Fifty years of research at CERN, from past to future: The accelerators

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Abstract

The evolution of the CERN accelerator complex since its inception is summarized. Emphasis is put on the salient features and highlights of the different facilities and on what has been learnt at each stage in terms of accelerator physics and technology. Possible future accelerator options for CERN are discussed at the end.

1 Introduction

This report, based on lectures given in the Academic Training Programme on the occasion of CERN's fiftieth anniversary, summarizes the evolution of the CERN accelerator complex with an emphasis on the highlights in accelerator physics and technology. The description of the early part of the development is based on the available documents [1–3] and the reminiscences of senior colleagues who have been my teachers and friends. The later evolution is presented with a more personal touch, based on my own observations made after I joined the legendary CERN Accelerator Research Division in 1964, when the studies for the upgrading of the Proton Synchrotron (PS) and the construction of the Intersecting Storage Rings (ISR) and the Super Proton Synchrotron (SPS) were in full swing [2–4]. The achievements presented here have been made mainly by CERN staff but the continuous support and the significant contributions from our colleagues outside CERN must be gratefully acknowledged.

The first part treats the early accelerators, the Synchro-Cyclotron (SC) and the PS and their evolution. The second part deals with the accelerators built by CERN after its expansion into France, the ISR and the SPS. The third part is dedicated to the period when CERN had to choose from a number of options which finally led to a family of powerful particle colliders, starting with the conversion of the SPS into a proton–antiproton collider, followed by the Large Electron–Positron collider (LEP) and then by the Large Hadron Collider (LHC) which will be housed in the tunnel drilled for LEP. The fourth part sketches the accelerator options for the future which have already been under study for a number of years since, as the accelerators become more and more complex, the lead times for a project become very long. Finally, a very personal account is presented of what we have learnt in terms of management in all these large projects.

I have given only a few references. A selection of references for further reading on the future options for CERN is presented.

The lectures and this paper are dedicated to Mervyn Hine, distinguished accelerator physicist and man of vision, who made eminent and varied contributions to the build-up of the accelerator complex at CERN. He joined CERN in 1952 and became one of the leading figures for the construction of the PS. As Director for Applied Physics, responsible for planning under J. B. Adams and V. Weisskopf, he laid the foundations for the expansion of CERN beyond the SC and PS. He died in April 2004.

2 Early times

2.1 Starting conditions

In May 1952 the provisional CERN Council decided on the creation of two Study Groups: the first Group to study a proton Synchro-Cyclotron (SC) led by Cornelis Bakker of Amsterdam, and the second Group to explore a weak-focusing proton synchrotron similar to the 3 GeV Cosmotron being commissioned at Brookhaven National Laboratory. The leader of the second Group was Odd Dahl of Bergen. The energies of these accelerators were discussed in a meeting in June 1952 in Copenhagen and the recommendation reported by Heisenberg to aim for 600 MeV for the SC and 10 to 20 GeV for the synchrotron was accepted at the second Council session in June 1952.

A group led by Odd Dahl visited BNL in summer 1952 and learnt about the alternating-gradient (AG) focusing principle [5]. Although a design of a Cosmotron-like synchrotron had been worked out, it was decided after this visit to forthwith design a synchrotron embodying the new principle, which held the promise that a higher energy could be reached for the same cost. In October 1952 the still provisional Council fortunately accepted this bold proposal, which meant abandoning the scaled-up weak-focusing Cosmotron-type 10 GeV synchrotron and studying instead a 30 GeV proton synchrotron based on the untried AG principle.

The audacity of Council to make a large step in energy of the synchrotron using a scheme which had never been tested can be appreciated from Fig. 1(a) where the energy of various types of accelerators in the US is plotted as a function of the year of start-up. It also gives the energy of the two first AG synchrotrons, the PS at CERN and the AGS at BNL, as a function of the time when the proposal was made. (The Stanford Mark III 1.2 GeV electron linear accelerator (linac) which was completed by 1950 is not shown.) Figure 1(b) shows these two proposals with the accelerators in Europe.

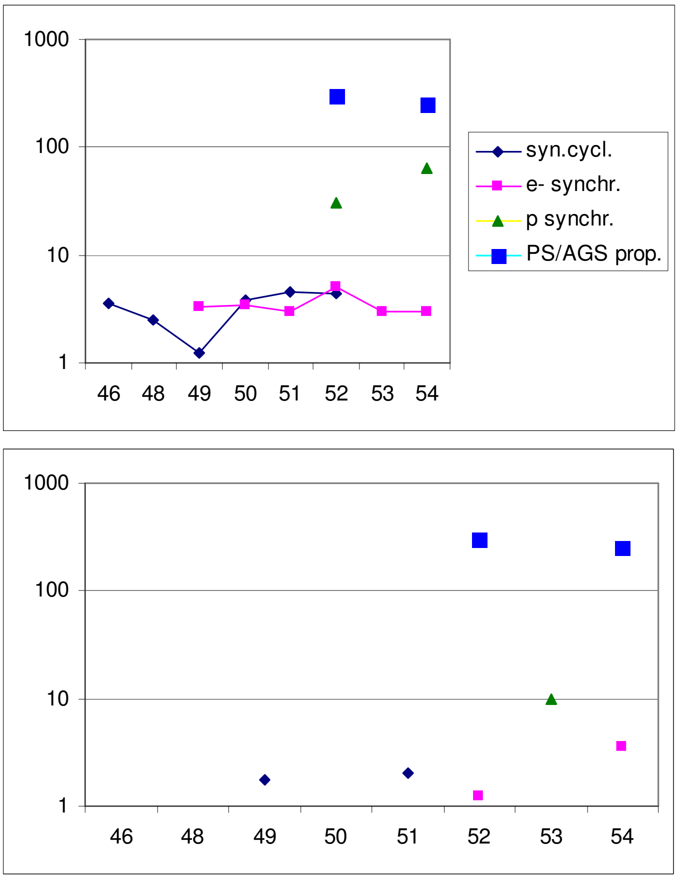

Fig. 1: (a) The energies of the proposed PS and AGS in units of 0.1 GeV are plotted as a function of the time of the proposal in comparison with the energy of the US accelerators as a function of their start-up. Synchro-cyclotrons (diamonds); electron synchrotrons (small squares); non-AG proton synchrotrons (triangles); PS and AGS proposal (large squares); (b) the same plot for European accelerators.

Obviously, this decision immediately put Europe in the forefront of accelerator physics. CERN started on an equal footing with the US and ahead of other European Countries. This helped the UK to decide to join CERN, even though the UK was the leader in accelerator technology in Europe at that time. However, it was considered an "adventurous high-risk high-gain course of action" according to J. B. Adams, or as R. Peierls put it more poetically "for awful gamble stands AG but if it works or not we'll see".

In the long term, this choice turned out to be decisive for the development of the CERN accelerator complex as only a synchrotron with AG focusing could provide the high-brilliance beams required for colliders with a high luminosity.

Others did not trust the new AG principle and weak-focusing proton synchrotrons such as the 10 GeV Synchro-Phasotron (start of construction in 1952) at JINR/Dubna, the 7 GeV Nimrod (1957) at RAL in the UK, and the12 GeV ZGS (1959) at ANL in the USA were still constructed.

2.2 The CERN Synchro-Cyclotron

In October 1952 the provisional CERN Council also decided to go ahead immediately with the construction of the 600 MeV SC, well before the construction of the PS, in order to secure an early start in meson physics and as a training ground for European experimental physicists and accelerator technology. The design was almost complete in 1953, fifteen months after the setting-up of the Group which then moved to Geneva in 1954.

Construction started in 1955 and the first beam was obtained in 1957, immediately at maximum energy. Figure 2 shows this accelerator.

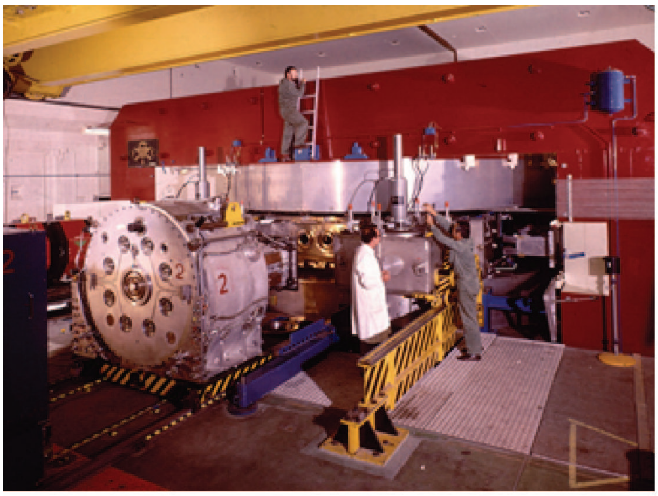

Fig. 2: The CERN 600 MeV Synchro-Cyclotron (SC) with the red iron yoke, the coils, and, in the foreground, the cylindrical rotating condenser for frequency modulation

The physics programme started in 1958 and a number of excellent results were obtained such as the discovery of the rare decay $\pi^- \to e^-\nu$ and of the pion 'beta decay', $\pi^+ \to \pi^0 e^+\nu$, the $g-2$ measurement of the μ, and many other contributions to μ physics. Until the start-up of the PS the SC was the centre of scientific life at CERN, providing the physicists with an opportunity to gain experience. However, this attraction of the SC had an adverse impact on the early scientific programme at the PS. The SC was later taken over by nuclear physics in 1964, in particular for experiments with the isotope separator on line, ISOLDE.

