# Chapter 2
# The CERN Proton Synchrotron: 50 Years of Reliable Operation and Continued Development

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**Abstract** This contribution, a personal recollection by the author, is part of a special issue titled *CERN's accelerators, experiments and international integration 1959–2009*. Guest Editor: Herwig Schopper [Schopper, Herwig. 2011. Editorial. *Eur. Phys. J. H* 36: 437]

## 2.1 Introduction: A Brief Excursion into the History of CERN

On the 24th of November 1959 the CERN Proton Synchrotron (CPS), the most important project on the program of the young CERN laboratory, reached its design energy of about 25 GeV for the first time. This recollection is dedicated to the 50th anniversary of that day.

The history of CERN began 10 years earlier at the Congress on European Culture, organised in Lausanne from 8 to 10th of December 1949 by the Genevan philosopher Denis de Rougemont. During that meeting a message submitted by Nobel laureate Louis de Broglie was read, suggesting the idea of

> '*… establishing a laboratory or institution where it would be possible to do scientific work, but somehow beyond the framework of the different participating states.*'

This first public proposal for scientific collaboration in Europe resulted, a few years later, in the foundation of CERN.

De Broglie's suggestion was encouraged at a UNESCO Conference in June 1950, where Nobel laureate Isidor I. Rabi read an important supporting statement

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from the USA. Pierre Auger, a pioneer of cosmic-ray physics, was then mandated by UNESCO to set up a Group of Experts who would make a proposal for a European laboratory for nuclear research.

High-energy particle beams are the prime tool for the investigation of the structure of atomic nuclei. Particle accelerators are used to accelerate beams of electrons or protons for this purpose to ever-increasing energies. The initial electrostatic accelerators, which provided beams of some 20 MeV, were replaced around 1930 by machines exploiting radio-frequency fields in linear or circular geometries, the latter coming in subsequent generations of cyclotrons (up to 50 beam energy), synchro-cyclotrons (up to 700 MeV) and synchrotrons. The maximum energy of a synchrotron is, as for a linear accelerator, unlimited in principle, i.e. limited only by practical considerations, such as the site or the budget available. By 1950, the two largest proton accelerators, both under construction in the USA, were the Cosmotron at the Brookhaven National Laboratory (BNL) with 3 beam energy and the 5 GeV Bevatron at the Berkeley Laboratory of the University of California.

In May 1951 the Group of Experts submitted an ambitious proposal for the principal equipment of the future European laboratory: a proton synchrotron 'bigger than any existing at present' of, say, 10 GeV and a synchro-cyclotron of 600 MeV. With this goal in mind, a Provisional Organisation for Nuclear Research was founded in February 1952 of which Edoardo Amaldi was appointed Secretary General and (amongst other nominations) Odd Dahl chairman of its Proton Synchrotron (PS) Group.

In the summer of 1952, members of the PS Group on a study trip to the USA were, much to their surprise, invited to participate in discussions at BNL on a new idea for focusing particle beams known as 'alternating gradient focusing'. This approach would reduce the beam size by about an order of magnitude compared to the traditional technique, in exchange however for an increased sensitivity to alignment and field errors. Correspondingly, the dimensions of the guide and focusing magnets would be reduced, so that within a given budget substantially higher beam energies could be achieved. O. Dahl convinced the CERN Council in its session in October 1952 to commission a detailed study of a synchrotron based on the novel alternating gradient (A.G.) principle—very likely one of the most important decisions in CERN's history.

During that session, Council also decided to locate the future European laboratory in Geneva. The definitive foundation of the CERN organisation occurred on 27th September 1954 with the deposition of the Member States' signatures. Many more details of the history of CERN in general, from the early contacts to the late seventies, were the subject of a detailed analysis by a team of science historians, published in three volumes (Hermann 1987, 1990; Krige 1997).

The PS Group, whose members were still working in their respective home institutions spread over several countries, then set to work on the conceptual design of an A.G. synchrotron and its main components, as well as on extensive mathematical modeling so as to understand the feasibility (or not) of the novel accelerator. Their work was discussed in Geneva at a conference (Blewett 1953) with international attendance in October 1953, when it was decided that all members of the Group should move to Geneva as soon as possible. After O. Dahl's withdrawal under the direction of John B. Adams, the Group felt ready to decide on the main parameters of the CPS at the end of 1954: 25 GeV beam energy to be attained at 1.2 T magnet induction (extendable to 28 GeV); protons to be provided by a 50 MeV linear accelerator; a magnet mass of 3,300 tons, to be housed in a toroidal tunnel of 200 m diameter. A similar project was launched at the BNL in mid-1955.

Although the two projects were carried out in a spirit of friendly competition with frequent contacts, the task that faced the CERN Group was enormous: of only a dozen full-time members initially, they carried the responsibility for the design ab initio and the construction of a completely new machine estimated to cost about 100 Million Francs, to be built on a green field in a new laboratory. At the same time, an international staff complement had to be recruited and manufacturing contracts to be placed with industries all over Europe. By autumn 1959, after 5 years' construction time, the CPS was ready for start-up, the staff of the PS division then comprising some 180 members.

The state of the machine at end of 1959 has been described in CERN Yellow Reports (Regenstreif 1958, 1959, 1961). This article will concentrate on an overview of the many purposes the CPS has served during its 50 years of operation, most of them unexpected and, in fact, not possible had the innovative A.G. principle not been adopted in 1952. The beam current was increased by more than three orders of magnitude, and other physical beam properties were adapted to the varying needs of its many users. All of these developments, which for most subsystems meant a complete rebuilt and involved the addition of dedicated injectors, are reviewed in detail with appropriate references by 24 contributors in a CERN Yellow Report (Gilardoni 2011a, b).

## 2.2 The Start-Up of the CERN Proton Synchrotron

On 24th November 1959 at 19:35, after some 8 weeks of fruitless trials and a final successful modification of the acceleration system, acceleration to 25 GeV/c was achieved for the first time (Fig. 2.1).

