Chapter 2

The 600 MeV Synchrocyclotron: Laying the Foundations

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2.1 Introduction

On 15 February, 1952, the agreement was signed constituting a "Council of Representatives of European States for Planning an International Laboratory and Organizing Other Forms of Co-operation in Nuclear Research." I. Rabi, Nobel Prize 1944, considered this "The official birth of the project fathered in Florence" with a resolution submitted to the Fifth General Conference of UNESCO in June 1950. While the UNESCO resolution was deliberately vague and abstract, it lent authority to the ensuing debates among the leading scientists, spearheaded notably by E. Amaldi, P. Auger and N. Bohr (Nobel Prize 1922), on the possible mission of such an international laboratory, considering accelerator-based fundamental ("nuclear") physics as the most attractive choice. The signing of the February 1952 Agreement set in motion a sequence of events unfolding with astounding swiftness and purposefulness. Barely three months later, in May 1952, the first meeting of the (provisional) Council agreed on a detailed and prescient "business plan" for the future laboratory, laid down the major lines for two accelerators and established the corresponding study groups in several European countries. Council also initiated and sponsored a conference, to be held in June 1952 chaired by Bohr to evaluate scientific topics related to the planned laboratory.

The second Council meeting was held in June 1952, following the two-week Copenhagen Conference. At that meeting, W. Heisenberg (Nobel Prize 1932) summarized the key conclusions of the conference in a remarkable *tour d'horizon* of particle physics and accelerators. This led to the recommendation that one group should design a 600 MeV synchrocyclotron (SC) and a second group should undertake a feasibility study of a powerful proton synchrotron (PS) [Box 2.1]. The larger one would be a frontier proton machine with energies in the 10 to 20 GeV range, while the smaller one should be based on well-established principles and provide beams as soon as possible. This would allow the laboratory and the community of users to acquire expertise in the techniques required to handle a variety of particle beams (protons, pions, neutrons, muons) [1, 2]. In short, the small machine should be ready early, it had to be successful, and it had to be meaningful for physics.

Council adopted the report on the Copenhagen Conference. At the same meeting, C. Bakker was appointed to lead the group responsible for the design and construction of the SC. By October 1952 the group had divided their work into five main sectors and distributed the responsibilities among laboratories in several European countries. Six months later cost estimates for the major items were at hand; by the end of 1953 the group was ready to start the tendering process with industry. Formal construction started in June 1955, as shown in Fig. 2.1.

Fig. 2.1. On 1 June 1955 F. Bloch, CERN's first Director-General, watched by M. Petitpierre, President of the Swiss Confederation, laid the foundation stone of the SC.

In parallel with the technical work, steps were taken to establish the permanent organization. In October 1952 Geneva was chosen to be the site for the laboratory. In April 1954 F. Bloch, Nobel Prize 1952, was designated as first director-general of the yet-to-be established permanent Organization. In May 1954 earth was broken in the fields just outside Geneva. By September 1954 all documents for the ratification of the Convention establishing the permanent laboratory were deposited at UNESCO and the provisional CERN Council disbanded. In the following month the first permanent Council appointed C. Bakker to lead the SC and J. Adams the PS construction. However, already in September 1955 C. Bakker was named Director-General, succeeding F. Bloch, who, on leave from Stanford University, could only serve the Organization during its first year. W. Gentner was appointed head of the SC. He recruited engineers and physicists, building the team responsible for the SC construction and working in an atmosphere of academic freedom. CERN's by now traditional dual role of building new accelerators at the frontier of technology and participating in cutting-edge research owes much to the effort and vision of Gentner.

Although the SC was the biggest European accelerator at the time of construction, it was not intended to be a 'pioneering machine' — in contrast to the PS, which was designed in parallel and opened new accelerator territory. It was inspired by and conceived as a scaled-up version of the Chicago 450 MeV machine where Enrico Fermi and his group had done their fundamental work on pion-nucleon interactions. The choice of 600 MeV, possibly influenced by a suggestion attributed to Fermi, was a compromise between the wish for the highest possible energies and the need to keep costs safely under control. The magnet, which is huge and a major cost driver, determined the energy. With magnetic fields of 1.8 T, achievable with good-quality, low-carbon steel, protons with a kinetic energy of 600 MeV have circular orbits with a radius of 2.25 m, setting the scale for the diameter D of the SC magnet, D = 5 m. The magnet was a classic window-frame design with a 45 cm gap (Fig. 2.2). The iron magnet yoke and the coils were the first major items to be ordered, because they required long manufacturing times, would present transport problems and would condition the assembly of all other elements. The pole-faces were manufactured in France, made from more than 50 pieces, each weighing more than of 50 tonnes. The two coils for the SC magnet, each weighing 60 t and measuring 7.2 m in diameter, were fabricated in Belgium. For reasons of cost, weight and relative ease of manufacturing, an aluminium alloy was chosen.

Accelerators **Box 2.1**

These devices accelerate charged particles such as protons, antiprotons, ions, electrons and positrons. They come in two main types: linear and circular.

Linear accelerators (linacs) work by passing the beam through a linear array of accelerating radio frequency (RF) fields interspersed with focusing elements and diagnostics. At CERN they are used to accelerate heavy particles (protons, ions) after the source, serving as injectors to the next stage (and also accelerating radioactive ions right up to the experiment). Protons reach 50 MeV (160 MeV) kinetic energy in present (future) injectors. Top energy is limited by the difficulty to adapt to particle velocity and diminishing returns on investment. For higher energies synchrotrons are more suitable, but linacs must be used for accelerating light particles (e^+ and e^-) to energies beyond the reach of conceivable large synchrotrons (e.g. E_{CM} = 0.35 TeV of FCC-ee, see 12.1) where radiation loss makes synchrotrons inefficient [Box 4.1].