A number of improvements were made during the long faithful service of the SC. The most notable was the work done in 1973/74 which included a new ion source, a rotary condenser for raising the dee-voltage and the repetition rate, and a new extraction channel. This led to an increase of the internal beam intensity from 1 μA to 4 μA and the extraction efficiency went up by a factor of 10% to 70% as expected from the design. Further modifications were made later for acceleration of ions with a charge-to-mass ratio of 1/3 to $^1\!/_4$ up to carbon.

The SC was stopped at the end of 1990 after the decision to move ISOLDE to the Booster Synchrotron of the PS (PSB) which had a higher proton-beam power than the SC.

2.3 The CERN Proton Synchrotron (PS)

The PS Design Group was initially spread out over Europe but it quickly became obvious that such a project needed a centralized team. The first members of the PS group moved to Geneva in autumn 1953, and started to seriously review the design after the approval by Council in October 1953 with a reduction in the energy to 25 GeV in order to contain the cost.

The advantage of the AG principle was that the size and, therefore, the cost of the vacuum chamber, the magnets and their foundations, and the tunnel cross-section could be reduced dramatically. However, it made the synchrotron much more sensitive to the errors in the magnetic field and alignment. To find the right balance required a number of iterations, generating a sizeable fluctuation of the parameters during the design until the start of construction in 1954. This is illustrated in Table 1 which gives the total weight of the magnets at the different design stages. The last column gives the final weight which is still rather reasonable. In comparison, the weight of the magnets of the 10 GeV Synchro-Phasotron at JINR/Dubna is 36 000 t.

Table 1: The evolution of the weight of the PS magnets during design

Date	**January/1953**	**April/1953**	**March/1954**	**As constructed**
Magnet weight (t)	800	10 000	3300	3800

Figure 3 shows the PS combined-function magnets which provide a dipole field for bending with an alternating gradient for beam focusing.

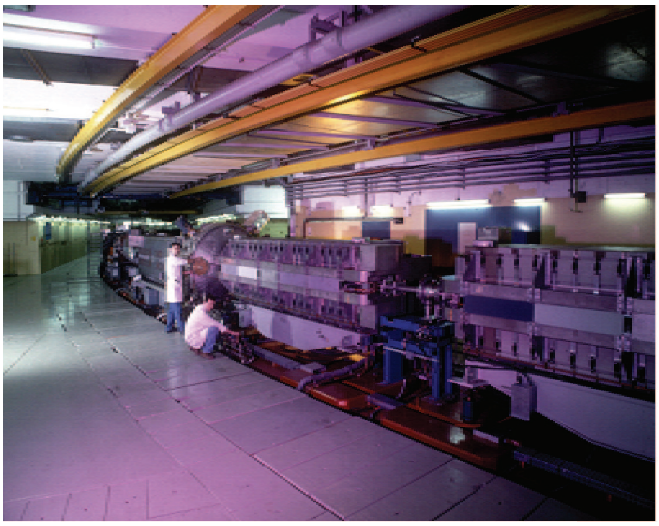

Fig. 3: The combined-function magnets of the PS

The ground breaking took place in May 1954. The construction of the ring with a circumference of 628 m was completed in 1959, and the proton beam energy reached 28 GeV (kinetic) in December 1959.

The PS group had learnt beam physics in a circular accelerator with AG focusing; how to produce magnets with tight tolerances; how to design stable supports for them; how to align them; how to properly control the beam and the accelerating radio-frequency system, and, last but not least, how to manage a large project, invaluable know-how for the future of CERN.

The experimental programme started in spring 1960 but was hampered by the lack of secondary beam equipment and adequate particle detectors, and of experienced physicists. This was partly a consequence of the SC programme having cornered substantial resources which were then not available for the work with the front-line accelerator. Hence CERN could not exploit the advantage of a six-month head start of the PS over the AGS at BNL.

2.4 Upgrading the PS

In order to be better armed for the fierce, but friendly competition, the PS has been continuously improved and adapted to serve as injector for a number of accelerators.

In a first vigorous step, the efficiency of the secondary beam production was improved in comparison with that of an internal target by extracting the primary proton beam onto an external target:

- A fast extracted beam was produced for the first time in 1963, by a technique allowing the extraction of the totality or part of the beam bunches from the ring within one turn. This was accomplished by a novel kicker magnet with a very short rise-time moved over the beam at the end of the acceleration cycle when the beam was small. This led to a spectacular increase in the neutrino flux, which, in addition, was enhanced by the magnetic horn, another device pioneered at CERN and installed in 1961. The kicker magnet was replaced in 1969 by a full-aperture kicker in order to remove the constraining kicker aperture. Figure 4 shows the extracted proton beam passing through a row of scintillators with a PS ring magnet at the right.
- A slow extraction system was brought into operation in 1963 providing a long spill (about 1 s) to the experiments and increasing the duty cycle; this was especially appreciated by the experiments with electronic detectors.

In order to raise the mean proton current, a new power supply and rf system were installed to increase the repetition rate by a factor 2 in the mid 1960s.

Since these two new extraction methods worked very well, it became conceivable to increase the PS intensity per pulse, which would have been impossible with the internal targets (the latter were contaminating the accelerator, heated too much, and were eradicated completely only in 1980). The number of particles per pulse N was limited by space-charge effects at injection. Since $N_{\max} \propto \beta\gamma^2$ for a given invariant emittance of the beam, where β,γ are the usual relativistic parameters, a synchrotron consisting of four superposed rings, the PS Booster (PSB), was inserted between the 50 MeV Linear Accelerator (Linac1) and the PS in order to increase the injection energy of the latter to 800 MeV. A theoretical gain of a factor 8 in intensity was expected from this new accelerator, which was constructed in 1968–1972. The PSB came on-line just in time for the experiments with the Gargamelle bubble chamber, which led to the discovery of neutral currents, one of prestigious accomplishments of CERN.

The third step was the construction of a new 50 MeV linac (Linac2) equipped with a new proton source in 1973–1978.

The steady evolution of the record number of protons accelerated in the PS and PSB is shown in Fig. 5. As early as 1960, 2.2×10^{13} protons per pulse were reached. A particular effort was demanded from these two accelerators during the last neutrino experiments in the CERN West Hall (CHORUS and

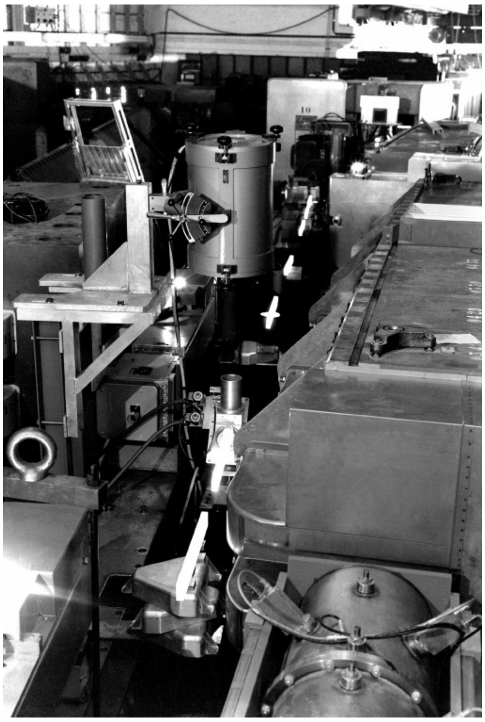

Fig. 4: The first extracted proton beam at the PS in 1963

NOMAD) in 1999 where the PS provided on average 2×10^{13} protons per pulse. Since the PS was originally designed for 5–8 $\times$ 10^9 protons per pulse, a good factor of 2000 has been gained over the years through continuous upgrading.

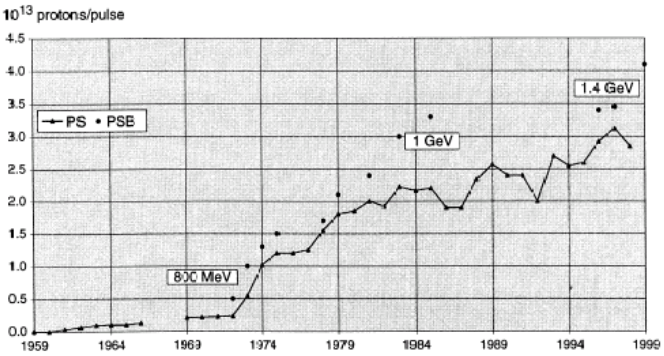

Fig. 5: Evolution of the PS and PSB peak intensity

The PSB impressed not only with a spectacular growth in intensity over the years but also with the step-wise increase in proton energy by an amazing 75% from 0.8 to 1.4 GeV (kinetic). It was possible to raise the field of the magnets, which, however, no longer operate in the long-term cost minimum.

Linac1 served the PS as its first proton injector and as the injector for a very successful ion programme. The first phase started in 1976 with deuterons for the ISR, which were also served with alpha particles in 1980. The second phase was the production of S^{16+} for the SPS from 1990 to 1992. In 1990, in a collaboration with other laboratories, construction began of a new Pb linac, Linac3. It became operational in 1994, and the PS started providing the SPS with ^{208}Pb ions which are fully stripped after extraction from the PS. Linac1 continued to provide p and H^{-}to the storage ring LEAR (see Section 4.3) for tests until the end of 1996 and was dismantled in 1997.

Furthermore, the PS was modified to permit the acceleration of positrons and electrons to 3.5 GeV for LEP (see Section 4.4) by adding a pre-injector, introducing a damping wiggler and an additional rf system in the late 1980s. A new control system allowed fast switching between cycles within a supercycle. An example of such a supercycle in Fig. 6 shows the interleaved acceleration of Pb ions, protons, positrons and electrons and, in between, the deceleration of antiprotons for LEAR.