That had not been an easy feat. The main power supply, which provided at 3 s repetition rate (1 to rise, 1 to fall, 1 s pause) the current per pulse of 6,000 A peak for the 100 magnet units, many auxiliary supplies, the 15 stations of the RF acceleration system, and the electronics for beam observation and steering systems—all had to work in perfect synchronicity for the beam to attain maximum energy. The pressure inside the 625 m of the vacuum chamber, provided by some 100 pump units then still equipped with oil diffusion pumps, had to be as low as was possible at that time.

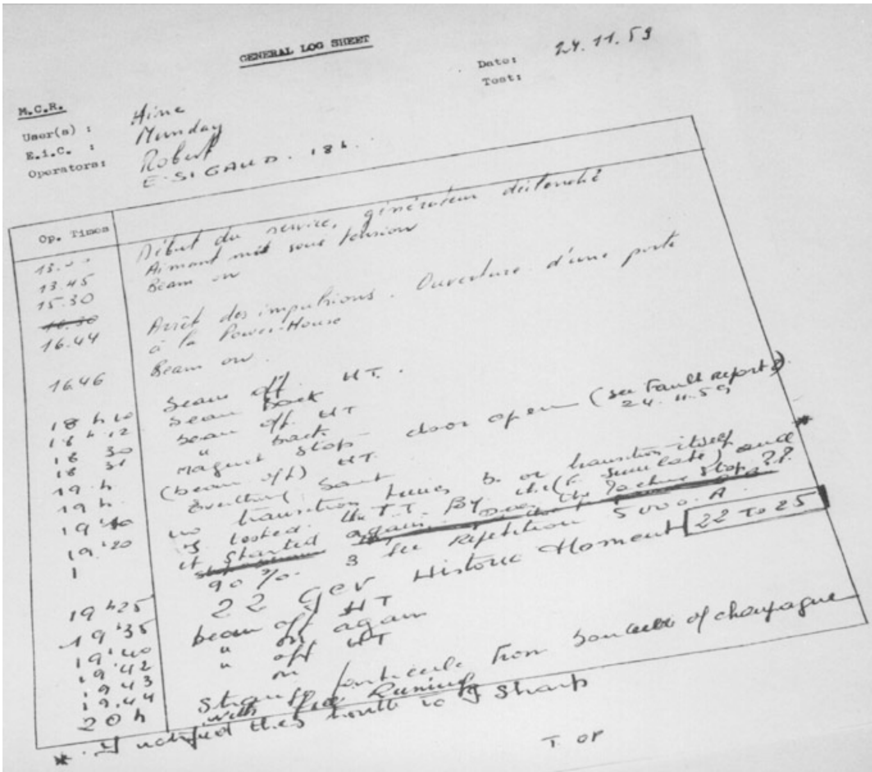


**Fig. 2.1** A historic page from the logbook

Any remaining doubts as to the validity of the new focusing principle that might have persisted during the years, despite the extensive investigations, were thus lifted. There was still a long way to go, however, towards a real understanding of the beam behaviour during acceleration, as pointed out in the first Quarterly Report of the PS Machine Group by an anonymous author (J.B. Adams?):

> '*Thus the situation in December 1959 was that the synchrotron had worked successfully up to its design energy, and already beyond its design current, but with its builders and operators in a state of almost complete ignorance on all the details of what was happening at all stages of the acceleration process*.'

This statement may sound like an exaggeration to somebody used to today's means for controlling and observing the functioning of our accelerators. It presents, however, a fairly true picture of the state of electronics and supporting technologies around 1960. The development of modern digital electronics—then in its infancy—was an essential ingredient for the development of beam diagnostics and beam control techniques. These were developed and re-developed during the five decades under review, resulting in the present detailed

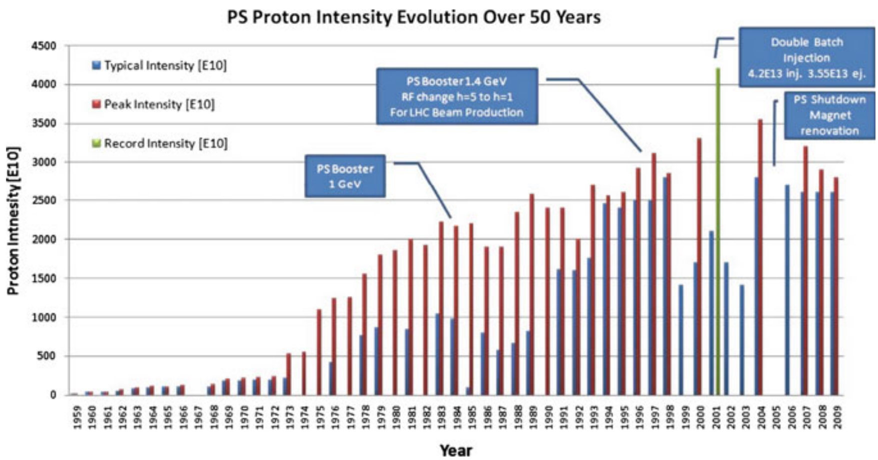


**Fig. 2.2** The high intensity proton beam

understanding in space and time, as well as the control of all details *of what is happening at all stages of the acceleration process.*

The above statement also illustrates the inherent robustness of a carefully designed A.G. synchrotron, which was expected to be extremely delicate to operate; to the contrary, once the critical 'transition energy' was passed, where a jump in the phase of the accelerating RF field is necessary in order to compensate for the effects of the relativistic mass increase of the protons, the beam was accelerated through to design energy with nearly no operator intervention. Time and again, the experience of the past 50 years has shown that the designers of the PS had a very lucky hand indeed in choosing the basic parameters as well as the detailed layout of the machine. The CPS could be adapted to support many different users, providing them with protons and antiprotons, electrons and positrons, as well as with a wide range of ions.

The start of the CPS, smooth as it appeared once the passage of the transition energy was mastered, triggered an avalanche of proposals for experimentation on beams derived from the PS, upgrades to be implemented, and for future facilities to be built, of which a necessarily very brief overview is given in the following chapters.