Circular accelerators come in two types: *cyclotrons* and *synchrotrons*. *Cyclotrons* have a single large cylindrical magnet producing a constant vertical field, with particle injection from a source at the centre. The particles are accelerated by a RF field of fixed frequency, which twice per turn provides a kick to the particles. These spiral outwards due to the combined action of magnetic field and acceleration until they emerge at the edge of the magnet. Higher energies are reached with an improved version, the *synchrocyclotron*. If E_k and $E_0 = m_0 \cdot c^2$ are respectively the kinetic and rest energy of the particle, the RF frequency $\propto E_0 / (E_k + E_0)$. For cyclotrons $E_k \ll E_0$ and the RF frequency can be constant. This is not the case at higher energies, where the RF must vary to ensure synchronism between the electric field and the particles. This technique extended the range of cyclotron-type machines, but to attain still higher energies the magnet becomes unrealistically large. The way out is the *synchrotron*, where an array of relatively small dipole magnets deflects the particles so that they follow a quasi-circular orbit. This structure has been adopted for most of CERN's accelerators, storage rings and colliders. The particles are accelerated by RF cavities located between the magnets. The magnetic field is ramped so that particles receiving the accelerating kick in the cavities stay on the same orbit. The RF is synchronized with the magnetic field such that the particles, grouped in bunches, always experience an accelerating electric field, with the decelerating phase occurring in gaps between bunches. The beam is focused with quadrupoles, interspersed among the dipoles. They provide a magnetic field that increases linearly across the aperture, focusing in one plane but defocusing in the orthogonal plane. Alternating focusing and defocusing quadrupoles results in overall focusing. This *alternating gradient principle* has been adopted for all synchrotron-type accelerators at CERN. The quadrupole fields can be superimposed on the dipole field of the bending magnets, so-called *combined-function magnets*. If the quadrupoles are separate, the array of magnets is a *"separated-function lattice"*. This provides greater flexibility for tuning the focusing and is used in most recent synchrotrons. Magnets producing non-linear magnetic fields are required at certain points in the lattice for special purposes, e.g. control of beam instabilities, and pulsed dipole magnets with short rise and fall times are required for injection and ejection.

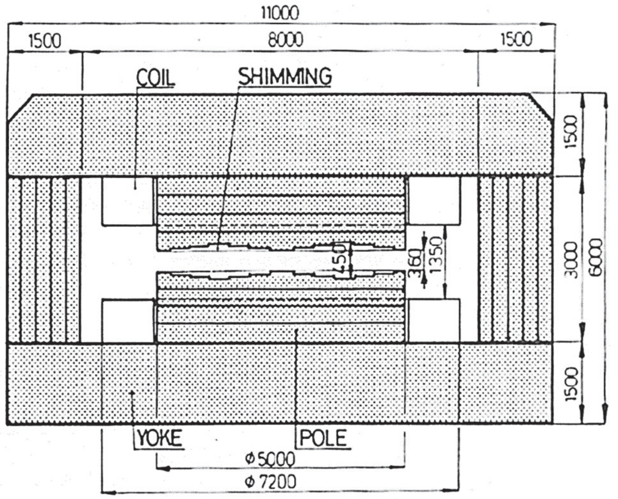


Fig. 2.2. Cross section of the SC [2]. Transport of the 7.2 m diameter coils to Geneva after shipment from Belgium to Bale was an adventure. Passing through the villages required tilting the coil on the lorry, leaving 3 cm clearance between the coil and the walls of the houses [2, 3].

The radiofrequency system (RF) providing the accelerating electric field for the protons was arguably the most challenging item for the CERN engineers and their industrial partners. The frequency of the electric field accelerating the particles has to change to stay in tune with the revolution frequency, which decreases due to the relativistic effects at energies higher than a few tens of MeV. This is done by changing the value of a capacitor in the resonant circuit. Most synchrocyclotrons had adopted mechanical, rotating capacitors, reminiscent of the tuning capacitors of old-fashioned radio receivers. To avoid recurrent difficulties encountered with rotating capacitors, arising from operation in high vacuum, overheating, broken bearings and sparking, the CERN team adopted a solution, as bold as it was elegant: a vibrating capacitor in the form of a tuning fork, manufactured from a carefully chosen aluminium alloy. The self-oscillating operation at 55 Hz was driven from the base of the fork, via an electromagnet (Fig. 2.3). Feedback circuits assured the control of the amplitude. During the intense development period there were many problems, e.g. parasitic vibrations and metal fatigue, and unconventional solutions adopted. Not surprisingly, the tuning fork was on the critical path for timely completion of the SC. With one week to go to the official inauguration, to which ministers, government officials and dignitaries had already been invited, the RF system was still not ready. But the problems were solved, and operation of the accelerator started on 1 August 1957, after a remarkably short construction time of three years [4] (Fig. 2.4).

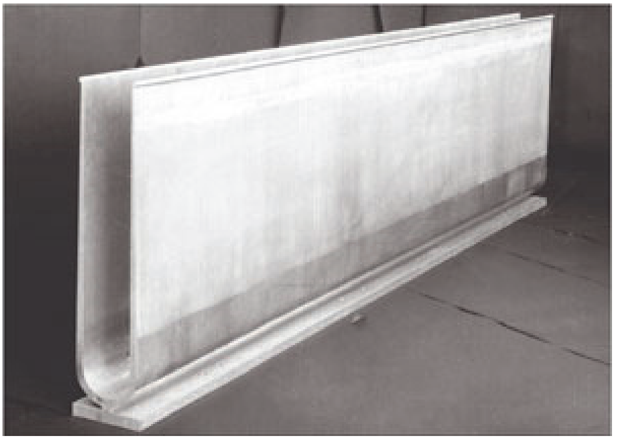


Fig. 2.3. The 2 m-wide aluminium alloy tuning fork, part of the variable capacitor used to modulate the frequency of the RF system for the SC.

Fig. 2.4. The SC in December 1957, ready for physics.

The successful completion of the SC was a milestone for CERN: it gave confidence to its staff and proof to the governments that large international collaborations between scientists and industry can be made to work. It provided the European physics community with an instrument for research on a par with those in the USA.

Next on the agenda was optimizing the SC for physics use and learning to develop the research programme. Beams of high energy particles were developed and their intensity gradually increased. Initially, such beams could only be produced from internal targets that could be remotely positioned at different radii and azimuthal angles. One of the earliest such devices was a mobile chariot of a type first used at the Chicago synchrocyclotron, invented by Fermi, hence aptly called the 'Fermi trolley'. In this way, beams of neutrons, pions and muons were directed into the Neutron Hall on one side of the accelerator, while a magnetically shimmed channel allowed an extracted proton beam on the other side, from which secondary pion beams could be delivered into the Proton Hall. An internal proton beam of about 0.5 μA was available, of which about 5% could be extracted. One SC speciality was an innovative muon beam line, consisting of a series of closely spaced quadrupoles inside the 6 m thick concrete shielding wall.

