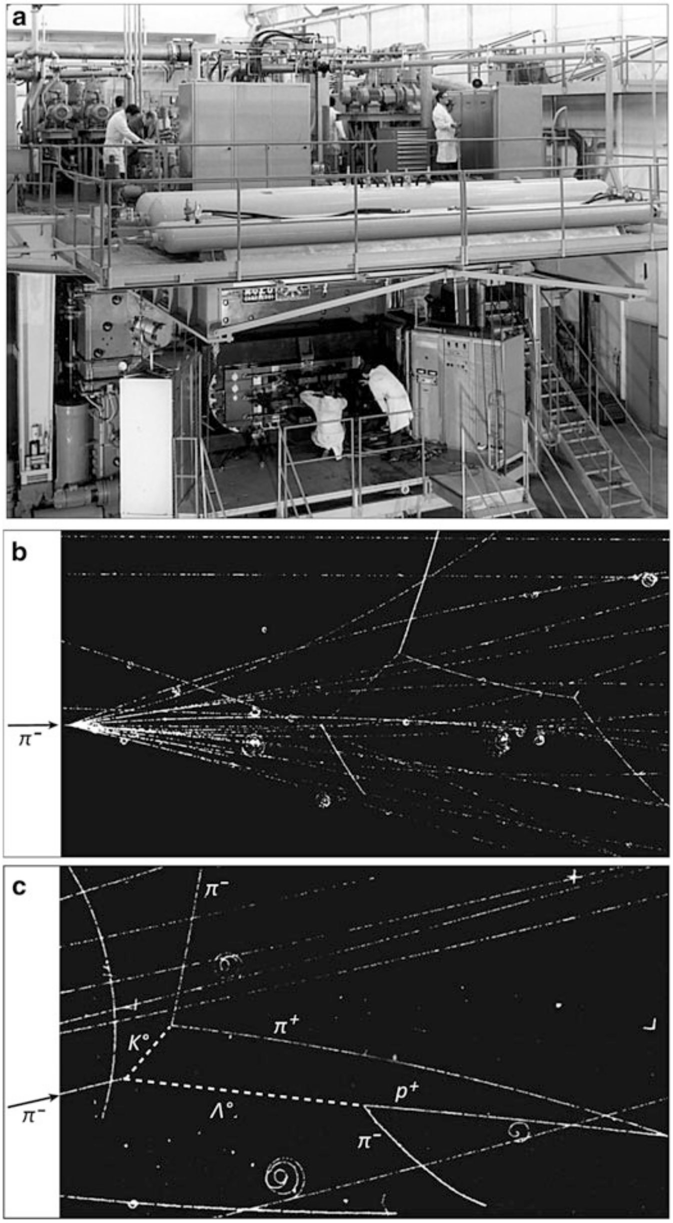

Fig. 2.15 The 2-m hydrogen bubble chamber began to operate in 1967 in a secondary beam from the PS. Below are two events: in the first the collision between an incident pion and a proton creates many particles; in the second two neutral particles are created (a kaon K^0 and a lambda Λ^0 with trajectories indicated by the dotted lines). After a few centimetres both decay into two charged particles ((**a**) Courtesy CERN; (**b**) CERN, Science Photo Library; (**c**) Courtesy Florida State University)

collision, the produced particles continue to move, carrying with them some energy owing to their motion, i.e. their kinetic energy. The production of new particles would be much more copious if the two particles collide one against the other while both are in motion, in the same way that the damage caused by a head-on collision of two lorries is much greater than when a lorry collides with a wall. This is actually what happens in particle colliders, which will be discussed in the next chapter.

To explain in a simple way the energy advantage, consider the collision of a *very energetic* positron with a *stationary* electron, in which the two particles annihilate producing a flash of energy. If the positron travels at 99.99 % of the speed of light, its total energy 35.3 MeV is obtained multiplying the mass ($M = 0.5$ MeV) by the relativistic factor 70.7 quoted on page. Because the stationary electron has only the energy of its mass ($M = 0.5$ MeV), the flash has energy equal to $35.3 + 0.5 = 35.8$ MeV; it continues to move, by inertia, in the direction of motion of the positron.