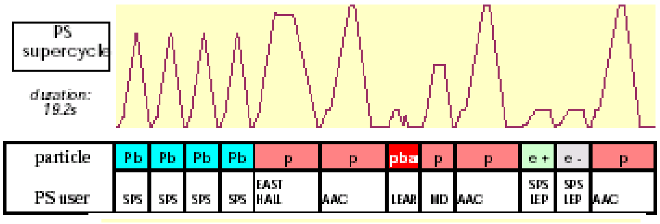

Fig. 6: Example of a PS supercycle [6]

The highlights of the work of the accelerator groups during the upgrading of the PS were the design and running-in of the novel fast and slow extractions, the mastering of the high-intensity proton beams and of the ion beams, the merging of the proton bunches for antiproton production by using more than one rf system, and the refining of the computer control system allowing the creation and manipulation of supercycles without time-consuming commissioning.

3 Expansion into France with the ISR and SPS

3.1 The Intersecting Storage Rings (ISR)

While the SC and the PS were being built, the study for the second generation of CERN accelerators started at the end of 1956 and gradually swung towards a proton–proton collider. In addition, from 1961 onwards, a study of a 300 GeV proton synchrotron was conducted. In 1965, at the end of a lengthy and intense debate, it was decided to first construct the ISR, though a number of physicists were not in favour as the ISR would not provide secondary beams and was considered to be too much of a shot into the dark.

The ISR were constructed from 1966 to 1970 on land in France, adjacent to the original CERN site in Switzerland. It operated from 1971 to 1983 for physics. The combined-function magnet lattice, providing AG focusing, formed two independent, interleaved rings, intersecting in eight points. Five of these points were used for experiments. The ISR were housed in a big tunnel constructed by the cut-and-fill method. A view of the ISR at intersection point 5 is shown in Fig. 7.

The circumference of the orbits was 943 m, exactly 1.5 times the circumference of the PS. The maximum beam momentum was 31.4 GeV/c. With dc proton currents up to 40 A (single beam up to 57 A!) it reached a luminosity of 1.4×10^{32} cm^{-2} s^{-1} in the superconducting low-beta insertion, a factor 35 above the design luminosity. It was a pioneer of accelerator technology:

- ultra-high vacuum and ion clearing (residual pressure 10^{-13} Torr in the experimental areas),
- low-impedance vacuum envelope,
- high-stability power supplies (only 0.1 ppm ripple in the dipole current),
- superconducting low-beta insertion to squeeze the beam in the intersection point (increasing the luminosity by a factor of 6.5).

Fig. 7: View of the ISR at intersection point 5

Figure 8 shows as an example the evolution of the pressure in the vacuum chamber averaged over the circumference. The design figure was 10^{-9} Torr. The excellent vacuum allowed physics runs with the beam coasting for 60 h with beam lifetimes in excess of many months, which rendered excellent background conditions.

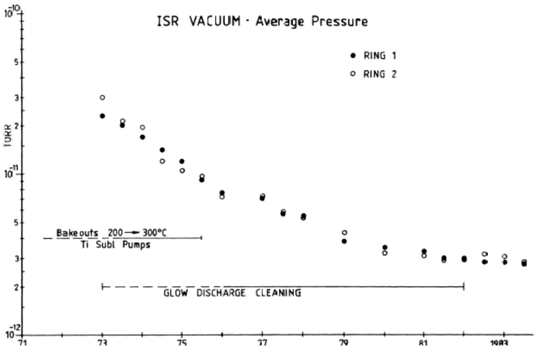

Fig. 8: The evolution of the average vacuum pressure in the ISR [7]

Since it was the first hadron collider, the ISR provided a unique opportunity to study effects which were predicted by theory, such as beam–beam effects, space-charge detuning, beam-equipment interaction, and intra-beam scattering, and to discover unexpected phenomena such as pressure rise due to multipacting. Two prominent examples are given.

The invention of non-destructive beam diagnostics for coasting beams with Schottky noise was of enormous impact. Figure 9 shows the beam noise picked up by an electrode.

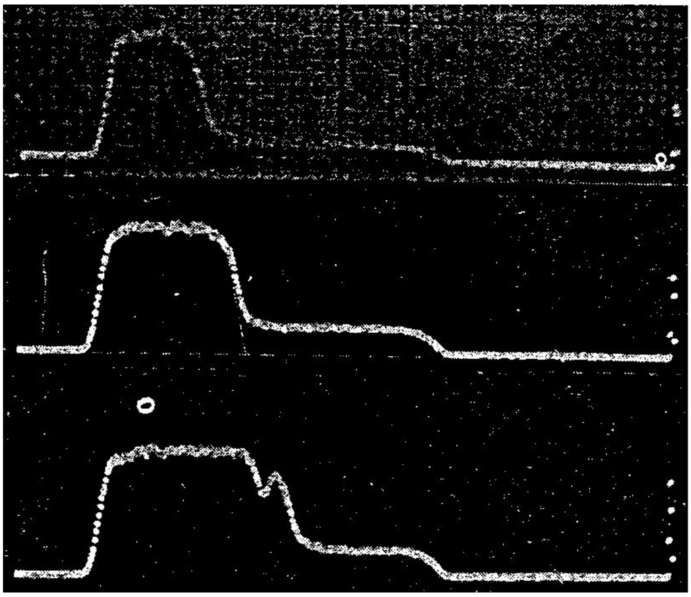

Fig. 9: Longitudinal Schottky scans of coasting proton beams of 10, 15, and 19 A [8]

The signal is proportional to the square of the proton density as a function of beam momentum. The scan with 19 A beam current (bottom trace) shows a dent in the distribution due to beam loss at a non-linear resonance.

This Schottky noise signal became an indispensable tool for monitoring the average momentum, the momentum spread, and the density evolution of the coasting beam without disturbing the beam. Online correction of the space-charge tune-shift became possible because the betatron tunes of the stack-edges or of a resonance could be determined with high precision from the fast and slow transverse-wave Schottky signals.

This discovery of the transverse Schottky signals led to another unique accomplishment, the resurrection of the idea and the first experimental test of stochastic cooling invented by S. van der Meer in 1968. Figure 10 shows the result of the first test. The beam height is blowing up on account of multiple-scattering on the rest gas when the cooling is off.

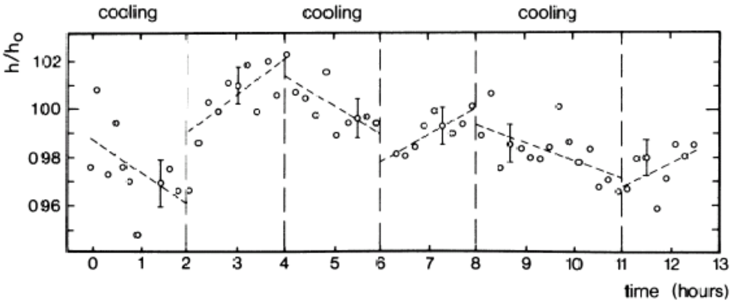

Fig. 10: Measurement of relative beam height as a function of time with stochastic cooling on and off [9]

Later, physics runs with colliding proton–antiproton beams took place with a more refined cooling system so that an antiproton beam (see Section 4.2) could circulate up to 345 h without any significant deterioration.

The ISR were decommissioned in 1984 in order to free resources for LEP. Very interesting physics results were obtained with this machine but the main discoveries in this period, the J/ψ and the Υ, were made elsewhere though they could have been made at the ISR, very likely with some of the experiments that had been proposed but unfortunately were degraded or turned down.

3.2 The Super Proton Synchrotron (SPS)

Work on the concept of a 300 GeV proton synchrotron started in the early 1960s at CERN. After the decision in favour of the ISR, the discussions resumed but were soon dead-locked over the choice of the site, elsewhere in Europe, for which 22 offers had been received. The issue was settled in favour of a site in France near CERN with the argument of using the PS as injector and other savings being made from synergies if the SPS were built close to CERN.

The project was approved in 1970. After some fluctuations between an initial energy of 150 GeV with missing magnets and 600 GeV with superconducting magnets, the decision was made in 1973 to aim for 400 GeV with conventional magnets. A magnet lattice with a circumference of 6912 m, eleven times the PS circumference, provides AG focusing. In contrast to the ISR, it is of the separated-function type, i.e., the bending is provided by pure dipole magnets and the focusing by separate quadrupole magnets (Fig. 11). This allows the attainment of a magnetic field in the dipoles about 50% higher than with combined-function magnets.

Fig. 11: View of the SPS tunnel with dipole magnets (red) and quadrupoles (blue)

The first beam circulated at top energy in mid 1976, and the design intensity of 10^{13} protons per pulse was reached in the same year. Later the top energy was increased to 450 GeV and the intensity reached 4.5×10^{13} protons per pulse. In the period 1982 to 1991, the SPS played a key role in CERN's antiproton programme discussed in Section 4.2. The SPS has accelerated ions from 1990 onwards (S in 1900 to 1992 and Pb from 1994), underlining the flexibility of this synchrotron which served also as LEP injector, accelerating electrons and positrons from 3.5 GeV to 22 GeV. This required the installation of an additional powerful rf system, careful shielding against synchrotron radiation, and new injection and extraction systems. At present, the SPS is being modified and improved to become the LHC injector.

Two large experimental halls (West, North) provide the required floor space for the experimentation with secondary beams of highest energy. The West Area, including the neutrino beams, was operational from January 1977, a few months after the start-up of the SPS, avoiding the mistake made with the PS. The neutrino programme in the West Area was terminated in 1998, but a new neutrino beam (CNGS) is under construction in order to send neutrinos to the Gran Sasso Laboratory of INFN 730 km away. CNGS will start operation in 2006, continuing the search for neutrino oscillations in Europe which commenced with the West Hall beams.