One SC development aimed at improving the conditions for experimentation. Short spills of a secondary beam lasting approximately 150 microseconds were produced after the acceleration cycle every 55 milliseconds on a target of the 'Fermi trolley'. These rather short pulses were not optimal for most experiments using counter techniques. Ingenious ways were developed to "stretch" the secondary beam and to achieve a more favourable ratio of beam pulse length to acceleration cycle or "duty cycle". In one method a vibrating target intercepted the internal proton beam. Clever, but being a mechanical device, its reliability proved to be problematic. It was superseded by an elegant manipulation of the internal proton beam at the end of the cycle, where an auxiliary accelerating field gently moved the beam into the target, achieving a duty cycle of 30%.

The development of the various beams and SC operating conditions had to reflect the changing emphasis in physics research. Initially intended "to do good meson physics" the research surpassed by far these modest aspirations [5]. One reason was that during the start-up of SC operation in 1957, the physics world was shaken by a monumental revolution: in weak interactions (i.e. the force responsible for the radioactive decay of certain nuclei), the laws of physics are not symmetric under reflection in a mirror: "parity" is not conserved [Box 2.2].

Spin and mirrors **Box 2.2**

Spin is an intrinsic form of angular momentum carried by an elementary particle, a concept of quantum mechanics (QM). Any classical image to visualize spin, such as a spinning top, is quite misleading. The property 'Spin' is characterized by the spin quantum number, s, with $s = n/2$ and n any non-negative integer. Particles with half-integer spin, e.g. $s = 1/2$, are called *fermions* while those with integer spin, e.g. $s = 0, 1$, are called *bosons* [Box 6.4]. They have very different roles in the Standard Model (SM): fermions are the constituents of matter; bosons are the force carriers between them. SUSY [Box 7.2] would bring some symmetry between the two species.

The spin of a charged particle is associated with a magnetic dipole moment (MDM). MDM is proportional to spin, related by the particle's g-factor. For charged fermions, e.g. the muon, the Dirac equation gives $g = 2$. But loop corrections [Box 5.1] involving all three types of interaction, induce a slight departure from 2. Calculating and measuring the tiny $g - 2$ value is one of the triumphs of particle physics [Highlight 2.4].

QM requires the component of spin measured along any direction to take discrete ("quantized") values. Choosing as direction the particle momentum, fermions having spin $s = 1/2$ can be along the direction of momentum or opposite to it. This defines a right-handed (RH) or a left-handed (LH) fermion. A normal clockwise corkscrew (RH) pointed at a mirror has a LH image, a perfectly conceivable instrument, preferred by LH drinkers. Not only corkscrews, but also all physical systems, were thought to have a mirror image representing a possible system. Our right hand is the mirror image of our left hand, hence the term of *handedness*. This expresses the symmetry of physical systems under mirror reflection, or "parity operation (P)". This "sacred belief" was shattered in 1957, when it was shown that the weak interaction (WI) violates P and does so in a radical way: e.g. the neutrino was found to be a LH particle, but its mirror image, a RH neutrino, does not exist. Each charged fermion exists in both its LH and RH form, but couples differently to the carriers of the weak force. The W boson couples only to LH fermions. The Z couples to both species, but in different ways. The SM gives an explicit expression for these couplings, where the weak mixing angle intervenes. This is the point where the subtleties of SM testing start (Chapter 7 and Box 7.1).

With evidence for parity violation, physicists postulated that CP, the combined operation of charge conjugation C (changing a particle to its antiparticle) and P was a "good mirror". But in 1964 it was found that neutral K-mesons also violate ("break") the CP mirror in the world of weak interactions. A vast program followed, to study kaons and later beauty particles, aimed at identifying and measuring the different sources of CP violation, in particular the "direct" CP violation in meson decay (Chapter 5 and Box 3.4). In the SM the possibility of CP violation is found to be linked to the existence of three families of fermions. Another crucial fact is the dominance of matter over antimatter, which requires CP violating processes during the evolution of the Universe. However, the degree of CP violation as described by the SM does not explain the observed dominance of matter: another reason to expect Physics beyond the SM.

At LEAR an experiment has given direct proof of the non-invariance of the WI under time reversal T, and a precise demonstration of the validity of the TCP symmetry.

Good reading: R. K. Adair, A flaw in the Universal Mirror, *Scientific American*, February 1988.

Quickly a new theory of the weak interaction (technically called V-A theory), was formulated by Feynman (Nobel Prize 1965) and Gell-Mann (Nobel Prize 1969), accounting for parity violation. Weak interaction studies were to take the centre stage of SC research, leaving a legacy of several very important results. One longstanding issue was the decay of the pion into electron and neutrino, $\pi \rightarrow e\ \nu$. Assuming universality of the coupling of the pion to electrons and muons, this decay was calculated to be rare (a spin effect), at the level of 10^{-4} relative to the dominant $\pi \rightarrow \mu\ \nu \rightarrow e\ \nu\ \bar{\nu}$ decay. Several experiments searched for this decay. They failed to observe it, posing an apparent serious obstacle to the understanding of the weak interaction and to the V-A theory. One SC Team took up the challenge and succeeded, because it developed imaginative ways to suppress the background of electrons produced in the dominant decay of the pion and quickly discovered the rare decay mode at the predicted level [Highlight 2.3] [6]: a world-class experiment in the first year of SC operation! These early years saw other related fundamental studies, such as the first observation ever of the extremely rare decay-mode $\pi^+ \rightarrow \pi^0 + e^+ + \nu$, a further crucial test of the theory of weak interactions.

The muon (μ) was another preoccupation at that time (and still is today). As said famously by I. Rabi: 'Who ordered that?' Is there more to it than being a 200 times heavier copy of the electron? In a visionary experiment the decay mode $\mu \rightarrow e + \gamma$ was searched for, but not observed. Today we know this mode is 'forbidden' in the Standard Model, but it is once again the centre of interest: a finite, albeit tiny probability of such a decay would be a "smoking gun" for new physics.

