Fifty years of the CERN Proton Synchrotron

Volume I

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Abstract

This report sums up in two volumes the first 50 years of operation of the CERN Proton Synchrotron. After an introduction on the genesis of the machine, and a description of its magnet and powering systems, the first volume focuses on some of the many innovations in accelerator physics and instrumentation that it has pioneered, such as transition crossing, RF gymnastics, extractions, phase space tomography, or transverse emittance measurement by wire scanners. The second volume describes the other machines in the PS complex: the proton linear accelerators, the PS Booster, the LEP pre-injector, the heavy-ion linac and accumulator, and the antiproton rings.
It was on 24 November 1959 that the proton beam in the CERN Proton Synchrotron was accelerated to a kinetic energy of 24 GeV. Thus the first strong-focusing proton synchrotron ever built has been faithfully serving the international physics community for 50 years. It has been the subject of a virtually continuous upgrade boosting its intensity per pulse from $10^{10}$ protons by more than three orders of magnitude to $3 \times 10^{13}$ protons. Various injectors have been added and it has been modified such that, in addition to protons, light and heavy ions, positrons and electrons, as well as antiprotons could be accelerated or even decelerated often within the same supercycle. This would not have been possible had the initial design not been solid and sound allowing for maintainability, flexibility, and versatility and whose intrinsic potential was brought to fruition by the efforts and the ingenuity of generations of accelerator physicists, engineers, operators, and technicians.

This report has been written to mark the fiftieth anniversary of the first operation of this unique accelerator. Volume I outlines the euphoric spirit in the European physics community in which such a bold design could be suggested, and gives an overview of the evolution of this unique accelerator described in a wealth of publications. This volume provides also a description in more depth of the outstanding achievements and highlights in its development. Volume II provides an overview of the injectors of the PS and of the accelerator system used for antiproton accumulation and storage, which has been closely associated with the PS.
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Simone Gilardoni and Django Manglunki (Editors)
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The origins and the evolution of the CERN Proton Synchrotron

1 Setting the scene

The history of CERN and its accelerators dates back to the early post World War II years [1], [2]. In a Europe largely destroyed during the war, many people, including some far-sighted statesmen, were convinced that common action, as envisaged by the European Movement in the early 1920s and again proposed by A. Briand around 1930, was a prerequisite for successful reconstruction, for re-establishing Europe’s position in the world. The first move in that direction, following a proposal by R. Schumann, was the treaty establishing the European Coal and Steel Community, signed in April 1951 and ratified in July 1952.

Scientific collaboration between European countries found a first expression at the ‘Conference Européenne de la Culture’ in Lausanne (an offspring of the European Movement re-founded at the end of February 1949) in December 1949. A declaration by L. de Broglie was read containing a proposal for setting up scientific collaboration, possibly even in the form of a laboratory, amongst European countries. This thread was taken up and reinforced in June 1950 at the General Conference of UNESCO at Florence when I. Rabi read a declaration that lent American support to organizing European collaboration on topics of fundamental research. The suggestion was quickly picked up by physicists (some of them friends of Rabi) interested in fundamental nuclear research where ever larger accelerators are required, too large for any one of the European countries who had been leading the field before World War II to build.

P. Auger, then active in cosmic ray research, accepted the charge of assembling a Group of Experts who would on the basis of the UNESCO resolution work out a proposal as to how to proceed. By December 1950 the Centre Européen pour la Culture in Geneva called a Commission for Scientific Collaboration under the chairmanship of Denis de Rougemont which Auger attended.

The first meeting of Auger’s Group of Experts took place at UNESCO in May 1951. After months of personal contacts, eight countries were represented by some of their leading scientists. The future laboratory already took shape: the Group proposed the construction of two accelerators, one of which ‘should be very ambitious so that it would not easily be overtaken elsewhere in the world’, and a smaller, more conventional one. The first one could, of course, be nothing but a proton synchrotron. In December 1951 a meeting of duly invested government representatives was organized at UNESCO under the chairmanship of F. de Rose (a future President of the CERN Council). At the following meeting in February 1952 in Geneva a Convention was signed, establishing a provisional organization for nuclear research, in fact the provisional CERN. Obviously, experts in leap-frogging normal governmental procedures had achieved a masterpiece.

2 Getting down to business

Once the Convention of the provisional organization was ratified, its Council held its first meeting in early May 1952 and appointed the first senior staff members with E. Amaldi [3] as the Secretary-General. Four Study Groups were established: Theory under N. Bohr, Laboratory services under L. Kowarski, Synchrocyclotron under C. Bakker, and Proton Synchrotron under O. Dahl [4] with F. Goward as deputy. Further members of the Proton Synchrotron Group were H. Alfvén, J. Fry, W. Gentner, K. Johnsen, E. Regenstreif, Chr. Schmelzer and R. Wideröe. From here on we shall follow in some detail the activities of the latter group.