## 2.3 Developing the Beam Intensity

During the 50 years under review ever-higher beam currents were the primary request, the beam intensity per pulse increasing by more than a factor of 1,000 (Fig. 2.2). The available beam was being shared between an increasing number of experiments, but at the same time the neutrino experiments in particular required the highest possible beam intensity. Since 1980, producing antiprotons for the proton-antiproton experiments in the Super Proton Synchrotron (SPS) and, again, neutrino beams—in recent years for experiments located as far away as the Gran Sasso underground laboratory—required top intensities.

A first ‘PS Improvement Program’ was initiated during the sixties which attacked the existing intensity limitations on several fronts:

- Shortening the magnet cycle by installing a stronger main magnet power supply;
- The construction of a high-power acceleration system;
- Many improvements of the injector linac; finally, construction of a new 50 MeV linac (Linac 2, in operation since 1978);
- Improving the current limitation due to space-charge tune-shift at injection: the PS injection energy was increased to 800 MeV by adding a synchrotron dedicated to acceleration from 50 to 800 MeV, the ‘Booster’ injector;
- Improving the transition crossing by a rapid change of the beam focusing (‘transition jump’ by a set of pulsed quadrupole lenses);
- A general improvement of the machine vacuum: replacement of the rubber by metal gaskets or in situ welds, new cleaning procedures for the vacuum chamber, new pumping stations;
- A general drastic reduction of beam losses during acceleration and the removal of delicate electronics from the tunnel.

The peak intensity could thus be increased to $10^{13}$ protons per pulse from 1975. A further increase to more than $3 \times 10^{13}$ was achieved by increasing the transfer energy from the Booster to the PS from 800 MeV to 1 GeV, and in a final step to 1.4 GeV. The maximum achievable beam intensity today is limited by the 50 MeV injection energy of the Booster. Therefore a project to construct a new 160 MeV linac (Linac 4) was launched in 2008 to ensure that the beam brightness, i.e. intensity and density, required for LHC operation was attainable.

With steadily increasing beam current, radiation damage to components of the PS became a serious problem. Parts of the main magnet situated closest to the beam and near internal targets, the pole-face windings and the excitation coils with their organic insulation materials, as well as the glue between the steel laminations showed signs of radiation damage after some 10 years of operation. New pole-face windings were installed in 1978/1979 all around the ring and laminations bent by the pulsed magnet operation were stiffened. A complete overhaul of the main magnet was undertaken in 2003 when more than half of the units were rebuilt with new excitation coils and pole-face windings, essentially according to the original design.

At today’s high beam currents a very careful adjustment of beam steering and focusing during the whole cycle has become essential to keep beam losses to a minimum; internal targets were suppressed long ago and the accelerated intensity is limited to the minimum compatible with the research underway at all times.

## 2.4 An Ambitious Program for the New Synchrotron

In the original concept, beams for experiments were to be created by scattering from targets flipped up towards the edge of the circulating proton beam at the end of the acceleration cycle. Two experimental areas, the South and the North halls, were built initially, the targets being installed on the machine arc between the two halls. While it was not apparent during the design phase and before, in 1960, significant experiments appeared on the floor, it soon became clear that these experimental areas would not only soon be saturated, but were totally inadequate for the experiments being proposed by researchers from the various CERN member states, e.g. large bubble chambers and electronic experiments of increasing size. New experimental areas providing surface areas for electronic experiments, as well as accommodation responding to the safety requirements for bubble chambers filled with inflammable liquids (propane or liquid hydrogen), were built during the sixties.

The interest in neutrino experiments triggered the development of a beam extraction system, ‘Fast Extraction’, so as to dispose, from 1963 onwards, of the whole circulating beam in a short burst, within the window of sensitivity of the detectors. The fast extraction system made use of a pulsed magnet (rising within 100 ns, the gap between two bunches of the circulating beam) and a septum magnet, and produced a burst of 2 μs duration, corresponding to the revolution time in the PS. Extraction systems of that type were used for beam transfer towards the Intersecting Storage Rings (ISR) and other purposes involving the PS.

In order to reduce the irradiation of the PS components near targets and to supply long beam bursts to experimental areas at a distance from the CPS, a ‘Slow Extraction’ system was developed. On a flat top of the magnet cycle, beam focusing is modified so as to operate near a resonance of the betatron oscillations. Protons would thus be induced to jump the septum of an ejection magnet during periods of hundreds of milliseconds and be directed at an external target for the production of secondary particle beams.

More ambitious ideas were being discussed from the early sixties. The idea of profiting from the centre-of-mass energy available in the collision of beams of relativistic particles aroused great interest. The construction of a proton–proton collider—a system of two rings where counter-rotating beams provided by the CPS collide in one or several areas—was discussed. At the same time the competing proposal of building a proton synchrotron of about ten times the energy of the CPS—the ‘300 GeV machine’—was launched. For a number of years it was assumed that for this machine, a site larger than that available around CERN would be required, for which several Member States submitted proposals of (more or less) suitable sites and were eager to accept a second CERN laboratory. The proposal of underground tunneling in the underlying rock near the Meyrin site, of which the present author was one of the originators back in 1961, implied again making use of the CPS as pre-accelerator.

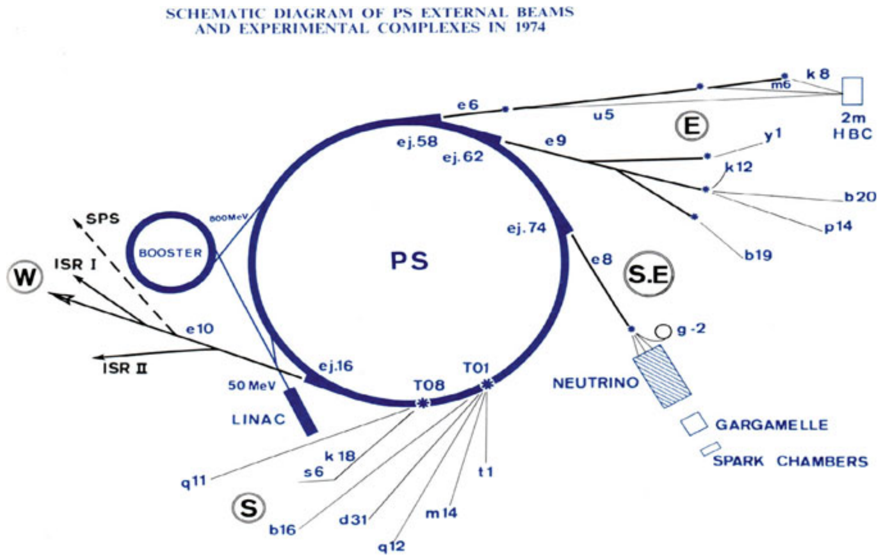


**Fig. 2.3** Beams from the PS—1974

The CPS would thus change roles from supplying beams from internal or external targets to experiments located in the East, South-East, South and West Areas as in Fig. 2.3 to becoming the injector to another machine downstream. In fact, from 1970 proton beams were transferred to the ISR and, from 1976, to the SPS.