Another series of studies, pioneered at the SC, made it into the physics textbooks. Electrons and muons have besides their electric charge a magnetic dipole moment involving the g-factor [Highlight 2.4], which could be precisely calculated in the newly formulated quantum field theory of electromagnetic interactions, Quantum Electrodynamics, QED [Box 2.3]. Precision measurements of the magnetic moment of the electron confirmed the theory. Measurements of the magnetic moment of the muon would either confirm the QED calculations or, if at variance, point to differences between the electron and muon. Very early on, SC researchers used muons from the decay $\pi \rightarrow \mu\ \nu$ in a pion beam in a very clever experiment. This was the first of a series of famous CERN $(g - 2)$ experiments, where the value $(g - 2)$ expresses the impact of quantum field effects on g, as explained in highlight 2.4 [7].

The experimental techniques built on the lessons learned from cosmic ray studies, with heavy emphasis on electronic counters to take full advantage of the high particle rates offered by the SC. The newly developed "plastic scintillators", sheets of a plastic doped with a fluorescent chemical, which would produce a tiny light flash, when hit by a charged particle, became dominant. With it came a new timescale, nanoseconds (10^{-9} s), rather than the microseconds characteristic of the Geiger–Müller tubes of the cosmic ray age. Photomultipliers, which register these tiny scintillation light flashes and convert them into electrical pulses, became ubiquitous. Vacuum tube based electronic instruments, amplifying, registering electronic pulses, forming logic operations ("coincidences" and "anti-coincidences") on signals from several detectors, found their way into the experiments. Information about time sequences of particles produced in a collision and their subsequent decays were displayed on traces on an oscilloscope and filmed. Films were then analysed with methods borrowed from the bubble chamber analysis. In those days the experimenters were truly "Renaissance Physicists", having to master all the skills from designing, constructing the experimental equipment and electronics to analysis and Monte Carlo calculations, mostly done after the experiment!

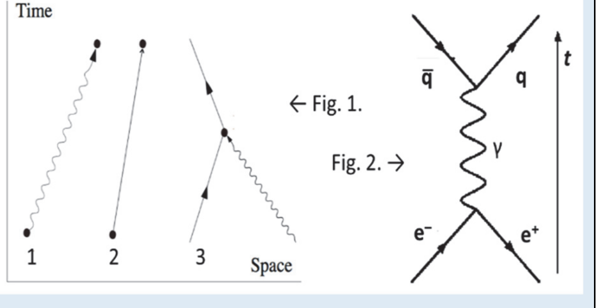
A pioneering spirit, rewarded by an unexpectedly successful research programme, characterized these initial SC years: CERN was off to a flying start thanks to the SC!

With the steady increase in intensity of the accelerator, novel programs could be imagined. One such project was ISOLDE (*I*sotope *S*eparator *O*n *L*ine *DE*tector), put into operation in 1967 [Highlight 3.8] [8]. An underground area had been constructed nearby to which an approximately 80 m long beamline delivered the extracted proton beam onto a variety of targets, e.g. uranium or other heavy elements. In the spallation or fission of these targets exotic nuclei far from stability were produced; these of course had short lifetimes, and so the design of the target had to allow the products to escape rapidly and be delivered via an analysing magnet to the detectors. ISOLDE thus started what would become a long and exciting series of experiments observing the properties of nuclei far from stability. Although a very successful venture, it was somewhat hampered by lack of proton intensity. By the early 1970s it was clear that an SC Improvement Programme (SCIP) was necessary [9], and for which the machine was shut down from June 1973 to January 1975. The aim was to increase both the internal intensity and the extraction efficiency by a factor 10. A new ion source was provided and measures taken to improve the intensity and duty cycle of the extracted beam. The tuning fork of the RF system did not meet the new requirements and had to be replaced by a rotating capacitor [Highlight 2.2]. The internal beam intensity rose to 8 μA and the extraction efficiency reached 75%: mission accomplished for the SCIP programme!

Quantum electrodynamics (QED) **Box 2.3**

The relativistic quantum field theory (QFT) of electrodynamics (ED), QED, describes the electromagnetic interaction. Its early very good — and later spectacular — agreement with experiment lent strong support to the QFT approach, ultimately culminating in the Standard Model (SM) [Box 6.4]. The theory goes back to the unified description of electricity and magnetism (Maxwell, 1861), special relativity (Einstein, 1905), and quantum mechanics (1920s). In 1928 Dirac developed the relativistic quantum equation describing the interaction of an electron (e) with a photon (γ). He treated the electromagnetic (e-m) field as an ensemble of harmonic oscillators and introduced the concept of operators creating and annihilating particles. The strength of the e-m interaction is characterized by the e-m 'coupling constant' $\alpha \sim 1/137$. As α is small, it should, in principle, be possible to compute any e-m process, expressing the result in a series expansion in α. However, it turned out that the computations were meaningful only to first order in α. Higher orders gave infinite and hence meaningless results, casting strong doubt on the validity of the theory. The breakthrough came by applying the concept of "*renormalization*", a well-defined mathematical procedure, which was used to connect these infinities to corrections of the mass and charge of particles in order to obtain their experimentally determined finite values. The infinities could *de facto* be absorbed into those constants, yielding finite results. It culminated in the relativistically invariant formulation of QED [1], finite to any order. Highlight 2.4 illustrates the marvellous agreement between theory and data. The measurement of the magnetic moment of the electron agrees with QED to better than 1 part in 10^{12}. Renormalizability is essential for any QFT to be acceptable [2], including the SM.

Three basic actions can be defined [1] as shown in Fig. 1: 1) a γ propagates from one space-time coordinate to another; 2) an e does likewise; 3) an e absorbs (or emits) a γ. Complex interactions of e and γ can be built up with the relevant actions (Fig. 2). These so-called "Feynman diagrams" visualize a process, but also represent "probability amplitudes", the square of which give the probability of a process to occur [1].



QED inspired the conceptors of the SM, and, unified with the weak interaction, it is the basis on which the model was built.

[1] R. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton U. Press, 1985).
[2] G. t'Hooft, *Scientific American* **242**, 104 (1980).

The gradual development of the new characteristics of the machine continued throughout the following years, which also saw the acceleration of heavy ions and a gradual shift in the emphasis of the physics programme. New ion sources were installed to produce beams of carbon and other ions with energies of close to 100 MeV/n. Carbon and oxygen ions were accelerated in a partially stripped state and were then fully stripped on exiting the SC before delivery to the experiments in the Proton Hall. This new line of experimentation attracted immediate interest.