At the end of June 1952 the PS Group presented a first proposal for the construction of a 10 to 15 GeV proton synchrotron, intended to be a scaled-up version of the 3 GeV Cosmotron at Brookhaven, which had just accelerated protons to more than 1 GeV in May of that year. Council asked that a detailed design and planning for a 10 GeV machine be presented by November 1953. Three members
of the group, Dahl, Goward, and Wideröe visited Brookhaven during the first two weeks of August 1952 to learn about details of the Cosmotron. In anticipation of the visit, the Cosmotron team discussed possible improvements to their machine design, and during these reflections discovered a new way of beam focusing [5]. The visitors were thus introduced, to their great surprise, to a brand new idea, alternating-gradient (AG) or ‘strong’ focusing of particle beams, which would reduce by a large factor the size of the vacuum chamber containing the beam and hence the magnet providing the guide field. An accelerator of higher energy could thus be built within a realistic budget.

Upon returning home the PS Group was faced with a very difficult decision: going ahead on the proven trail (which anyway was new territory for most of them) or changing course and proceeding with the new and untried idea. It might have been a deadly blow to the young team if they found themselves in a blind alley. But one could also hope that a machine of classical design might in this case be delayed only by a year or so. O. Dahl strongly advocated an intense study of the strong focusing system and obtained Council approval at its third session in October 1952 in Amsterdam, which also saw the decision for Geneva as the location of the future laboratory.

O. Dahl in his presentation to Council gave due warning of the risks involved in that choice but pointed out that a project based on the ‘classical’ design could not now be defended in view of the possible advantages inherent in the new invention. In fact, it was expected that a synchrotron of 30 GeV might be built at the same cost as a Cosmotron-type machine of 10 GeV (for which, however, no reliable cost estimate existed at that time).

The successful development of CERN during more than five decades was largely due to the surprising flexibility of the alternating-gradient PS. CERN would surely have developed in a very different way had this courageous decision not been taken.

In fact, as the theory of the alternating-gradient synchrotron was developed, two serious problems were soon discovered: first, the stronger the focusing, the higher a precision of the magnet field (see chapter The PS magnets) and of the alignment of the magnets is required. If the tight tolerances were not met, the beam would be lost due to resonant blow-up of the ‘betatron’ oscillations of the protons about the equilibrium orbit [6]. Secondly, the beam loses longitudinal stability at a point of the acceleration cycle, the ‘transition energy’, when the relative increase in particle velocity changes from being greater to being smaller than the relative variation of orbit length (see the chapter Transition crossing).

Several mathematical physicists [7] [8] joined in to analyse the sensitivity of the betatron oscillations to field errors and the limits of their stability. A mechanical analogue model, shown in Fig. 1, was developed as well for some experimental work [9]. The problem of the loss of phase stability was to first approximation solved by a jump of the acceleration phase angle and was studied in great detail by K. Johnsen [10], [11]. Still, it remained a subject of deeper study and several improvements as the beam intensity was increased during the whole life of the PS. In the meantime, more scientists were seconded by their home laboratories to the PS Group, amongst them J. B. Adams, A. Citron, P. Grivet, M. G. N. Hine, J. C. Jacobsen, J. Lawson and G. Lüders, and, very importantly, two colleagues from the Brookhaven Laboratory, Hildred and John Blewett. Several design options with different focusing gradients were explored resulting in magnet masses between 800 and 10 000 tonnes or more for a 30 GeV synchrotron. However, the precision required in machining of the pole profile and of the overall alignment of an accelerator with the smallest magnet turned out to be quite impossible. As a result of several iterations, the design converged on a 30 GeV beam energy machine with a 12 kG (1.2 T) magnetic field, and an average radius of 112 m. The focusing strength chosen required a vacuum chamber of 12 cm full width and 8 cm height, with magnets of about 4 000 tonnes total mass.

As from January 1953 work on the Convention of a final organization (as opposed to the provisional convention that had been in force for nine months) was launched. It was signed and submitted for ratification by the member states by the end of June 1953. So as to keep track of the developments, the PS Group was asked to organize a meeting with international accelerator experts. Thus in October 1953 the ‘Conference on the Alternating-Gradient Proton Synchrotron’ was held in Geneva, and attended
by Council members and many European and American scientists. In addition to the papers by the PS Group [12] on the design of the 30 GeV machine and aspects of beam dynamics, W. Heisenberg was asked to present the users’ view as to the beam energy required. He recommended to ‘build a machine that could be operated without difficulty in the region somewhat above 20 GeV but which could, in the limit, be extended in energy to 30 GeV’.