Furthermore, from 1980 the CPS provided antiprotons for the Proton-Antiproton experiments, and from 1989 electrons and positrons for the Large Electron–Positron (LEP) collider. Beams of light ions were produced from 1981. Proton beams of very high brilliance are now required for the Large Hadron Collider (LHC). A summary of all types of beams delivered by the CPS is given in Fig. 2.4.

### *2.4.1 New Experimental Areas for 'PS Physics'*

While in 1960 the CPS presented itself, to the outside observer, as a well finished project, in 1961 bulldozers had already moved in for the construction of the East Experimental Area. From 1963 this area comprised a large hall for beams and electronic experiments, as well as a building for hydrogen bubble chambers, This area was oriented in the direction of the ejected beams, so that several high-energy primary beams from fast and slow ejection systems as well as high-energy of secondary particles beams could be brought in.

The neutrino experiments located in the South Hall—which unfortunately arrived late in the competition with BNL for the discovery of the muon-neutrino—were discontinued in 1965 to be relocated to the South-East area, which was

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| HIGH INTENSITY PROTONS | 1960 | PS EXP. AREAS |
| | 1971 | ISR |
| | 1976 | SPS |
| | 1980 | ANTIPROTON PRODUCTION |
| | 2008 | LHC |
| ANTIPROTONS | 1981 | PPbar COLLIDER (to SPS at 26 GeV/c) |
| | 1981 | ISR |
| | 1983 | LEAR (at 0.6 GeV/c) |
| Electrons/Positrons | 1989 | LEP |
| LIGHT IONS | 1976 | ISR |
| HEAVY IONS | 1994 | SPS |
| | 2010 | LHC |

**Fig. 2.4** PS beams and their destinations

conceived for a high intensity neutrino beam and had enough space to accommodate the Gargamelle heavy liquid bubble chamber. It was there that one of the major discoveries at CERN, the weak neutral current, was observed in 1973 (Cashmore et al. 2004).

Later, the muon storage ring for the last of the CERN experiments measuring the magnetic moment of muons (with ever higher precision) was installed in the S-E area. This ring was rebuilt in 1977 to become ICE, the Initial Cooling Experiment, for the development of the novel technique of stochastic beam cooling (after the initial demonstration in 1974 in the ISR), in preparation for the Proton-Antiproton experiment in the SPS.

The West Hall (located at the far West end of the CERN site, beyond the site of the ISR), with the BEBC hydrogen bubble chamber and finally also the Gargamelle bubble chamber installed behind it, was opened in 1969 for beams from the PS. Both the fast and slow ejection systems of the PS provided beams till 1975, when the hall was turned over to beams from the SPS.

Later, in the wake of the closure of the synchro-cyclotron in 1990, the Isolde Isotope Separator was relocated to a dedicated experimental area fed by the 1 GeV beam of the PS Booster during machine cycles not used for the PS. A dedicated experimental area for the Neutron ToF (time-of-flight) experiment was opened in 2000 in the beam transfer tunnel through which beams from the PS has been sent towards the West Hall.

## *2.4.2 The CPS: A Versatile Pre-accelerator*

### 2.4.2.1 Injector for ISR

The successful start of the PS provided a sound basis for Council, in 1965, to give the green light for the construction of the ISR, a proton collider with 6 interaction areas and 31.4 GeV maximum energy per beam. From 1971, the ISR rings were filled with protons accelerated in the CPS to 26 GeV and transferred by Fast (single-turn) Ejection. Some 10 years later, the ISR received antiprotons and light ions as well.

From the point of view of accelerator physics, the ISR demonstrated the feasibility of a hadron collider, as well as that of stochastic beam cooling. Vacuum technology was pushed to its limits in the quest for ever higher luminosities and, last but not least, the impeccable performance of the combination of the PS and the ISR was a pre-requisite for launching the proton-antiproton collider program in the SPS.

### *2.4.3 Injector for the SPS*

In 1971 Council approved the proposal to build the SPS in a tunnel of 2.2 km diameter next to the original CERN site at Meyrin (on the other side of the route de Meyrin and some 50 m below ground), including the CPS as injector. The perfect performance of the CPS during the preceding 10 years of operation was certainly an essential ingredient to obtaining this approval. In addition, the location of the West Hall allowed its use as an experimental area for SPS beams. The maximum energy was set at 300 GeV initially, and extended up to 450 GeV in later stages.

In the CPS a new beam transfer system, the ‘continuous transfer’ (as opposed to the ‘bunch-into-bucket’ transfer by fast ejection), was developed in order to cope with the different orbit radii (a factor of eleven) and the different bunch structures of the two machines (Fig. 2.5). The key element of this system is an electrostatic septum deflector. This device cuts slices off the beam as it is deflected across the septum by fast kickers in ten steps of one revolution time’s duration, the successive slices of the beam being ejected by a downstream septum magnet. The intensity available per cycle in the SPS was increased in a later stage by transferring two successive PS cycles of 5 slices each.

### *2.4.4 An Essential Link for the P–P$^{-}$, Collider*

The SPS reached its design energy early in 1976. It had just seen its first proton beams when Carlo Rubbia, in a memorable seminar at the end of March 1976, proposed to turn the accelerator into a proton-antiproton collider at 270 GeV beam energy (extended in a final stage to 315 GeV) for an experiment to establish the existence of the elusive Z and W bosons. In this proposal the then novel technique of stochastic beam cooling, invented by Simon van der Meer (Fig. 2.6), would provide a vast increase in the antiproton flux density.