However, the heavy ion experimenters gradually moved to new machines such as GANIL in the early 1980s and the SC continued with ISOLDE as practically its only client, with two alternating target stations to give the more flexibility. Then, in the late 1980s a study was made of how ISOLDE might use the 800 MeV (later, 1 GeV) beam of the Booster (PSB) [Highlight 3.4], using free beam cycles that were not needed by the PS. This was found to be perfectly feasible.

With the advent of the much more powerful PS the emphasis changed from fundamental physics studies to nuclear physics and chemistry, solid state physics, using the muon as a probe of material properties, and an ever evolving program at ISOLDE. With the move of ISOLDE to the PS machine complex, the days of the SC were numbered. The machine delivered its last beam to ISOLDE on 17 December1990 after 33 years of service — far beyond its call of duty [10].

Conceived with modest aspirations, the SC was a watershed for the European physics community providing them with a state-of-the-art accelerator facility. It drove the transition from cosmic ray- to accelerator-based experimentation. This new source of high energy particles also required new tools for their study. With cosmic rays most of the fundamental discoveries were made with ‘imaging’ detectors. Cloud chambers and nuclear emulsion stacks provided the tracks, the image of new particles and their interaction. While these techniques still played a role in the early SC research, they were inadequate to take full advantage of the factor 10^{12} intensity increase compared with Cosmic Rays, as Heisenberg remarked to the 2nd CERN Council. Work at the SC required and spearheaded a revolutionary technology: the image was replaced with digital information and logical decisions. Many highlights in this book are witness to this transformation.

Throughout its distinguished 33 years of operation the SC worked remarkably well, constantly adapting to the changing research imperatives and delivering a rich physics harvest. Today the SC has been refurbished and turned into an exhibit for the public visiting CERN. As a fitting tribute to the pioneering spirit of its ancestors the European Physical Society, EPS, has recognized it as a “Historical site of the EPS”.

2.2 The Rotary Capacitor: Tuning Acceleration

Reinhold Hohbach and Kurt Hübner

The orbital frequency of the protons in the synchrocyclotron decreases during the acceleration because of the relativistic increase of the mass of the particles and the radial decrease of the magnetic field required to focus the outwardly spiralling particles. The decrease of orbital frequency calls for a large frequency sweep of the accelerating electric field (this being the potential difference between a D-shaped metal box, called the Dee, and the grounded vacuum chamber). The Dee is located in the magnet gap where it covers about 150° of the orbital plane. The particles experience the accelerating field at the entrance and exit of the Dee. The required modulation of the radio frequency (RF) accelerating field from 30 to 17 MHz was initially obtained by means of a vibrating capacitor, the so-called tuning fork (Fig. 2.3) [11].

The synchrocyclotron (SC) was designed [11] to provide an average internal proton current of 1 μA at 600 MeV. In 1967 an improvement programme [12] was initiated to increase the current to 10 μA and improve the beam quality. Amongst other measures it was decided to raise the accelerating voltage from 20 to 30 kV and the repetition rate from 54 Hz to 500 Hz. The latter required a modification of the RF system: the tuning fork had to be replaced by a rotating capacitor, a device used in other synchrocyclotrons at that time. Figure 2.5 shows the layout of the new RF system [12, 13]. The acceleration time was 1.4 ms.

The power oscillator feeds the system through the constant value coupling capacitor C_{CL} and two rotary capacitors, for coupling (C_{cos}) and modulation with respect to earth potential (C_{mod}), both synchronized on the same shaft. Their capacitances vary as a function of the azimuthal position of the shaft. The function of C_{cos} is to present a constant load to the power oscillator, which provides 180 kW peak. The transmission line formed by the stub and the Dee has a carefully designed tapered impedance distribution to achieve the required variation of the resonant frequency for practical values of C_{mod} while keeping the voltage across the capacitors at acceptable levels.

The rotary capacitor C_{mod}, which the team affectionately dubbed Rotco (the old term for capacitor being condenser), consists of an aluminium alloy rotor of 1.5 m diameter rotating on a cantilevered shaft between earthed stator blades. It is driven by a variable speed motor and rotates in vacuum at speeds of up to 2600 revolutions per minute (rpm). Both rotor and stator blades are shaped and tapered to provide the required variation of capacitance. All blades are water-cooled and designed in such a way as to avoid mechanical resonances (Fig. 2.6).

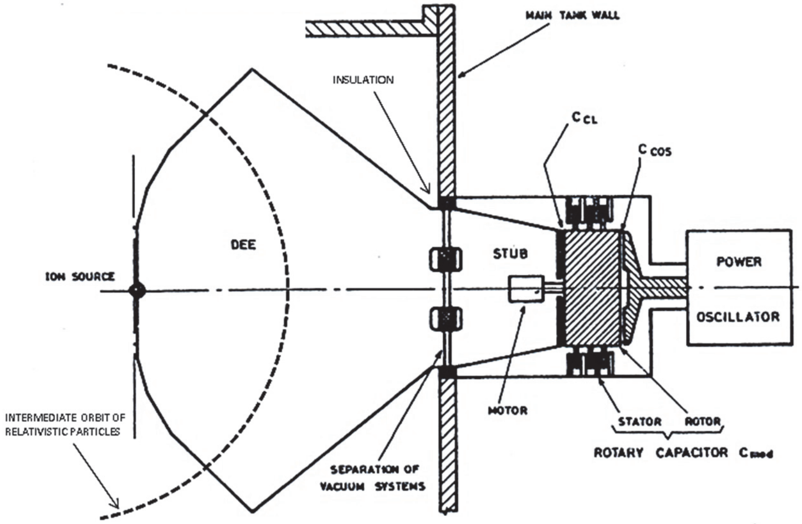


Fig. 2.5. Schematic plan view of the RF system [12].

The entire assembly was housed in an Al-alloy casing evacuated by a turbo-molecular pump that was later replaced by a cryo-pump. To reduce the risk of voltage breakdown due to oil vapour, a rotary-face seal retained the oil and a turbo-molecular pump mounted on the shaft removed any leaking oil. Despite these precautions, electrical breakdown caused by condensation of oil vapour remained a serious concern. A delicate element was the ceramic insulating bushing and the vacuum seal of the main bearing. Since the Rotco was also subject to a flux of activating high energy neutrons, two identical assemblies were constructed to provide a spare for reducing downtime after a breakdown.