After the conference, the Council, satisfied by the very positive response to the work of the PS Group, gave the green light to building an alternating-gradient proton synchrotron with nominal beam energy of 25 GeV at 12 kG and 3 s cycle time (which could in fact at reduced repetition rate be driven up to 28 GeV) at a cost provisionally estimated at 130 MCHF. The Council also approved the proposal that the PS Study Group should move to Geneva and nominated a ‘chief architect’ (R. Steiger from Zürich) so that construction work on the site could be organized without delay. Group members could use temporary offices and a hall for experimental work made available at the Institut de Physique (where some barracks were added) and – with the exception of Dahl – began moving their families to Geneva. The collaboration between them was of course enormously improved.

At Brookhaven the construction of a similar machine, the AGS, was authorized shortly afterwards, including a small-scale model electron synchrotron, which provided an experimental demonstration of the feasibility of going through the transition energy. For years to come, a friendly competition developed between the teams building the two machines, with full exchange of information.

3 Construction of the PS

Once the Council had decided on the basic parameters of the machines to be built, work on their realization could begin (Fig. 2). But also the infrastructure of a future laboratory – personnel and purchasing offices, site and safety management – had to be set up and recruitment of staff at all levels and from all member states had to be organized. Thus the responsibility for a quite unusual large-scale operation was entrusted to the two dozen or so members of the provisional CERN, of whom few had industrial or managerial experience.

While the parameters of the PS were further refined for cost and performance, a realistic project planning had to be set up. All components of the synchrotron had to be designed ab initio with very few
Geneva was selected as the site for the CERN Laboratory at the third session of the provisional Council in 1952. This selection successfully passed a referendum in the canton of Geneva in June 1953 by 16,539 votes to 7332. On 17 May 1954, the first shovel of earth was dug on the Meyrin site under the eyes of Geneva officials and members of CERN staff.

Fig. 2: Geneva was selected as the site for the CERN Laboratory at the third session of the provisional Council in 1952. This selection successfully passed a referendum in the canton of Geneva in June 1953 by 16,539 votes to 7332. On 17 May 1954, the first shovel of earth was dug on the Meyrin site under the eyes of Geneva officials and members of CERN staff.

Precedents, which might have been copied, existing. Preliminary design work of the main components, the magnet, RF acceleration system, and the injection linac had already been undertaken at, respectively, O. Dahl’s laboratory in Bergen, Prof. Grivet’s laboratory in Paris, the University of Heidelberg, and at the Harwell laboratory. All of that work and the staff were transferred to Geneva during 1954. By September, the PS staff numbers had grown to 54 persons and on 29 September 1954 the CERN Convention came into operation. O. Dahl resigned in October and was replaced by J. B. Adams who then became Director of the PS Division. The final parameters of the PS were adopted in December 1954 [13] (see Fig. 3 showing the members of the PS Parameter Committee). The number of betatron oscillation cycles per revolution was set at Q=6.25, with a magnet field gradient corresponding to a ‘field index’ of n=282. The latter was initially thought to be as high as n=4 000. The elliptical aperture of the vacuum chamber is 8 × 15 cm, the magnet pole width is 36 cm and the total steel mass of the 100 magnet units is 3 200 tonnes. Around the circumference, 628 metres, there are 100 magnet units of 4.4 m nominal length, 80 short straight sectors of 1.6 m, and 20 straight sectors of 3 m (see Fig. 4). Sixteen long straight sections were to be equipped with acceleration cavities, 20 short ones with quadrupole correction lenses, and 20 short ones with sets of sextupole and octupole lenses, see chapter The PS magnets. Other straight sections were reserved for beam observation stations and injection devices, targets and (later) ejection magnets. The energy of the injected beam was set at 50 MeV, corresponding to a magnet field of 140 G. As the field gradient varies due to remanent fields at low field levels and due to saturation at high fields, each magnet is equipped with correcting pole-face windings.

The target date for finishing the project was set for the end of 1959.

Not much time was left for the groups responsible for the large number of machine components to produce the final design of all machine components which had to be developed, prototypes made and tested, and specifications written; finally, contracts had to be awarded, production in industry supervised,
Magnets and power supplies, RF cavities and transmitters, vacuum chambers and pumping stations, controls, beam observation stations, much electronics and cables have to come together to make an accelerator. There is not space in this chapter to comment on more than a selection of these systems.