It required the most complicated ‘beam gymnastics’ scheme (Fig. 2.7) the accelerator community had seen to date and (to the delight of many PS staff) the CPS had key functions in it. Firstly, the CPS had to produce a 26 GeV proton

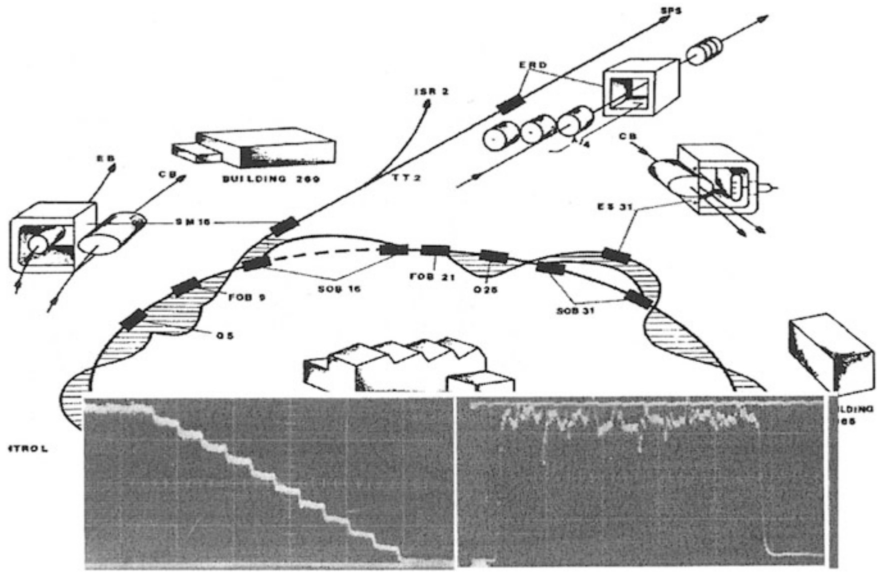


**Fig. 2.5** Beam transfer towards SPS. Below: intensity signal in the PS (decreasing) and in the transfer channel

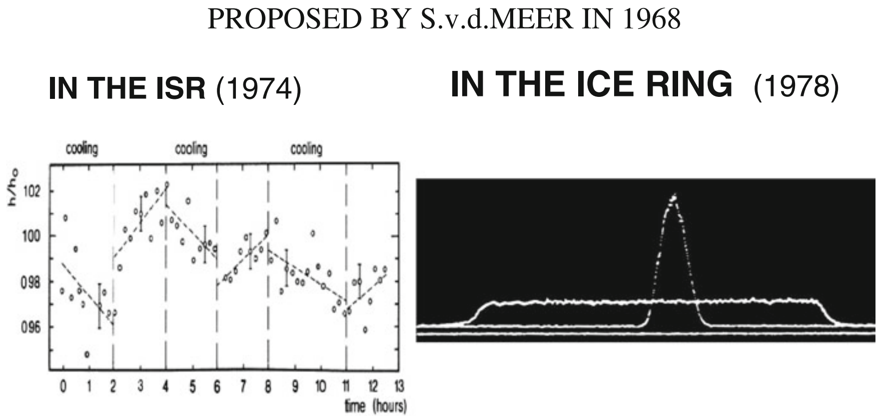


**Fig. 2.6** Demonstrations of stochastic cooling

beam of maximum intensity, which had to be concentrated to one quarter of the circumference by merging the standard 20 into 5 bunches (Fig. 2.8a–c). The proton beam was then directed onto a target surrounded by a 'magnetic horn' (another invention of S. van der Meer) so as to collect as many of the produced antiprotons as possible in a beam before transporting them towards the Antiproton Accumulator (AA), a ring of some 50 m diameter. There they were accumulated at

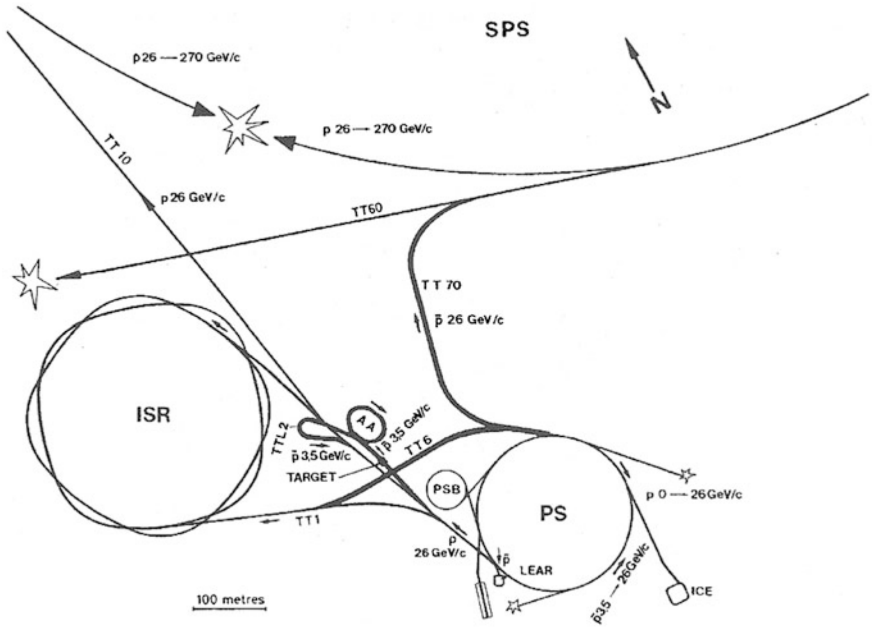


**Fig. 2.7** The antiproton factory

3.5 GeV/c, the energy where the best yield was obtained, and underwent stochastic beam cooling to improve the beam density. Three single bunches of antiprotons, the precious harvest of one full day's accumulation, were then transferred from the AA back to the CPS and, after acceleration from 3.5 to 26 GeV, sent to the SPS for further acceleration to 270 GeV. The antiproton beam was then steered so as to collide with pre-prepared bunches of protons. The very successful demonstration of the W and Z bosons in the detectors surrounding the collision area provided essential support for the Standard Model of particle physics (Cashmore et al. 2004).