The RF circuit design was initiated at CERN with modelling and simulation, and continued by industry where detailed design of the hardware was made to a functional specification and construction was started. But the project suffered significant delay and in 1973 it was agreed to transfer the partially built equipment to CERN, which undertook further development and finalised the construction. The CERN team had to carry out numerous repairs and improvements of the electrical and mechanical elements in order to get it working. The Rotco and its spare were put into operation in 1974. However, the design was intrinsically fragile and both assemblies were plagued by electrical and mechanical problems for several years, and the team had to make a continuous effort to gradually improve reliability. This has entailed the redesign of many components [14].

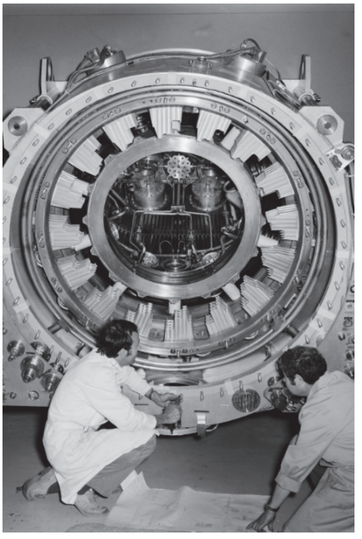


Fig. 2.6. View of the stator of the modulating capacitor seen from the generator side. The rotor is removed.

This project is an example of a technological development where the design and construction was entrusted to an industrial partner who in retrospect was over-ambitious and had taken on work that extended beyond its competence level. This was a hard lesson for CERN, signalling the need to better prepare in-house the design of complex technical apparatus, including the construction and thorough testing of models and prototypes.

2.3 Discovery of the π → eν Decay: Rare and Precious

Giuseppe Fidecaro

In 1948 at Berkeley, π-mesons were produced for the first time with an accelerator [15] and observed in its prominent decay π → μν. Several searches for the π → eν decay remained however unsuccessful. These searches were motivated by the idea that all Dirac particles, such as electrons and muons, would have the same weak interaction constant ("electron-muon universality"). Assuming the Fermi description of weak decay and the symmetric coupling of electrons and muons to π-mesons [15] the ratios R= (π → eν) / (π → μν) for the so-called Axial-Vector and Pseudo-Scalar interaction were calculated to be 1.28×10^{-4} and 5.49 respectively. For scalar, vector and tensor interaction the decay π → eν was expected to be forbidden.

This theoretical issue motivated intense searches for $\pi \rightarrow e\nu$. Neither three emulsion experiments, carried out in 1950 and 1951, nor the following electronic counter experiments at Nevis [16] and Chicago [17] succeeded in detecting this decay (although they did allow to rule out a Pseudo-Scalar interaction). The result of the Chicago experiment, using a powerful magnetic spectrometer, was particularly striking: the observed ratio $R = (-4.0 \pm 9.0) \times 10^{-6}$ led the authors [17] to conclude: "This appears to be statistically significant as it allows only a 1% probability that R is greater than 2×10^{-5}". Absence of the decay at the expected rate posed a real conundrum that theoretical physicists were trying hard to solve.

In 1954 at the Varenna Summer School the author learned first-hand about the Nevis experiment in a seminar by Jack Steinberger (Nobel Prize 1988). This was followed up by careful studies of the merits and drawbacks of the experiment and by gaining experience at Liverpool University with their brand new 400 MeV synchrocyclotron. In January 1958 he attended a meeting of the American Physical Society in New York, where R.P. Feynman (Nobel Prize 1965) presented an invited paper, "Theory of Beta Decay", dealing with the apparent absence of the $\pi \rightarrow e\nu$. Not convinced by the arguments advanced by Feynman and despite the prevailing view that the $\pi \rightarrow e\nu$ decay might be exceedingly rare (or non-existent), an initiative was launched for a new experiment at CERN [6]. In this experiment (Fig. 2.7) the 127 MeV positive pions from the 600 MeV SC were incident on the telescope $123\overline{4}$, consisting of four scintillation counters, and stopped in counter 3, which functioned as an active target and source of possible positrons. Veto counter $\overline{4}$ rejected contamination muons and positrons having the same momentum as the incoming pions. The positrons were detected by a range telescope, formed of scintillation counters 5–12 in coincidence, which also served as a variable thickness absorber to measure exploratory integral range curves (see below). With its 12 counters it was a rather complex and sophisticated apparatus for the time!

In principle, this was all that was required for the search. Tell-tale additional information was obtained by combining the output from counter 12 with that of counter 3 on the same oscilloscope trace. This direct visual coincidence of the signals generated by the same particle in the pion stop counter and in counter 12 clearly exposed the positron as the last particle in the signal sequence.

The novelty and the power of the experiment consisted in the complete recognition of the sequential signals of the particles of the two decay chains $\pi^+ \rightarrow e + \nu$ and $\pi^+ \rightarrow \mu + \nu \rightarrow e + \nu\overline{\nu}$, identified by two or three pulse sequences (Fig. 2.7). A single trigger tagged the two decay chains, which were distinguished exclusively by the absence or presence of the muon. The use of the active target to stop pions and to recognize a decay muon was a condition *sine qua non* for the success of the experiment.

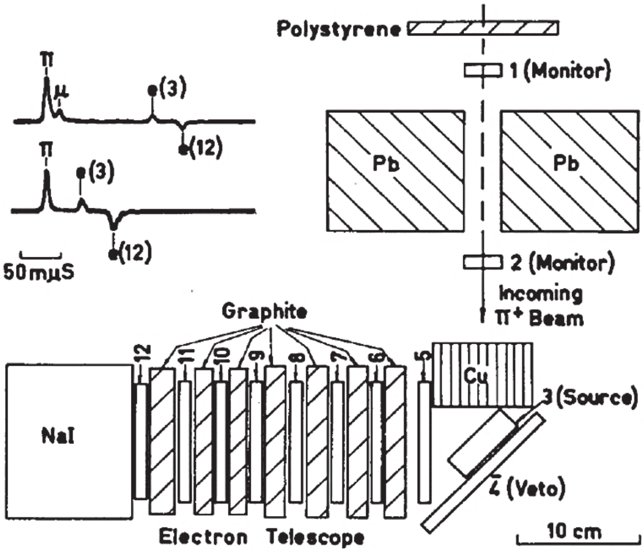


Fig. 2.7. Experimental layout and (insert): typical π → μ → e (top trace) and π → e pulse (bottom trace). This "electron telescope" detected positrons. Elements labelled 1 to 12 are scintillation counters [18].