New expertise was acquired and new techniques have been learnt during SPS construction and commissioning: deep tunnelling with a precision of 2 cm over 1.2 km, direct powering from the grid with reactive power compensation (peak active power 150 MW), and computer control from the start (both had been done already on the PSB albeit on a smaller scale), and very refined, high-efficiency beam extraction techniques (fast, slow, fast–slow) to serve users requiring very different spill times and intensities, often within one and the same acceleration cycle.

4 The quest for world leadership

4.1 Search for the next steps

Knowing the long lead-times of a project, the search for the next steps started after completion of the ISR in 1974, while the SPS was still under construction. A variety of options was examined up to 1978:

- CHEEP: 27 GeV electrons in an additional ring, colliding with 270 GeV protons in the SPS,
- LSR/SISR: pp collider with 400 GeV per beam,
- MISR: 60 GeV protons in a storage ring built from ISR magnets to collide with SPS protons,
- SCISR: two new superconducting rings for pp collisions with 120 GeV per beam in the ISR,
- Proton–antiproton collisions in the SPS requiring the construction of an antiproton source,
- Large Electron–Positron (LEP) ring in a new tunnel.

In 1978, the decision was made to go for the proton–antiproton collisions in the SPS as the medium-term project, and to concentrate on LEP as the future long-term flagship, with the hope that it would be powerful enough to discover the Higgs.

It is also useful to recall the international context of these decisions: the study of ISABELLE, a pp collider with 200 GeV per beam at BNL, was in full swing. Hence CERN had to take a quick and economic approach to be first to discover the predicted intermediary W and Z bosons. Incidentally, ISABELLE was stopped at the construction stage in 1983 in favour of the superconducting pp collider (SSC) with 40 TeV in the centre of mass which in turn was abandoned in 1993. The study of the proton–antiproton option at FNAL had been stopped in 1978, to a large extent because the vacuum system of the FNAL ring could not be upgraded with reasonable effort to reach the required beam lifetime.

4.2 The antiproton programme in the SPS

In order to achieve a reasonable luminosity in the proton–antiproton collision in the SPS, the phase-space density of the secondary antiproton beam, produced by protons hitting a target, had to be increased by many orders of magnitude by stochastic cooling. However, only transverse stochastic cooling had been demonstrated at the ISR. Hence it was decided in February 1977 to experimentally prove momentum cooling and simultaneous stochastic cooling in all three dimensions in a new test ring, the Initial Cooling Experiment (ICE). The latter was constructed and commissioned in record time and successfully completed its mission in May 1978. In June, the decision was made to perform the proton–antiproton experiment in the SPS. Figure 12 shows an example of momentum cooling in ICE.

ICE also established a new lower limit for the antiproton lifetime (32 h at rest) increasing it by nine orders of magnitude, which was fortunately about three times the minimum required beam lifetime in the upgraded SPS.

Thereafter, the Antiproton Accumulator (AA) was built very quickly from 1979 to 1980. It was a storage ring, downstream of the target hit by 26 GeV/*c* protons from the PS, with 157 m circumference

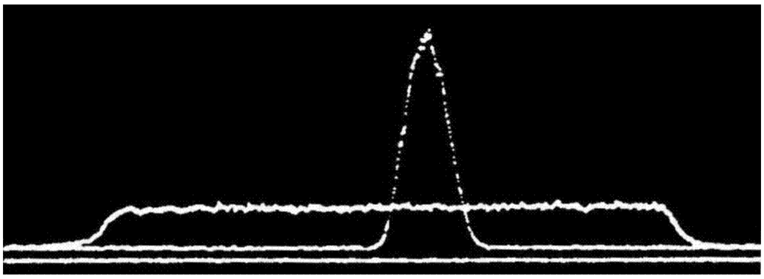

Fig. 12: Distribution of protons as a function of momentum before (wide rectangle) and after cooling (narrow peak) in ICE

operating at 3.5 GeV/c and equipped with powerful stochastic cooling devices. In the SPS, the vacuum system had to be upgraded from the 200 nTorr (design) to better than 2 nTorr, low-beta insertions were installed in straight sections 4 and 5 for the UA2 and UA1 experiments, electrostatic deflectors were produced to separate the beams, each consisting of 6 bunches, in 9 of the 12 crossing points, and the rf system was upgraded. New transfer lines to and from the AA and from the PS to the SPS (TT70) were built. In addition, transfer line TT6 was added to channel antiprotons to the ISR. Figure 13 shows the layout of the accelerators.

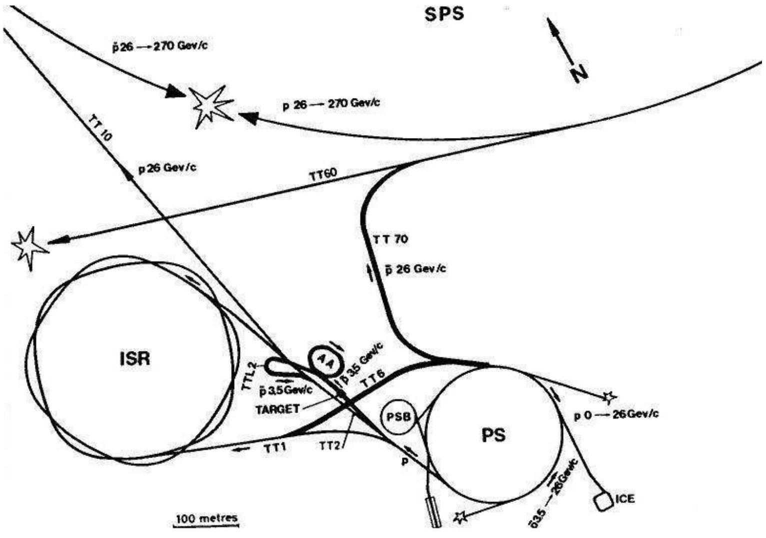

Fig. 13: Accelerators and beam lines for the antiproton–proton experiment in the SPS

Later, in order to shorten the cooling times and to obtain a higher antiproton density, the Antiproton Collector (AC) ring with a circumference of 182 m was added around the AA in 1987. Operated also at 3.5 GeV/c, its purpose was to capture more antiprotons, thanks to its much larger acceptance. After reduction of momentum spread by bunch rotation of the injected beam, the stack was subjected to fast three-dimensional pre-cooling and then transferred to the AA. The combined action AC and AA eventually raised the daily antiproton production rate by a factor 6 and the six-dimensional antiproton phase space density by up to a factor 4×10^9. Although 10^{12} antiprotons per day were accumulated for about two fills of the SPS, where the beam lifetime was 10 h, this left little margin and the whole operation was a continuous cliff-hanger because there was always the risk of losing the stack in the AA or losing the beam during acceleration in either the PS or the SPS with the resulting loss of a whole day.

The energy of the colliding beams was 273 GeV between 1982 and 1985. It was raised to 315 GeV from 1987 to 1991 when the programme was terminated. Figure 14 shows the performance of the SPS as collider in terms of peak luminosity and integrated luminosity per year.

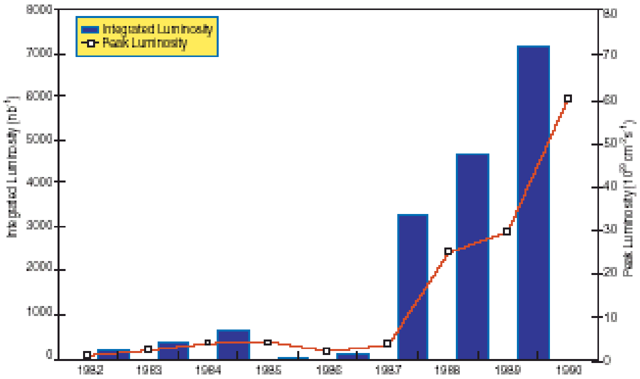

Fig. 14: Performance of the SPS antiproton–proton collider [10]

The luminosity was rather low before the advent of the AC but still sufficient to firmly establish the existence of the W and Z in the runs of 1982 and 1983 which won Carlo Rubbia and Simon van der Meer the Nobel Prize in 1984. The large 4π detectors, which had been denied to the ISR, had been decisive.

The rewards for CERN were extremely important not only in particle physics but also in accelerator physics and technology. For the first time the beam–beam effect with bunched hadron beams could be studied, including long-range beam–beam forces and the effect of very unequal beam sizes in the interaction points, invaluable experience for the LHC. The bunches collided in three crossing points: in the two experiments and in the point mid-way in between. In order to avoid beam collisions at the other nine out of the twelve possible crossing points when operating with six bunches per beam, the orbits of the protons and antiprotons were separated in these nine points by distorting the orbits to a 'Pretzel' shape by means of electrostatic separators, providing important experience for LEP. New civil engineering know-how was acquired with the digging of the large caverns in the molasse bedrock for the two experiments UA1 and UA2, which turned out to be extremely useful for LEP and the LHC.

4.3 The low-energy antiproton programme

The existence of a powerful antiproton source motivated the construction of the Low-Energy Antiproton Ring (LEAR), a buffer and decelerator ring, producing antiprotons with a kinetic energy of 5 to 1270 MeV in long spills for the physics community interested in low-energy physics with antiprotons. It was built between 1980 and 1982 and operated until the end of 1996.

In order to counteract the blow-up of the beam during deceleration below the kinetic injection energy of 180 MeV, stochastic cooling and electron cooling had to be used. A highlight was the ultra-slow ejection with a noise signal feeding the particles into a non-linear resonance, so that smooth spills of up to 10 h became possible. The ring also had an internal target which served to produce the first anti-hydrogen atoms ever seen. Unfortunately, only a handful of these atoms were produced and not at rest as required for precise tests of the charge-parity-time (CPT) conservation theorem.