### 2.4.5 *A Source for Low-Energy Antiprotons*

First proposed as a 'parasite' user of a small fraction of the available antiprotons, physics with low-energy antiprotons has today become a research program in its own right. Antiprotons at 3.5 GeV/c are returned from the AA to the CPS for deceleration from 3.5 to 0.6 GeV/c and transferred to the Low Energy Antiproton Ring (LEAR), where they were further decelerated to below 100 MeV (or accelerated up to about 2 GeV). More recently, LEAR has been replaced by the antiproton decelerator (AD), extending the deceleration range down to 5 MeV, with a dedicated experimental area for low-energy antiproton physics. Recently

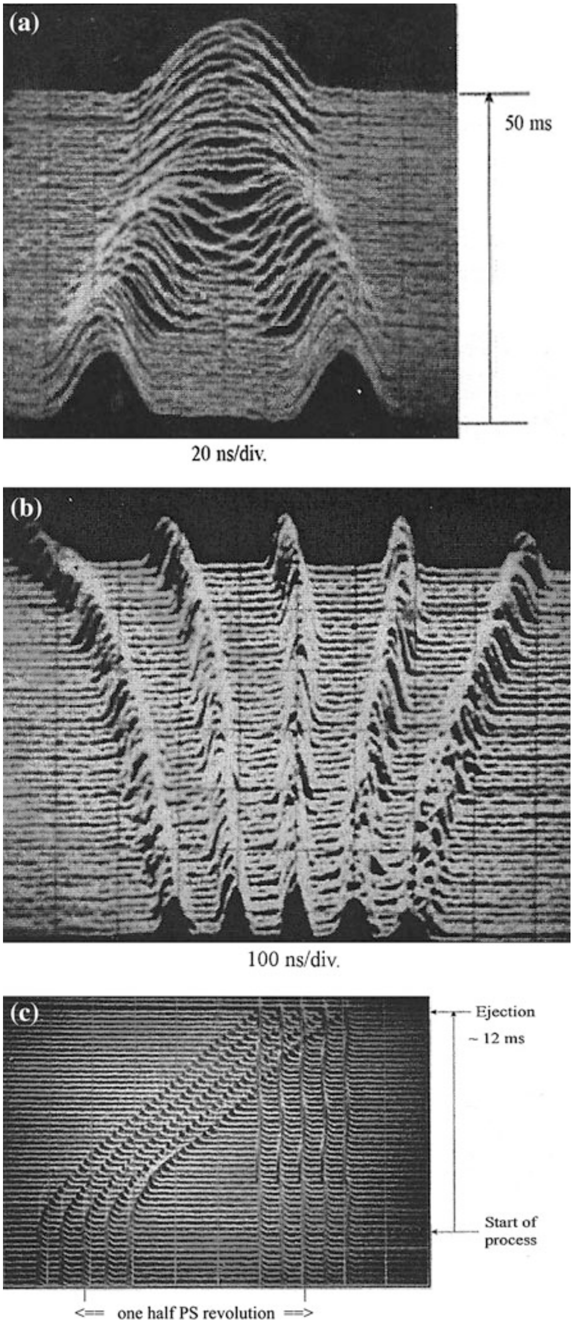


**Fig. 2.8** **a** Bunch merging in the PS: Delicate gymnastics for the RF system. **a** Act 1: Merging 2 bunches (out of 20 around the machine) into 1 (20 bunches = > 10 bunches). **b** Act 2: Arranging 5 bunches (*on top*) out of the 10 around the machine as a closed set (*bottom*): there are now 2 sets of five. **c** Act 3: 2 sets of 5 bunches drifting towards overlap

the addition of another stage of deceleration, the small ring ELENA, was authorised which will allow deceleration down to 5 keV, an energy low enough to allow trapping of the antiprotons for experiments on antihydrogen.

### 2.4.6 Electrons and Positrons for the e-p Collider LEP

After several years of discussion, in 1981 Council approved the construction of the large electron–positron collider (LEP) at CERN with 55 GeV beam energy in the initial stage (this was later increased to 104.5 GeV by the use of superconducting acceleration cavities). The main aim of the LEP was the verification of the Standard Model with the best possible precision. Most of the LEP tunnel (some 26 km circumference) could, by a careful choice of its location, be placed at some 100 m below surface in the same favourable rock formation that supports the CPS and the SPS.

The CPS (as well as the SPS) was adapted for use as one step in a chain of pre-accelerators for electrons and positrons. Firstly, a new injector for these particles had to be built, which consisted of a 200 MeV electron linac, a converter for the production of positrons, a 600 MeV linac for $e^+$ and $e^-$ and an accumulator ring. Space for this set of machines, built in collaboration with the LAL at Orsay, could be found near the then-decommissioned South-East neutrino area. Space also had to be freed in the PS straight sectors for the new injection devices as well as for acceleration cavities dedicated to electrons.

Council approved the LEP project in 1981 on the condition that the ISR was stopped in 1983, after 12 years of operation. The construction of the LEP was finished by mid 1989; its operation was stopped at the end of 2000 after nearly 12 years operation, so as to free the tunnel for the installation of the LHC. It may be interesting to note that the electron linac has become an important facility for the CLIC (the Compact Linear Collider—an option for the long-term future of CERN) development project.

### 2.4.7 Pre-Injector for the LHC

It was envisaged at the beginning of the LEP project that the tunnel dug for LEP might one day be used for a LHC, consisting of superconducting magnet channels for two counter-rotating proton beams. Pre-studies of that machine had already begun before 1980, so that after some 15 years of preparations Council could approve the project in 1994. It took until 2010 to complete the construction, and learn by experience the delicate procedures necessary for the operation of an accelerator comprising some 25 km of superconducting magnets cooled to 1.7 K by superfluid Helium II. The CPS—now 50 years of age!—and the SPS are expected to serve as the source of protons and Pb ions for another long stretch of time and at beam intensities near the record $(4 \times 10^{13})$ achieved to date.