The most important residual background consisted of π → μ → e events in which these π → μ decays could not be resolved, resulting in so-called false π → e events. Their fraction was determined by measuring the e+ rate without absorbers in the positron telescope, which was then dominated by positrons from π → μ → e, providing the correction factor of their misidentification. This correction, found to be in the range of 10%, was applied to the comparatively small number of π → μ → e events observed during the data taking (with absorber for the π → e decay search). Measurements with varying amounts of absorber confirmed the spectral distribution of e+ from the π → μ → e decay whereas the rate of the mono-energetic e^+ from π → e was unaffected within errors. To arrive at the absolute value for the branching ratio, counter efficiencies were evaluated with a Monte Carlo program (another First) written for the new CERN central computer.

The setting up of the experiment in the Neutron Hall started in February 1958 and data taking with first beam from the SC in August 1958. One month later, first results, based on 124 photographs displaying some 40 events, were presented in Geneva at "The Second United Nations International Conference on the Peaceful Uses of Atomic Energy" [18]. The local newspaper "Tribune de Genève" ran the headline "Découverte au CERN", the first such event for the Organization. The final result [19] for the ratio R (π → eν) / (π → μν) = $(1.22 \pm 0.30) \times 10^{-4}$ was perfectly consistent with theoretical calculations and definitively established the universality of the weak interaction. It opened the way to a more profound understanding, culminating in the discovery of the Weak Intermediate Bosons, the W and Z, at CERN 25 years later.

2.4 Measuring the Muon ($g - 2$): Precision with Precession

Guido Petrucci

A classical rotating top of mass m, angular momentum L and electric charge q behaves as a bar magnet of magnetic moment M. The ratio $(2m/q)\ M/L$ is the g-factor. If charge and mass have the same distribution, the value of g is precisely one, $g = 1$. A charged lepton has also a magnetic moment and the angular momentum is replaced by its quantum analogue called "spin" [Box 2.2]. Quantum Electrodynamics (QED) [Box 2.3] to first order and the Dirac theory predict $g = 2$, but due to quantum field effects [Box 5.1] g differs slightly, by about 2×10^{-3}, from this value. Hence, the accurate measurement of g forms a prime test of the validity of QED calculated with all corrections to highest order. A deviation from the theoretical value might also hint at fundamental differences between electrons and muons.

In 1958, at the CERN 600 MeV synchrocyclotron (SC), the first CERN "g – 2" experiment (1958–1964) started, aiming to measure the anomalous magnetic moment of the muon (μ), a charged lepton about 210 times heavier than the electron. This very successful experiment [7] was followed by a second and a third one, both at the PS, with improved experimental techniques. Each time a much more precise result confirmed the previous one. The most recent and a still more precise experiment done at BNL (US) in the late 1990s and involving some of the CERN pioneers, agrees with the CERN values, while enhancing the scope of this measurement: although consistent with QED at the 10^{-6} level, it indicates a tiny discrepancy between data and that expected from the full Standard Model (SM) [Box 6.4] calculation. If confirmed by the ongoing programme, it may be an indication of new physics beyond the SM.

The $g - 2$ measurement is performed using polarized muons (magnetic moment and spin aligned in the same direction) moving in circular orbits inside a magnetic field, in which the spin axis rotates, or precesses, around the field axis like a spinning-top around the vertical axis. The precession period is slightly higher than the muon period of revolution, by an amount linked to $g - 2$. The measurement consists of recording, as a function of the muons storage time, the electron produced in the muon decay, whose direction is correlated with the polarization of the parent muon. The electron decay rate versus time shows a typical beat curve

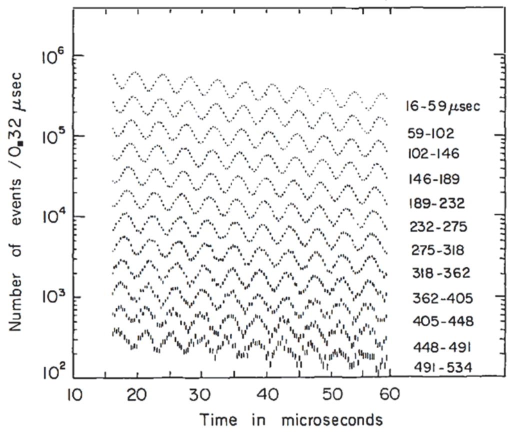


Fig. 2.8. The electron decay rate versus time in the muon storage ring 2 [20].

between the two rotation frequencies (Fig. 2.8) [20]. The precision of $g - 2$ increases with the degree of initial polarization, the observation time, hence the muon storage time, the number of electrons recorded and a better knowledge of the magnetic field, which is the main focus of this highlight.

In the first $g - 2$ experiment, the longitudinally polarized muons (100 MeV/c momentum) were produced on an internal target inside the SC and, after channelling through a focusing solenoid, were injected into a 6 m long straight magnet, with a field of 1.6 T, 52 cm wide poles and a 14 cm gap. A beryllium moderator at its entrance reduced the energy and hence the radius of the spiralling muons improving its observation. The poles faces were shimmed in order to superimpose a longitudinal movement along the magnet to the circular orbits of the μ (Fig. 2.9). The magnetic field was measured with NMR probes, Hall probes and a large moving coil. The muon trajectories were calculated with the first computer installed at CERN and the shims progressively adjusted to increase the storage time of the muons in the magnet (up to 2000 turns, about 2500 m of trajectory). The complete muon trajectory was in vacuum. Exiting the magnet, the muons were stopped in a non-depolarizing, non-conductive target.

A pulsed coil, flipping their spin by ± 90°, turned any transverse polarization into longitudinal. Backward or forward decay electrons were detected in counter telescopes, and tagged by the time spent in the magnet by the parent muons (2.0–6.5 μs). The measurement gave a value $a = (g - 2)/2 = (1162 \pm 3) \times 10^{-6}$, in agreement with QED up to the order calculated at that time, implying that the μ was behaving just like a heavy electron [7, 20, 21].