Hence in order to pursue seriously this line of research and, it was hoped, once with sufficient quantities of anti-hydrogen at rest, the AC ring was modified between 1998 and 2000 to become the Antiproton Decelerator (AD), providing a very stable antiproton beam at 5 MeV after deceleration from 2.7 GeV. Again, the beam blow-up inherent to deceleration is compensated by stochastic and electron cooling. A highlight is a special linear Radio-Frequency Quadrupole Decelerator (RFQD) lowering further the kinetic energy of the extracted beam to a value which can be chosen at will between 120 and 10 keV; this increases the intensity by a factor 50 compared to beams having their energy lowered by degraders.

4.4 The Large Electron–Positron Ring (LEP)

The design of the future CERN flagship started in 1975. It went through a number of iterations, each the result of a compromise between the desiderata of the physics community and feasibility, as shown in Table 2. The last column gives the final design parameters.

Table 2: LEP design iterations

	1977	1978	1979	**1984**
Beam energy (GeV)	100	70	86	**55**
Circumference (km)	52	22	31	**27**
Number of experiments	8	8	8	**4**
RF power (MW)	109	74	96	**16**

The discussions about a possible site were cut short by proposing the PS/SPS as injector chain, complemented with a new Lepton Pre-Injector (LPI) feeding the PS with either electrons or positrons at 600 MeV. The LPI was constructed with the help of and in close collaboration with LAL/Orsay.

After approval at the end of 1981, construction started immediately and the first beams collided in LEP in 1989 at 46 GeV per beam, at the Z_0 resonance (LEP1). In the framework of the LEP2 programme, the beam energy was increased in steps from 1995 onwards depending on the installation schedule of the superconducting cavities. In 1997 the threshold for W-pair production was reached and the final energy of 104.5 GeV per beam was attained by LEP2 in 2000 when all available spares were mobilized in a dramatic final spurt to find the elusive Higgs particle. The accelerator was dismantled in 2001 to make space for the LHC.

A number of technical challenges had to be met by innovative designs. Some examples follow. The cheap and rigid steel–concrete dipole magnets consisted of spaced iron laminations with cement mortar in between (27% steel filling), kept together by four pre-stressing rods running over the whole length of 6 m. The concentration of the magnetic field in the laminations avoided reproducibility problems at injection energy where the average dipole field was only 240 G while the field in the laminations stayed below 5 kG at maximum energy, avoiding any saturation effect. In order to avoid disturbance of the solenoid field in the detectors, warm-bore, iron-free, superconducting, low-beta quadrupoles had to be developed.

Since the bending field at injection was below the threshold of distributed sputter-ion pumps, a non-evaporable getter (NEG) pumping system was used for the first time in the LEP dipoles and dealt effectively with the large gas load induced by synchrotron radiation at high energy. A cross-section of the vacuum chamber in the dipoles is shown in Fig. 15.

In order to minimize power consumption, the 352 MHz Cu rf cavities operating at ambient temperature were coupled to single-cell spherical storage cavities operating with a mode having vanishing fields on the walls and, therefore, very low losses. The coupling was chosen so that the electromagnetic energy was stored in the storage cavities in the intervals between the bunches.

Since the required rf voltage scales with γ^4, it had to be increased massively from the 0.4 GV required at the Z_0 resonance to reach the W threshold and beyond. Thus superconducting cavities were required to keep the power bill within reasonable bounds. The management had the vision and courage to start R&D for these novel and complex components as early as 1979, i.e., long before the approval of LEP1, and by 1989, 20 Nb bulk cavities operating at 352 MHz and at 4.5 K could be ordered from industry. However, for the next batch of 160 cavities, CERN switched to the Nb-film technology where

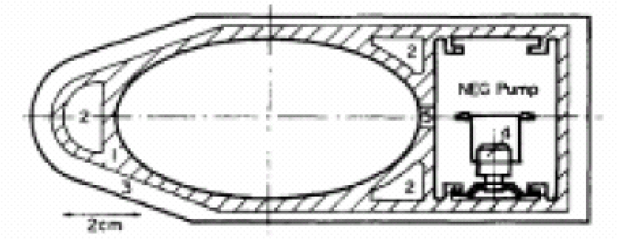

Fig. 15: Vacuum chamber in the dipole magnet made of extruded Al profile (1) with the elliptic beam channel, three water cooling ducts (2), and surrounded by a lead shield (3). The NEG pump (4) is connected by longitudinal slots (5) [11].

the film is obtained by sputtering Nb on Cu sheets. This technology has inherent advantages such as better thermal stability against quenching, savings on Nb material, insensitivity to stray magnetic fields, and a higher quality factor. The cavity production was an example of successful transfer to industry of technology developed at CERN.

LEP2 required a number of modifications and improvements apart from the upgrading of the rf system: two new klystron galleries had to be dug and equipped; a cryogenic system with long transfer lines and four refrigerators, each providing initially 6 kW and later 12 kW, was required for cooling all the superconducting cavities and the increased number of superconducting quadrupoles.

The final rf configuration comprised 272 Nb-film cavities operating on average at 7.5 MV/m (nominal 6 MV/m), 16 Nb bulk cavities (4.5 MV/m), 56 Cu cavities (1 MV/m) fed by 43 klystrons of the 1 MW class. It was the largest superconducting rf system ever with 490 m total active length of superconducting cavities, which together with the Cu system eventually provided an rf circumferential voltage of 3.6 GV. Figure 16 shows the evolution of the available rf voltage and the beam energy of LEP2 over the years.

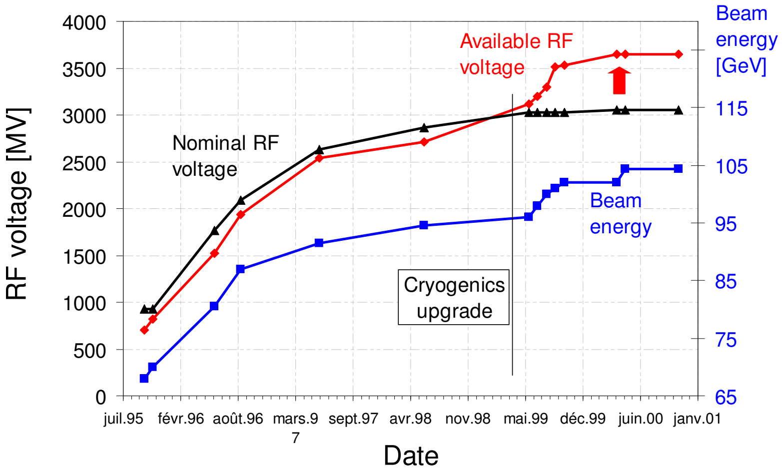

Fig. 16: Evolution of beam energy, available and nominal rf voltage of LEP2 [12]

LEP1 reached an integrated luminosity of 206 pb^{-1} at Z_0 energy, and 784 pb^{-1} at and above the W threshold were collected with LEP2. LEP underwent a practically continuous improvement which pushed the integrated luminosity per year from 9 pb^{-1} in 1990 to the record of 254 pb^{-1} in 1999.

New challenges had to be mastered during LEP construction and operation. The civil engineering know-how acquired with the SPS had to be applied on a large scale for the construction of the 27 km circumference tunnel and the big experimental halls. One of the largest rf and cryogenic systems for accelerators had to be designed, installed, and operated. Operation with strong synchrotron and radiation damping of beams, and very strong beam–beam effects provided new insights for accelerator physics. Refined methods for beam energy calibration had to be developed reducing the contribution to the uncertainty in the W mass to only 10 MeV. The operations group learnt to deal with perturbations from earth currents caused by near-by dc-operated trains which produced a relative variation of the magnetic dipole field of 2×10^{-4}, changes in the circumference of LEP caused by tides, changes in the underground water table and rain leading to variations of 1 mm in circumference resulting in deviations of 10 MeV in beam energy, and, last but not least, with beer bottles found in the vacuum chamber after a shutdown.

Although a large number of unique physics results were obtained from LEP, solidly confirming the Standard Model, the LEP machine energy was not enough to produce the elusive Higgs particle or the postulated supersymmetric particles. Whether it was a wrong decision in 1996 to discontinue the industrial production of the superconducting cavities and, therefore, not to exploit LEP fully with 384 Nb-film superconducting cavities providing 4.8 GV to reach 220 GeV in the centre-of-mass, will only be known from the results of the Tevatron and LHC in a few years' time.

4.5 The Large Hadron Collider (LHC)

The option to complement or to replace LEP later with a large hadron collider had been in the minds of European particle physicists since the mid-1970s. The design of the LHC started in 1983 and the project was approved in two steps: a two-stage approach was first proposed in 1994 with a missing-magnet scheme providing 5 TeV per proton beam which could be upgraded to 7 TeV by adding the missing complement of magnets; in 1996, when substantial contributions from non-member states had been secured, a single-stage construction with 7 TeV top energy was accepted. The start of operation is scheduled for 2007.

The nominal luminosity is 1×10^{34} cm^{-2} s^{-1} with protons of 7 TeV per beam and 1×10^{27} cm^{-2} s^{-1} when operating with Pb ions of 2.8 TeV/u. The counter-rotating beams are horizontally separated in the arcs and go from the inner arc to the outer arc and vice versa in the four crossing points where the beams interact in the detectors at a small crossing angle.

The project team has to master a number of challenges in technology and accelerator physics. The most important components are the 1232 dipole magnets with a mass of 28 t and length of 14.5 m (iron yoke). The magnetic field is 8.3 T, bending the orbits of the counter-rotating particles which are separated by only 194 mm. A cross-section of the very compact 'two-in-one' magnet is shown in Fig. 17.