The electrostatic septum used as the first stage in the beam transfer from CPS to the SPS (see above) turned out to be one of the major causes of radiation damage to PS machine components. Therefore an innovative, very sophisticated, multi-turn ejection (MTE) system was developed which suppressed the need for the septum. Nonlinear magnetic fields are used to generate stable 'islands' in horizontal phase space (Fig. 2.9a, b). Driving the betatron tune towards a fourth-order resonance will cause the beam to be split into five beamlets—four such islands plus the remaining beam core—which can then be kicked directly across the septum of the ejection magnet during successive turns, with only minor losses.

Furthermore, the longitudinal beam structure, bunch size and bunch spacing must be adapted in the PS to the special requirements of the LHC. To this end, delicate 'bunch splitting' procedures (Fig. 2.10), the inverse of the bunch merging procedures introduced for the antiproton project, are being applied. In routine operation, splitting in two is applied at low and at high energy, making some 80 bunches instead of the standard 20.

### *2.4.8 A Source of Several Species of Ions*

The construction of Linac 2 allowed the original Linac 1 to be used as a dedicated injector to the CPS for a wide range of ions. Deuterons and alpha particles were provided for d–p, d–d, alpha-p and alpha–alpha experiments in the ISR from the late seventies. For a SPS fixed-target program in the Omega spectrometer, fully stripped oxygen and sulfur ions were delivered between 1986 and 1993.

Collider experiments with lead ion beams are part of the LHC physics program. Since 2010 when Linac 1 was replaced by the more efficient Linac 3 ('lead linac'), $Pb^{53+}$ ions have been accelerated in the PS, stripped to $Pb^{82+}$ and transferred, via the SPS, to the LHC. The lead ion beam has been substantially improved by turning the antiproton ring LEAR into the dedicated ion accumulator LEIR (still located in the venerable PS South Hall), which includes an ion beam cooling system based on the electron beam cooling technique invented in 1970 by Budker.

### *2.4.9 Operations and Controls*

During the years of construction of the CPS and its initial operation, the electronics required were developed in-house, and often rebuilt more than once to keep up with the requirements of machine operation. With the number of users increasing, beams of different characteristics were requested during identical operational periods, implying the change of machine parameters on successive magnet cycles. Machine controls were soon taking advantage of the rapid progress of computer technology to enable more and more complicated modes of multi-task operation.

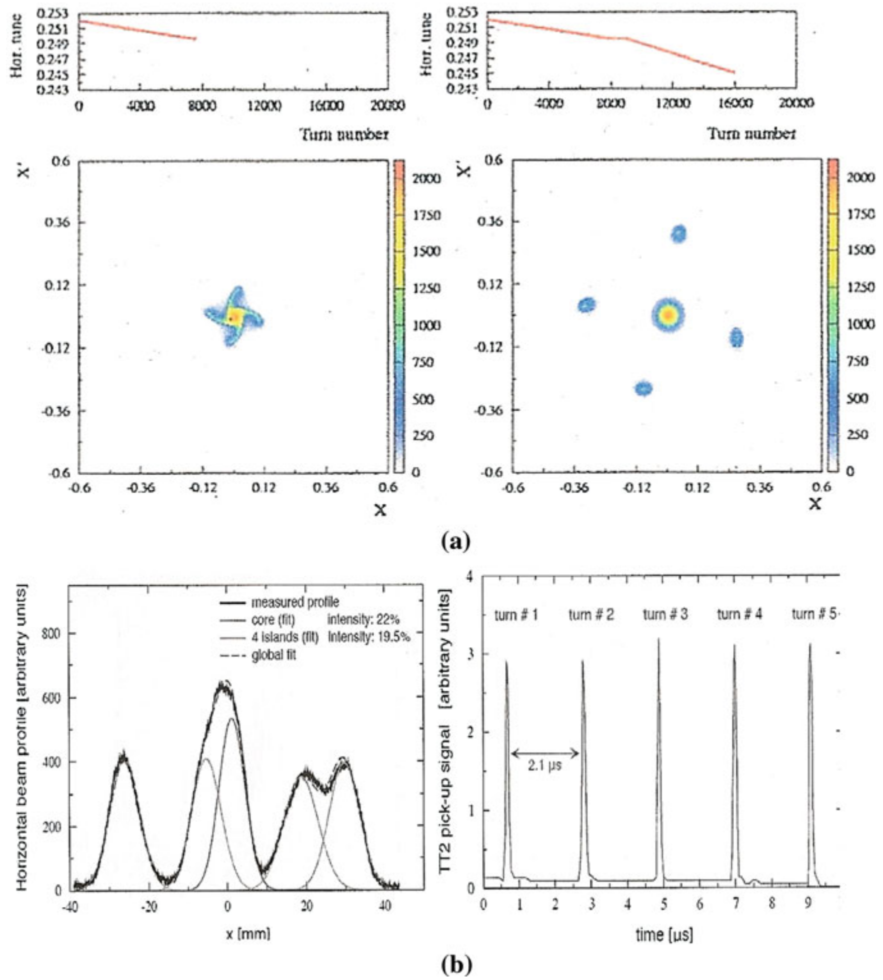


**Fig. 2.9** **a** New multiturn extraction for high intensities beam splitting on stable phase space Islands, approaching a 4th order resonance. **b** New multiturn extraction for high intensities. *Left*: Split beam in the PS, as seen on a beam profile monitor. *Right*: Beam signal in the transfer channel beyond the PS

An 8 kbyte IBM 1800 was acquired in 1967 and used for automatic program sequencing. In the seventies a PS control upgrade project was launched, aiming at an integrated system for all machines—injectors and accumulators—within the growing CPS complex. The upgrade was based on CAMAC technology and Norsk Data mini-computers. In view of the rapid development of industrial products, an integrated controls project for all CERN accelerators, including the CPS complex at the Meyrin site as well as the SPS and LEP (whose control rooms had been installed at the Prevessin site), was undertaken from 1990 on the basis of DEC