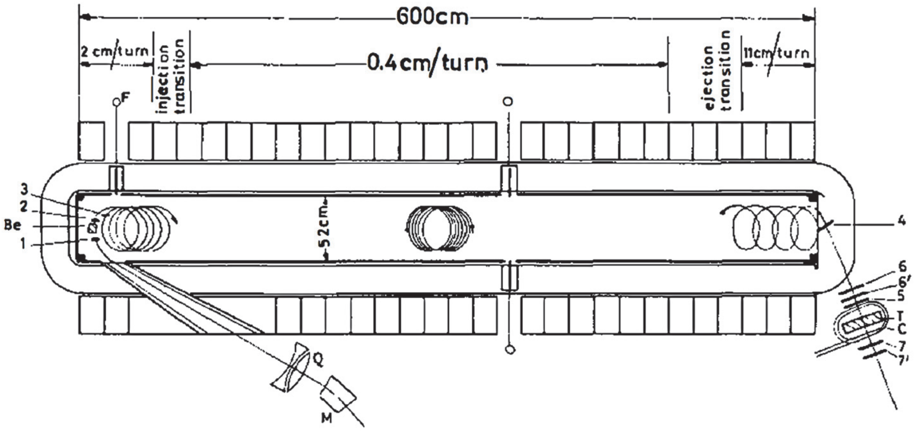


Fig. 2.9. The first $g-2$ experiment [7].

The second $g-2$ experiment (1962–1968) innovated by using for the first time a muon storage ring. Protons of 10.5 GeV/c momentum, fast-extracted from the PS (one to three radio frequency bunches, each 10^{-8} seconds (10 ns) long separated by 105 ns), hit a target located at the edge of the storage region of the magnetic ring. This ring, designed by S. van der Meer (Nobel Prize 1984), was of the weak focusing type [Box 2.1], with an orbit diameter of 5 m, a useful aperture of 4 cm (V) × 8 cm (H) and a magnetic field B = 1.711 T (Fig. 2.10). The muons were stored with a momentum of 1.28 GeV/c, resulting in a relativistically dilated muon lifetime $\gamma\tau$ of 27 μs, where $\gamma = \{1 - (v^2/c^2)\}^{-1/2}$, 12 times its lifetime τ at rest, allowing a much longer observation with correspondingly improved precision. The protons hitting the target produced a large background of particles, "blinding" the detection counters for the first 25 μs. Any pion crossing the storage volume and having an energy equal or higher than those accepted by the ring could produce stored muons. However, the muons born from parents of much higher energy were poorly polarized and the average μ polarization in this first ring was only about 30%. A fraction of the electrons produced by circulating muons were deflected inside the ring and detected by counters recording them versus time. The result of this second $g-2$ experiment was $a = (g-2)/2 = (116616 \pm 31) \times 10^{-8}$, almost two standard deviations above the theoretical value. As it turned out later, part of the discrepancy was due to the neglect of the $(\alpha/\pi)^3$ term in the QED calculation and motivated theorists to improve their estimates.

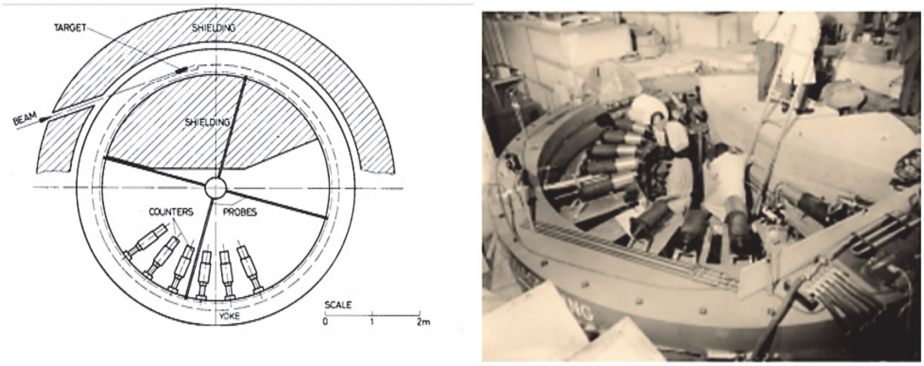


Fig. 2.10. Left: sketch of the second $g-2$ experiment. Right: view of the same experiment, using for the first time a storage ring [20].

The third CERN experiment (1969–1976) was a much improved version of the previous storage ring. The proton bunches extracted from the PS produced a secondary pion beam tuned to trap muons of 3.1 GeV energy. The ingenious new idea was the choice of this "magic" energy with its value $\beta^2\gamma^2 = 1/a$, for which the electric field has no influence on the spin motion. It was thus possible to focus the circulating beam with electrostatic fields (instead of magnetic fields) and design a more uniform magnetic configuration. Efforts were put in two directions: developing a suitable quadrupole electrostatic field and designing a B-field as uniform in space and constant in time as technically possible.

The electrostatic field had to be pulsed in order to avoid discharges caused by ions slowly accumulating in the vacuum chamber. This field provided vertical focusing, partially reducing the horizontal focusing effect of the circular motion (the ring was therefore weak focusing like the previous one). The electric field was used also to scrape the beam, both horizontally and vertically, after each injection to avoid subsequent beam losses that could introduce errors.

The magnet was mounted in a separate thermally stabilized hall. Its continuous, concrete support ring was itself kept at constant temperature by means of water circulating in pipes cast within. The magnet coils had independent supports; their very small deformations had no influence on the field. The iron yoke was made of 40 blocks, whose pole faces were very accurately ground by a specially designed, computer-assisted grinding machine. The field map finally showed variations in time and space of less than 1 ppm. During measurements, the field was monitored by 40 NMR probes with feedback loops acting on 40 compensating coils. The result of this third $g - 2$ experiment was $a = (g - 2)/2 = (1165924 \pm 8) \times 10^{-9}$ (a precision of 7 ppm). The validity of QED was confirmed up to the 6th order, i.e. terms $(\alpha/\pi)^3$. Further results from the Brookhaven $g - 2$ programme now hint at a slight discrepancy between the experimental result and the Standard Model prediction involving QED and the effects of weak and strong interactions.

As former Director-General J.B. Adams once put it: "$g - 2$ is not an experiment; it's a way of life". Indeed, one pioneer has participated and contributed greatly in all $g - 2$ experiments at CERN and BNL. A new experiment is planned at Fermilab starting in 2017. One awaits eagerly further results of this outstanding programme, which has seen a long lasting and stimulating competition between experiment and theory, a "tennis game with well-matched players on either side of the net," as one of the principal actors remarked. More information and a list of references can be found in [20, 22].

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