The superconducting coils are wound with cables made from 6–7 μm Nb-Ti alloy filaments embedded in a Cu matrix which has to absorb the heat dissipation in case the magnet quenches. The cable carries 12 kA. An elaborate quench protection is required as the stored electromagnetic energy is 7 MJ per magnet and the heat capacity of the cable is very much reduced at this low temperature. The non-magnetic steel collars keep the coil under compression over the whole operating range in order to avoid any movement of the cables or the coils despite the very strong electromagnetic forces (2 MN/m acting transversely per coil quadrant). The magnets are cooled by superfluid liquid He at 1.7 K generated by the modified and upgraded LEP cryogenic plants.

The vacuum required for a beam lifetime of about 100 h is provided by the pumping action of the vacuum tube at 1.9 K. However, the built-up gas layer on this cold tube has to be protected against direct synchrotron radiation (0.2 W/m) emitted by the protons, making the LHC the first proton storage ring where synchrotron radiation has an impact on the hardware design. In addition, the proton bunches produce primary electrons by ionization of the rest gas, which are transversely accelerated by the electric field of the bunches and hit the walls, where the number of electrons gets amplified as a result of secondary emission. This beam-induced multi-pacting, an effect discovered at the ISR, will produce a substantial heat load.

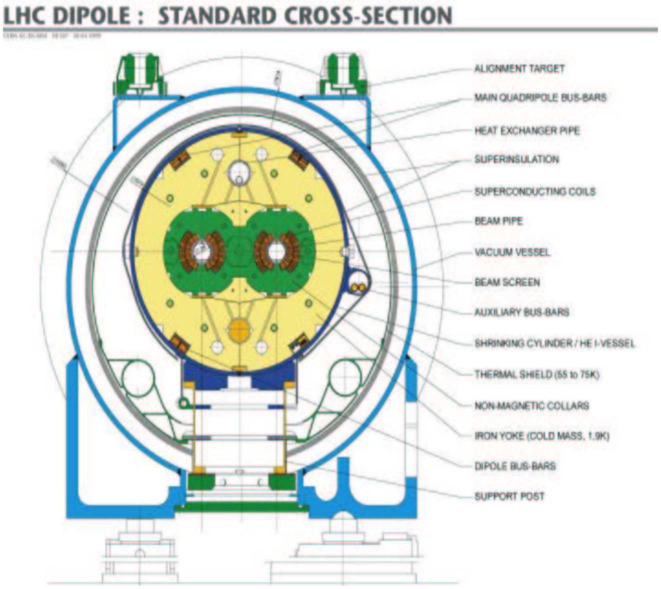

Fig. 17: Cross-section of the LHC dipole magnet [13]

In order to avoid desorption of the adsorbed gas by direct synchrotron radiation emitted by the proton beam or by photoelectrons and to absorb the heat load, an elaborate beam screen (Fig. 18) cooled to 5–20 K protects the cold vacuum chamber and its gas layer. A slight saw tooth on the surface of the screen reduces photon reflectivity, and coating the warm vacuum chambers with a special getter lowers the secondary emission yield. Scrubbing the walls with synchrotron radiation and electrons for a while during running-in will further reduce the secondary emission yield. This will be performed at lower beam energy and/or with increased bunch spacing to limit the heat load.

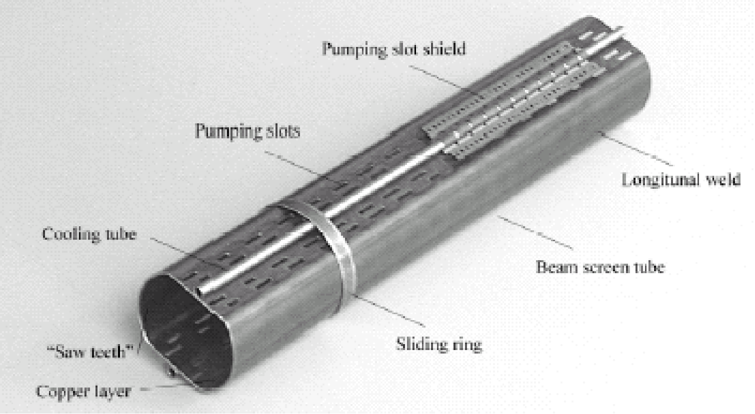

Fig. 18: Model of the LHC beam screen [13]

Important beam dynamics issues have to be tackled: i) the long-range beam–beam forces in the 120 parasitic crossings near the interaction points, because the beams contain 2808 bunches each and, therefore, the two beams 'see' each other in a common vacuum pipe before the actual interaction points; ii) multibunch instabilities, especially those induced by the electron clouds which cannot escape to the walls because the spacing of the bunches is only 25 ns.

Figure 19 shows the CERN accelerator complex with the LHC in the LEP tunnel, the SPS and the PS complex with all the transfer lines and the experimental areas of the PSB (ISOLDE), the PS (East Area, neutron Time-of Flight facility (n-ToF)) and of the SPS (West and North Area). The CERN Neutrino beam to Gran Sasso (CNGS) is under construction.

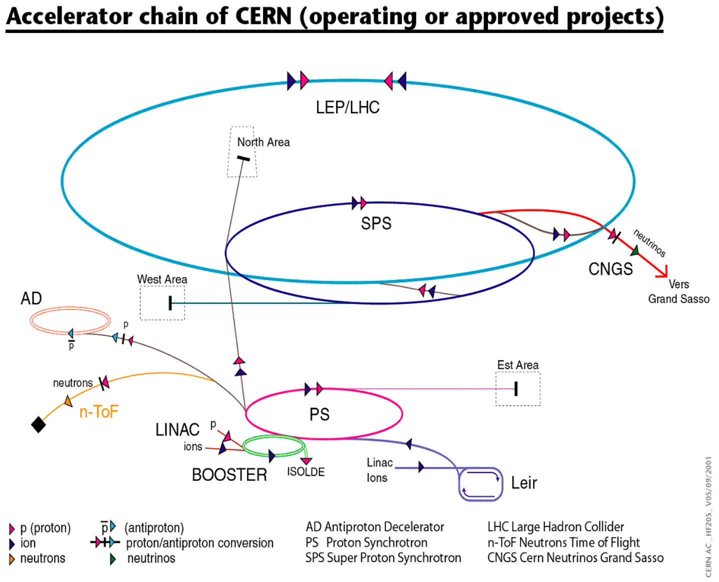

Fig. 19: The CERN accelerator complex

The new LEIR ring is also shown as an important element in the ion injection scheme of the LHC. It is nothing but LEAR modified to become a buffer accumulation ring for ions, inserted between the fast-cycling Pb linac, Linac 3, and the slow-cycling PS. It will convert four to five long linac pulses of low density into two bunches of high density at 4.2 MeV/u by means of electron cooling, more efficient than stochastic cooling at this low energy, before accelerating these bunches to 72 MeV/u and transfer to the PS.

LEIR is a good example of the tradition of CERN fully exploiting past investment as done, for example, with the PS and SPS, both of which in parallel to the fixed-target programme served as LEP injectors and will be so used for the LHC.

5 Future accelerator-based options for CERN

5.1 Overview

Since there is increasing awareness of the long lead-times of large projects, it is timely that the discussion of this issue has already started in the physics community and in the CERN Council, probably continuing for a number of years even when the first results of the LHC become available. This situation will be very similar to the one we experienced earlier during the passionate, lengthy debates and scrutiny of options in the early 1960s after the construction of the PS, and in the middle of the 1970s after the completion of the ISR, although this time the discussion will be more global and will include our colleagues from other regions of the world.

There are three basic directions to take: hadron colliders, lepton colliders, and advanced neutrino beams. Each can lead either to exploratory experiments or to precision physics.

The most straightforward option for CERN seems to be the upgrade of the luminosity of the LHC by an order of magnitude to 10^{35} cm^{-2} s^{-1}. The upgrade of the LHC energy by a factor two yielding a centre-of-mass energy of 28 TeV has also been studied, although the step in energy is small and the length of the required shutdown to install new magnets, and probably also to upgrade the injectors, is somewhat deterrent. A Very Large Hadron Collider (VLHC) was considered but turns out to be excluded by the geology around CERN. According to the study by our colleagues in the USA, led by FNAL, it would require a circumference of more than 200 km to reach 40 TeV and, eventually, 200 TeV in the centre of mass.

The VLHC is apparently less attractive, for the next large new facility, because there seems to be a vast consensus in the international physics community that a linear electron–positron collider in the centre-of-mass range between 0.5 TeV and 1 TeV is the best choice. Although the energy reach of the latter is rather limited, it is considered to be complementary to the LHC and could provide hints beyond LHC energies, provided its luminosity is high enough to perform precision measurements. One could imagine CERN joining an international consortium to construct this International Linear Collider (ILC). In parallel with these studies for such a TeV-class collider based on the extension of known technology, conducted in particular by DESY, KEK, and SLAC, for a number of years a collaboration led by CERN has been studying a technology which would allow the exploration of the high-energy frontier beyond LHC with a Compact LInear Collider (CLIC), also operating with positrons and electrons. This frontier could also be reached with μ–μ colliders in the TeV class but the required technologies for the production of intense and dense μ beams appear so challenging that some disenchantment has replaced the initial enthusiasm.

Advanced neutrino beams also appear to be an interesting option, in particular since neutrino physics is rather decoupled from the LHC results and a number of synergies with nuclear physics and condensed-matter physics promoting a European spallation source can be imagined. In a first instance, a more powerful but still conventional neutrino beam ('Superbeam') based on a powerful superconducting linac (4 MW beam power) using LEP components feeding a new accumulation and compressor ring in the ISR has been considered. The next stage, using the same linac as proton driver, could be a 'Neutrino-Factory' based on a μ-decay ring providing pure neutrino beams. A competing idea is to add a decay ring to the SPS where an intense beam consisting of β emitters would coast producing a pure electron–neutrino beam. In both of these decay rings, charge-conjugate beams can also be produced: in the first case by using negative muons instead of positive ones, in the second case by choosing a positron emitter instead of an electron emitter.