The development of the acceleration system [10], [14], [15] had been undertaken at Heidelberg back in 1952 and relocated to Geneva in 1954. Measurements first on small-scale models and, as from the
end of 1955, on a full-scale cavity prototype served as a basis for the development of wide-band power amplifiers, AVC systems, and the tuning system between 5 and 16 MHz. Contracts for 16 acceleration units (plus spares) and all ancillary equipment were placed in November 1956. All the control electronics were installed in a building at the ring centre, and all acceleration cavities in the ring, by August 1959.

It may be interesting to illustrate in some more detail some of the procedures followed by the Magnet Group [16]–[18] in order to satisfy the tight tolerances on fields and gradients. The main magnet system consists of 100 units, each weighing 30 tonnes and made out of ten blocks with a common excitation winding. Extensive tests of several types of steel had been made in previous years, so that a low-carbon type steel could be selected with confidence for reasons of mechanical properties and price. Similarly, the model work since 1952 permitted the correct pole profile for the chosen field index to be readily determined. The specifications for production were ready in May 1956. In order to guarantee the required field uniformity around the orbit, an extensive two-stage mixing procedure was implemented.

As it is very difficult to control the magnetic properties of raw steel, the 1.5 mm thick steel sheets coming from the mill were laid out in some 260 piles in the manufacturer’s hall. When all the raw steel production was finished, one sheet of each pile was picked up and precisely cut to dimension. They were glued together to form a block (3 tons) thus containing material from the whole production quantity, and delivered to CERN where the magnetic characteristics were measured and the remanent field and the saturation characteristics recorded. Once all the blocks had arrived, been measured and stored, they were selected so that these characteristics averaged out for each batch of ten blocks and assembled to form, equipped with coils and pole face windings, units with equal magnetic properties.

Magnet blocks were delivered between autumn 1957 and summer 1958. Magnet units were installed between autumn 1958 and June 1959. As soon as the South experimental hall was partly finished in early 1957, the Magnet Group set up measuring benches and motor-generator sets for measuring the 1000 blocks coming out of the production line as well as the 100 magnet units into which the blocks were assembled.

Civil engineering operations on site began in May 1953 (even before ratification of the Convention)
Fig. 6: The PS construction (from the upper left corner): the construction of the foundations; the suspended ring beam; the suspended coupling elements; the tunnel completed, the installation of the first magnets

notably with the exploration of the subsoil by digging shafts and by test borings, so that the best position within the available site could be determined and the support structure designed. It was found that the underlying molasse rock was closest to the surface in the West corner of the site. Observations showed the molasse to be sufficiently stable to found the machine, via pillars, on it, whereas the superficial moraine layers showed a ‘breathing’ (2 to 3 mm over 100 metres) depending on the amount of rain. A support system [19] was hence designed where the magnet units are placed on a ring beam, supported through elastic coupling elements (which would isolate the ring from vibrations due to earthquakes, for example) on pillars founded on the rock. Figure 5 shows a scheme of the PS tunnel together with the suspended foundations.

The construction of the PS ring building began in the second half of 1955 and was finished by mid 1957. Special care was taken for the concrete ring beam of about $2 \times 2 \text{ m}^2$ cross-section on which the magnet units are placed. The composition of the concrete, chosen for minimal shrinkage, was controlled with utmost care all around the circumference and water pipes placed in it so that the uniformity of its temperature could be controlled continuously. In addition, the tunnel air was (and still is) carefully controlled. A six-month settling time was respected before loading it with magnet units. Figure 6 shows a few pictures of the PS construction from the foundations to the installation of the first magnets.

Surveying a delicate machine structure inside a ring-shaped underground building of 200 m diameter to a precision of better than a millimetre posed new problems for the art of long-distance survey [20]. Eight radial tunnels were provided each having a survey monument at the circumference of the machine, as well as a central pillar below the ring central building (see Fig. 7). The distances between the pillars
were measured with the help of invar steel wires calibrated against a standard base in one of the radial
tunnels, the readings being taken with measuring microscopes. The magnet units were then placed with
respect to the eight circumferential pillars. Needless to say, tunnel access was forbidden for those not
concerned during the survey campaigns.