Now suppose that the flash of energy, decaying, produces two particles of equal mass and let us ask what is the maximum value of the mass of each of them. At first sight it might seem that, having 35.8 MeV available, the mass of each of the particles could equal 17.9 MeV. However this is not true because the two particles cannot be produced at rest; the flash is in motion and, by inertia, the moving particles also travel with a non-negligible kinetic energy, which reduces the amount of energy available for the creation of their masses.

To determine the maximum value of the mass of the two particles produced, it is necessary to imagine to 'ride' the energy flash. In this case, Einstein's relativity tells us that the total energy of the flash, *seen from rest*, is given by a formula that is essential in the history of particle accelerators. For incoming particles of large velocities the formula can be written in an approximate and compact form:

$$\text{Available energy in MeV} = \sqrt{2ME},$$

where the M (mass of the target) and the E (total energy of the projectile) are both measured in MeV.[2]

This energy is available for creation of the two new particles that, from the very special perspective of the stationary flash, depart in opposite directions and with equal kinetic energies. Thus the energy which can be spent on the masses and kinetic energies of the new particles equals $\sqrt{2 \times 0.5 \times 35.3} = \sqrt{35.3} = 5.9\,\text{MeV}$, much less than the 35.8 MeV which the flash possessed when it was seen in a state of motion. Therefore the two particles that can be produced have masses not greater than half of 5.9 MeV, i.e. 2.95 MeV and *not* half of 35.8 MeV, which would be 17.9 MeV.

[2] The same formula applies if the available energy, the mass M and the energy E are all measured in GeV, as it is done most often in this book.

The formula therefore tells us that the collision between a very fast moving particle with a stationary one is an inefficient way to create new particles; in the example – because 5.9/35.8 = 0.16 – only 16 % of the total energy can be transformed into mass and kinetic energy of the new particles. Moreover, the efficiency diminishes gradually as the energy of the positron increases; if it were to have 3,580 MeV, i.e. an energy 100 times greater, because of the square root which appears in the formula, the available energy would be 59 MeV, only 10 times larger, and the efficiency would be reduced to about 1.6 %.

The same formula also holds in the case in which the particles are different one from the other, as in the case of the collision of a fast electron with a proton at rest. In all cases the efficiency decreases greatly with the growth of the energy that the accelerator imparts to the projectile particle. Indeed, the square root of the formula conveys a grave difficulty in using collisions with a fixed target: to *double* the available energy, it is necessary to *quadruple* the energy of the incident particle.

In the PS, for example, which is 600 m in circumference (Fig. 2.13) and produces protons of 25 GeV, the energy available in the collision with a proton of a target equals $\sqrt{2 \times 1 \times 25} = 7.1\quad$ GeV. If the energy of the proton is doubled, rising from 25 to 50 GeV – with a synchrotron of 1,200 m circumference – the energy available increases from 7.1 GeV to only 10 GeV (because $\sqrt{2 \times 1 \times 50} = 10$ GeV).

Of the 50 GeV energy which the proton has acquired in the acceleration cycle, only 10 GeV is available to produce new particles. After the collision with the fixed proton, the final particles retain a large fraction of the original energy, while only a small part is usable for creating new particles.

Is there another less wasteful way to increase the available energy? The answer is yes; the collision between two protons, moving towards one another with equal total energy E, is much more efficient compared to a collision between a moving proton and a fixed target, because all the energy is available to produce new masses and to provide the kinetic energies of the final particles:

$$\text{Available energy} = E + E = 2E.$$

To reach 10 GeV, each of the two protons must have an energy of only 5 GeV. To achieve this, the synchrotron which accelerates one of the beams of particles could have a circumference 10 times smaller than a 50 GeV synchrotron and therefore would be 120 m long instead of 1,200 m.[3] This type of accelerator is what we call today a 'collider'.

[3] The circumference of the synchrotron, to achieve a certain total energy, is determined by the magnetic field in the bending magnets. If this is assumed to be fixed, usually at the maximum practical value, the size of the ring must increase proportionately with the total energy.

Springer
http://www.springer.com/978-3-319-08869-3

Particle Accelerators: From Big Bang Physics to Hadron Therapy
Amaldi, U.
2015, XVII, 284 p. 145 illus., 28 illus. in color., Softcover
ISBN: 978-3-319-08869-3