5.2 LHC upgrade

A staged approach has been suggested [14], briefly sketched here. First, the luminosity would be raised in steps. Examination of the formula for the luminosity shows the parameters which can be influenced

$$L = n_\mathrm{b} f_\mathrm{rev} N_\mathrm{b}^2 F/(4\pi\sigma^*) \tag{1}$$

where n_b is the number of bunches per beam, N_b the number of protons per bunch, σ^* the r.m.s. beam radius at the interaction points (round beam), and $F = 1/(1 + (\theta\sigma_z/2\sigma^*)^2)^{1/2}$. F is a form factor of order 1 depending on σ^*, the beam crossing angle θ and bunch length σ_z. For the LHC, its value is 0.9 for θ = 0.3 mrad.

In Phase 0, the maximum bunch intensity limited by the beam–beam effects is raised by colliding the beams in interaction points 1 (ATLAS) and 5 (CMS) only, and the crossing angle is decreased by modifying the layout of magnetic elements at these crossing points. This results in an increase of a factor 2 to 3 in luminosity.

Phase 1 requires new insertion quadrupoles to increase the beam focusing ($\beta^* = 0.5 \rightarrow 0.25$ m) resulting in a σ^* decreased by $\sqrt{2}$. Very likely these quadrupoles would have superconducting coils made from $\mathrm{Nb_3Sn}$, an alloy with a higher critical field but being very brittle (VLHC technology). Increasing further n_b and N_b results in a luminosity between 5 and 7×10^{34}.

Phase 2 is an energy upgrade, a major upheaval which cannot be envisaged before the next decade. In order to reach 14 TeV per beam compared to the present nominal 7 TeV, amongst many other components new magnets are required and, in particular, new dipoles with a magnetic field of 15 T compared to the present 8 T; the injection energy has to be raised to 1 TeV by equipping the SPS with pulsed superconducting magnets. Both these modifications demand a vigorous R&D programme in superconducting materials and magnet design. It is not likely that this energy upgrade could be accomplished before 2020, which diminishes the attractiveness of the proposition.

5.3 Electron–positron linear collider

Schemes for a linear collider with a centre-of-mass energy between 0.5 and 1 TeV and a luminosity around 3 to 6×10^{34} have been the subject of an intense R&D programme led by DESY, KEK and SLAC [15]. Recently, the International Technology Review Panel (ITRP) has recommended concentrating on the linac technology based on superconducting bulk-Nb accelerating structures operating at 1.3 GHz with an accelerating gradient of 25–35 MV/m as pioneered by the TESLA collaboration based at DESY. In the TESLA proposal, the facility had a length of 33 km, providing 0.8 TeV in the centre of mass. Figure 20 shows a schematic layout of TESLA with its X-ray free-electron laser (FEL) option which will not be adopted for the ILC.

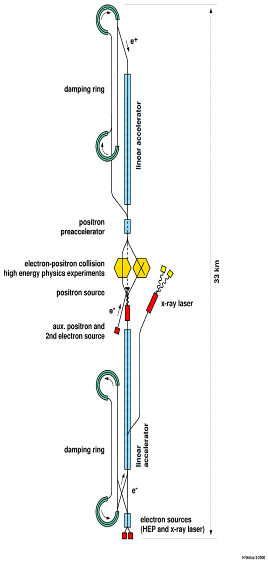

Fig. 20: Schematic layout of TESLA [16]

After the decision on technology, the next step towards the ILC is the setting-up of a central team and regional teams. They will review the TESLA design and its challenges, e.g., the very long dog-bone damping rings (2 × 17 km); the non-conventional positron production through laser light generated by the electron beam at top energy, which tightly couples the positron operation to the electron one; the focusing of the beams to $\sigma^*_{x/y} = 400$ nm$/3$ nm; and the safe tackling of 18 MW beam power per beam. Test facilities are under construction to test the basic components and to demonstrate the engineering margins required for such a big project.

In order to reach a very high energy in a reasonable length, CLIC [17] would use a very high accelerating gradient (150 MV/m) generated in normal-conducting accelerating structures operating at 30 GHz, though the optimum frequency may be somewhat lower. The choice of gradient and frequency makes the linac very short such that 3 TeV in the centre of mass are reached within an overall length of about 33 km (10 km for 0.5 TeV). The linac is also very compact in transverse dimension as the outer diameter of the accelerating structures is of the order of 10 cm. Figure 21 shows a cross-section of the CLIC tunnel of the same diameter as the LEP/LHC tunnel.

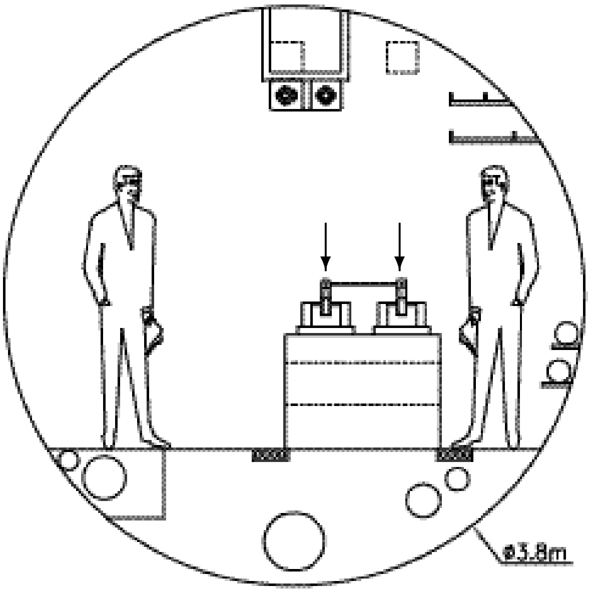

Fig. 21: Cross-section of the CLIC tunnel. The position of the drive linac and main linac are indicated by arrows. The linacs are linked by a horizontal waveguide [17].

The novel power generation scheme of CLIC does not use a vast array of klystrons but a number of drive beams which run along a considerable length (≈640 m) parallel to the main beam. The intense electron drive beam pulses of 150 A in 130 ns are decelerated from 2 to 0.2 GeV generating in the decelerating structures a 30 GHz rf power pulse which powers the structures accelerating the main beam pulse of low-intensity (1 A in 102 ns) up to 1.5 TeV.

Although CLIC holds the promise of a high potential, the linac technology of CLIC is certainly less mature than that of the ILC whose feasibility is fairly well established thanks to the TESLA Test Facility at DESY. The most important challenges for CLIC are the high accelerating gradient (150 MV/m), and the generation and control of the high-power drive beam. A disadvantage of CLIC is that its basic rf unit is relatively large, requiring a substantial investment for a full-scale test.

5.4 Advanced neutrino beams

There are basically two production mechanisms of neutrino beams: i) based on the decay of π and K mesons; ii) based on the decay of beta emitters.

5.4.1 Neutrinos from mesons or muons

The first process yields neutrinos either directly through the π and K decay or the μ decay

$$\mathrm{p} \rightarrow \text{Target} \rightarrow \pi^+ (\mathrm{K}^+) \rightarrow \mu^+ + \nu_\mu \tag{2a}$$

$$\hookrightarrow \mathrm{e}^+ \nu_\mathrm{e} \bar{\nu}_\mu \tag{2b}$$

Process (2a) has been the traditional way of producing neutrino beams, still used at present (KEK/K2K) and in the medium term future (FNAL/NuMI, CERN/CNGS). The neutrino ‘superbeams’ under study are based on it, using very powerful proton accelerators providing a beam power in the MW range at the target. Selecting by focusing negative π and K yields the charge conjugate particles. Note that this neutrino beam is always contaminated with neutrinos from the π and K of the opposite polarity which cannot be eliminated completely by the focusing of the secondary particles. Further sources of contamination are the neutrinos from μ decay and the neutrinos from the decay of $K_{\mu 3}$, K_{e3} and neutral kaons.

Process (2b) uses muons decaying in a suitable storage ring, resulting in a very pure neutrino beam of only two species. Since one hopes to obtain very intense beams from such a facility, it was baptized ‘Neutrino Factory’. Figure 22 shows the schematic layout of such a facility.

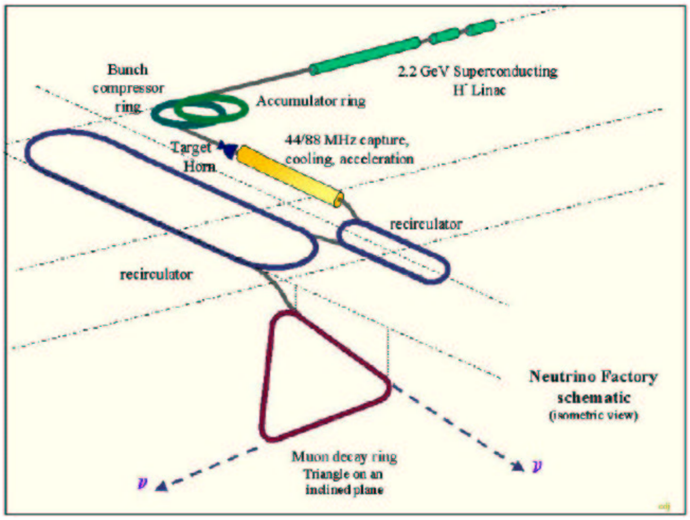

Fig. 22: Schematic layout of the European Neutrino Factory Complex [18]

The driver is a superconducting linac based on LEP components feeding negative H ions to an accumulation ring where they are stripped during the multiturn injection process. After compression in the twin ring, the 4 MW beam hits the target. The resulting π and K decay to muons which subsequently have their phase space density increased in a cooling device. Acceleration to 50 GeV has to be very rapid on account of the limited lifetime of the muons. It takes place in a linac followed by two recirculating linacs before the muons are injected into the decay ring. This is not a small facility. For example, the total rf voltage required is 15 GV, about four times the voltage installed in LEP2.