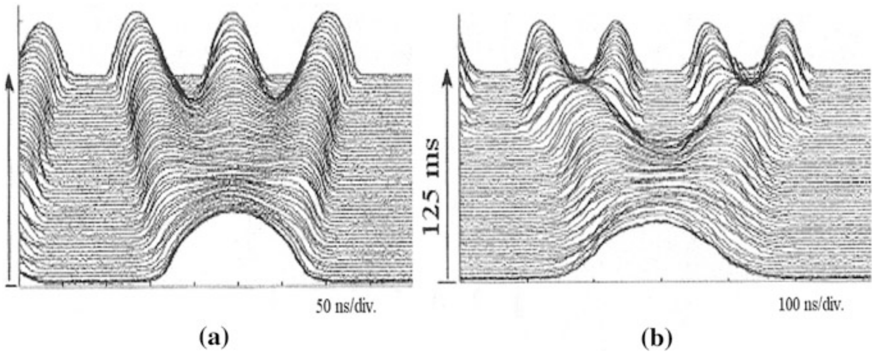


**Fig. 2.10** Bunch splitting: Examples of modifications of the bunch structure.**a** Triple splitting at 1.4 GeV. **b** Quadruple splitting at 1.4 GeV

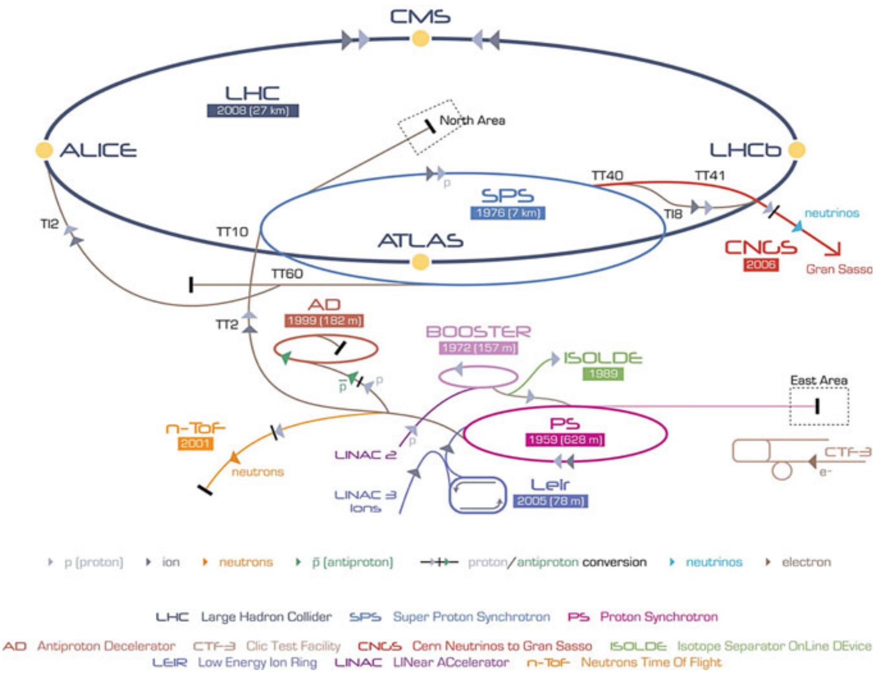


**Fig. 2.11** CERN accelerators in year 2009

workstations, and more recently of industrial PCs. Open standards (Linux) were adopted for the front-end computers.

The increasingly complicated timing of the cycling system—beams of varying particle species being accelerated in subsequent machine cycles to varying energies and with varying intensities—went through similar iterations until 2003, when

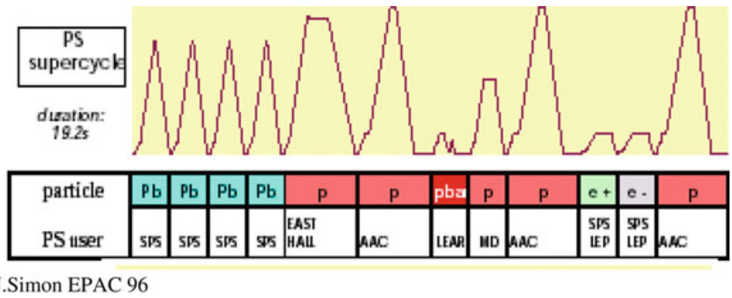


**Fig. 2.12** Serving multiple users of the PS: An example of a "supercycle"

the UTC second (PPS) system was introduced, which conditions an atomic clock producing a 10 MHz pulse train from which all other time trains are determined.

Controls of all accelerators as well as of the general CERN infrastructure are now located in a common Central Control Centre.

Beam observation systems constitute another indispensable tool for machine operation. Beam current transformers, beam loss monitors, electrostatic position pickups and profile monitors (moving targets, ionisation monitors, flying wire scanners) have been developed through several generations. The display of phase-space tomograms is one of the latest results of these developments.

All machines and beams active at present are presented schematically in Fig. 2.11, showing how all beams of different particles for the various users are passing through the CPS. A typical 'super-cycle' showing different users being served with beams of different particles on successive magnet cycles is displayed in Fig. 2.12.

## 2.5 Conclusions

The continued increase of the beam current and the acceleration of different particle species required a constant effort to improve the many subsystems of the synchrotron and the addition of new ones, as discussed in the preceding sections. It is quite impossible within the frame of this presentation to describe all this in technical detail, but as mentioned in the introduction, a comprehensive summary with detailed references concerning all developments of the CPS is presented in a CERN Yellow Report (Gilardoni 2011a, b).

The overall parameters of the CPS as specified in 1954 provided flexibility and space for numerous changes and additions, which made the CPS for many years a 'universal' particle accelerator simultaneously providing electrons, protons and their antiparticles as well as a range of heavier ions. The careful design of all its components was essential for its excellent reliability record.

The 50 years of active life of the CPS were a fascinating time for all who had the privilege to contribute to its extraordinary performance. That period included many years of fascinating investigations of the synchrotron, aimed at an ever-more-detailed understanding of *what happens to the beam at all stages of the acceleration process*, as well as its adaptation to new challenges with new systems and the development of ever more sophisticated operational procedures.

With a dedicated staff responding with enthusiasm to all challenges, the PS will surely remain a reliable source of beams for the LHC as well as for traditional users for many years to come.

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