The critical design issues related to the high beam power are the proton driver, the target, and the downstream μ collection system. The target has to withstand the shock of the proton beam, and the wide-band π collection system the intense radiation. The hardware must be designed to minimize induced radioactivity and to enable correct maintenance. The hitherto untried technology of ionization cooling of the μ beam has to be tested thoroughly. A Muon Ionization Cooling Experiment (MICE) has been worked out in detail and it is hoped that it will be conducted fairly soon using a μ beam either at PSI or ISIS/RAL. A further challenge is the rapid acceleration of the muons which have a very limited lifetime ($c\tau_\mu = 658$ m at rest) requiring high accelerating gradients at low energy to increase their lifetime as quickly as possible, the latter being proportional to γ.

5.4.2 *Neutrinos from beta emitters*

The idea is to generate suitable beta emitters by the ISOL technique, developed at CERN and currently used at ISOLDE, to accelerate them using the existing PS and SPS, and let them decay in a new storage ring. There they would produce an intense, pure neutrino beam of only one species with a narrow opening angle due to the high Lorentz factor which is $\gamma \approx 150$ at SPS top energy. Examples of suitable beta decays are

$$\begin{aligned} {}^{6}_{2}\mathrm{He} &\to {}^{6}_{3}\mathrm{Li}\,\mathrm{e}^{-}\,\overline{\nu}_{\mathrm{e}} \\ {}^{18}_{10}\mathrm{Ne} &\to {}^{18}_{9}\mathrm{F}\ \mathrm{e}^{+}\,\nu_{\mathrm{e}}\,. \end{aligned} \tag{3}$$

The He isotope has 0.8 s lifetime at rest; the Ne isotope has 1.6 s, which would give comfortable lifetimes of 120 s and 96 s, respectively at SPS top energy. The He isotope is obtained from the reaction Be (n, α) induced by spallation neutrons produced by protons hitting a heavy metal target; the Ne isotope is produced by protons hitting a MgO target.

A possible schematic layout of such a neutrino source (called ‘beta-beam’) using the CERN infrastructure is shown in Fig. 23. A new injection system for the PS is required with a Superconducting Proton Linac (SPL) as front-end providing protons at 2.2 GeV. The ions diffusing out of the target are collected, fully ionized, and bunched in an Electron Cyclotron Resonance (ECR) device and, subsequently, accelerated in a linac to about 100 MeV/c before being injected into a bunching ring which precedes a Rapid Cycling Synchrotron (RCS) [19].

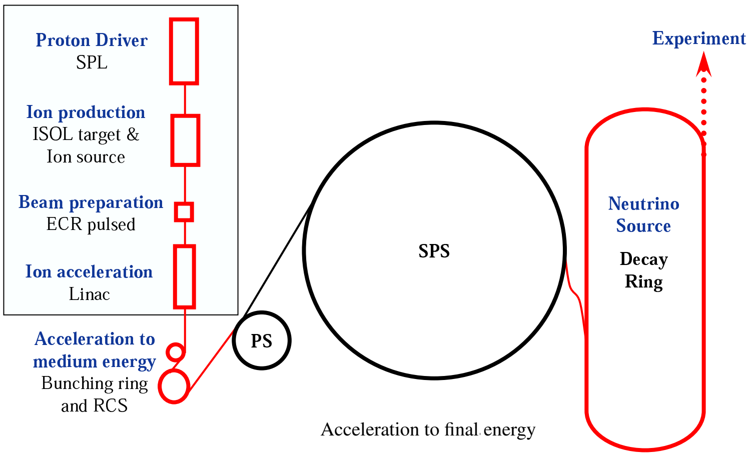

Fig. 23: Schematic layout of a neutrino source based on beta emitters [19]

The accelerator issues are the generation of an ion beam of sufficient intensity, the detailed understanding of the transmission efficiency of the many accelerators in this chain, the control of the inevitable losses during acceleration of the decaying ions in order to avoid contamination of the accelerators, and the accumulation of the ions in a very few bunches in the storage ring. Common issues with all the other neutrino sources are the handling of the hot target and the activated components downstream of the target, and the politically delicate and not easily controllable procedures to obtain and to retain the authorizations for the operation of a MW-class proton driver and target.

Since the front-end linac is virtually the same as the one needed for the superbeam for which it has to provide 4 MW beam power and since only 200 kW on target are required for the neutrino source based on beta emitters, the idea has been aired of having both facilities built at CERN with the two different neutrino beams pointing to the same detector. The advantage would be that data on $\nu_\mu \to \nu_e$

and $\nu_e \rightarrow \nu_\mu$ oscillations and, in a later run, on the oscillations of the charge conjugates could be simultaneously collected, significantly speeding up the data taking.

As the nuclear physics community is also very interested in spallation neutrons to generate radioactive ion beams, possible synergies are under investigation in a study sponsored by the European Union.

6 Conclusions, or what we have learnt in the past 50 years

It was the continuous stream of good and attractive projects that created a growing user community giving unfailing support to CERN. The strategy has included the full exploitation of existing facilities, either by upgrading or re-use after modification, and the timely stopping of facilities when they were no longer on the leading edge. This has led to an evolution of the accelerator park given in Fig. 24.

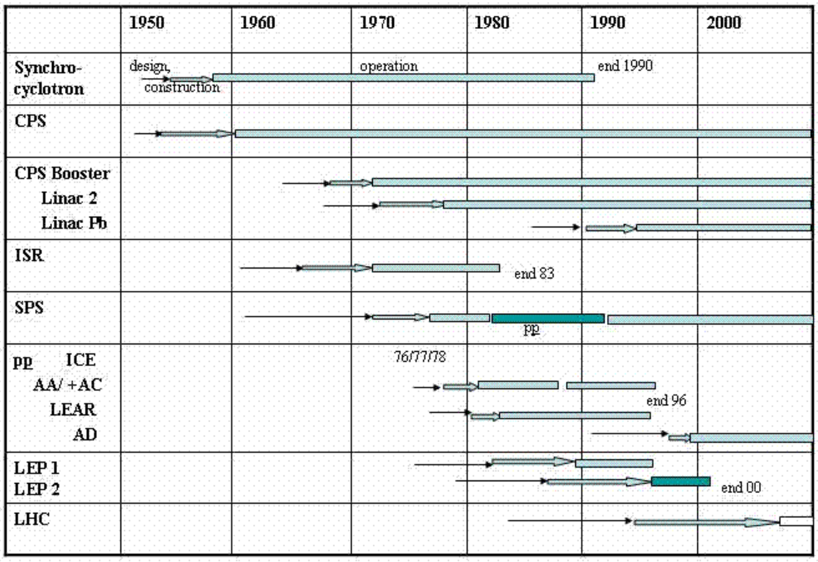

Fig. 24: Evolution of CERN's accelerator park

Examination of the graph indicates that colliders have a short lifetime compared to that of accelerators. The latter have turned out to be the real work-horses of CERN, serving as particle sources for the fixed-target programme, providing the indispensable test beams, and faithfully playing the role of injectors for leading-edge colliders. The SPS was even turned into a very successful collider for a while.

There are a number of lessons from this success story. First, CERN has always gone for projects and has carefully avoided losing time and reputation with uncommitted R&D. It realized very soon that large projects have long lead-times and, therefore, one has to think ahead, which nowadays means thinking in terms of decades. Obviously, key technologies must be mastered, preferably by CERN itself, before inviting tenders from industry. Industrial production has to be monitored meticulously and CERN must have the resources to immediately intervene with advice and active help in case a problem arises.

Work on operation and upgrading of existing accelerators and, simultaneously, either conducting R&D or constructing new facilities has turned out to be extremely beneficial for CERN. Operation immediately gains from the new insights obtained and techniques learned in R&D, and the design of the new facility is based on the experience and know-how acquired in operation, which keeps the project team on the floor of reality.

When drawing up a project it is imperative to work as closely as possible with the users but the parameters should be chosen based on existing know-how and, whenever possible, on full-scale tests of all critical components and not on the desiderata of the users, which do however provide the indispensable guide lines. Sufficient engineering margins guarantee long-term reliability and flexibility and should not be sacrificed to exaggerated competition leading to rush decisions which are bitterly regretted afterwards. All this is best underlined by citing from J. B. Adams's farewell talk to Council in December 1980.

> *The question of how much flexibility to build into a machine is obviously a matter of judgement, and sometimes the machine designers are better judges than the physicists who are anxious to start their research as soon as possible. But whatever compromise is reached about flexibility, one should certainly avoid taking risks with the reliability of the machine because then all its users suffer for as long as it is in service and the worst thing of all is to launch accelerator projects irrespective of whether or not one knows how to overcome the technical problems. That is the surest way of ending up with an expensive machine of doubtful reliability, later than was promised, and a physicist community which is thoroughly dissatisfied.*

CERN will have to adapt to the large size and complexity of future facilities at the high-energy frontier; this will increase the lead-times and require a global approach involving not only the European particle physics laboratories but also those of other regions, an approach already timidly started with LEP but then adopted for the LHC.

Although the infrastructure of CERN is one of its well-known assets, the most important one is the carefully selected young staff who have been hired in recent years. It is extremely important that they are taught not only in academic lectures like this one, but that they work with and are encouraged by experienced colleagues, as I was myself when I came as a young Fellow to CERN and the late Mervyn Hine, though then Director of Planning, took a personal interest in my work, for which to this day I am still extremely grateful.

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