The injection energy of a synchrotron is determined by a balance between the lowest acceptable
magnet field, the tuning range of the acceleration cavities and the acceptable beam blow-up on the one
hand, and by the cost of the injector on the other hand. It was clear from the beginning that an Alvarez-
type linac, similar to the 50 MeV linac under construction for the Harwell laboratory, would be used as
injector. Fortunately, the idea that strong focusing would vastly improve linac performance [21], [22] was
immediately implemented avoiding the cumbersome ‘grid focusing’ of the earlier machines at Berkeley.
Beam to the linac is provided by an ion source in a 500 kV pre-accelerator. The linac consists of three
tanks accelerating to 10 MeV, from 10 MeV to 30 MeV, and to the injection energy of 50 MeV. While
much of the early design was made at the Harwell laboratory, the resonator structure and the vacuum
envelope of tank 1 were delivered at the end of 1956 to the Adams Hall where they were assembled. The
tank was equipped with drift tubes containing pulsed quadrupoles and extensively tested together with
the RF power source. Tanks 2 and 3 were delivered directly to their final position in the linac building
(see Fig. 8).

By August 1959 all elements of the synchrotron had been installed (see Fig. 9, left), the vacuum
chamber closed and pumped down to some $10^{-5}$ Torr, considered as the best vacuum that could be
achieved on a large scale at that time. The new machine was ready for beam at CERN (see Fig. 9, right).

4 Running-in the facility

Given that the PS team had never before designed or worked on a synchrotron and even less on one
based on the novel alternating-gradient focusing, the accelerator was so well-conceived and constructed
that the basic running-in took a surprisingly short time. At the end of August 1959 the first 50 MeV
beam of the linac was obtained and the beam made its first turn in the PS at the first attempt in the
middle of September. The RF system was ready by the beginning of October and acceleration tests
could start. Relatively quickly a few GeV were reached with the beam control system switched on after
about 1 ms but beyond this energy the beam became unstable and erratic. After some nervous scrutiny
of all imaginable error sources, the remedy was found by letting the radial control loop act on the phase
of the accelerating voltage instead of its amplitude, and the protons reached 24 GeV kinetic energy on
Fig. 8: The first PS linac

Fig. 9: The PS ready for the first beam (left) and the CERN site (right)

Fig. 10: Left: transformer signal of the first beam accelerated up to top energy. Right: J. Adams announcing the PS success in the CERN Main Auditorium
the famous 24 November passing the dreaded transition without loss (see Fig. 10). The feeling in the PS team at the beginning of 1960 can be gauged from the following probably somewhat exaggerated statement [23]:

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.

Hence an intense effort began to better understand the accelerator, to facilitate its use for the experiments by increasing its intensity, improving its stability and reliability, and by expanding the experimental facilities. A constant issue was the improvement of the instrumentation, always applying the most modern technology available.

A pulse intensity of $3 \times 10^{10}$ had been achieved in 1959, well above the design intensity of $10^{10}$, and it was quickly improved to $3 \times 10^{11}$ at the end of 1960, with the linac providing 15 mA, up from 3 mA. By the end of 1964, $10^{12}$ protons per pulse were available and the PS had produced about $10^{19}$ protons in total, which led to first problems with radiation damage, mainly due to the internal targets. This performance was the result of an intense study of the accelerator together with improvement of the low-level RF control, increase of the available RF voltage plus new beam position monitors with an accuracy down to 0.1 mm, and an extended bandwidth. A professional operating crew had been built up from 1963 onwards, indispensable for such a complex facility.

In order to improve the duty cycle of the internal target, shown in Fig. 11, producing secondary particles for the experiments, the main power supply was modified in 1960 to provide a flat top in the cycle, a feature which surprisingly had not been specified. However, the cycle-to-cycle reproducibility was only 2% and the ripple was not satisfactory either. This was rectified in 1961 with a mean speed regulator of the motor-generator set providing now a reproducibility of 0.1%. Two types of secondary bursts were produced in the same acceleration cycle, a long one (up to 400 ms) from a thin target placed in the coasting beam during the flat top of the magnet cycle, and a short one (hundreds of $\mu$s) from the beam driven into a thick target by RF knock-out. Target techniques were developed to run more than one experiment simultaneously. In addition, in order to increase the particle flux to the experiments and to reduce the radiation damage by the use of the internal targets, methods for fast-ejection and slow-ejection were under study (see chapter Beam extraction).

More of a problem was the fact that the preparation of the experimental facilities was not at all in step with the development of the accelerator at the beginning of 1960. This was somewhat a consequence of the surprisingly quick coming on-line of the accelerator: no decent beam lines were installed, e.g., only three dipoles were available for the South Hall and welding generators of doubtful stability had to be used as power supplies. Only 2/3 of the South Hall was available for experiments. Nevertheless, the
first run of the 30 cm hydrogen bubble chamber took place in March 1960. At the end of this year, also a 1 m propane bubble chamber was in operation and a number of counter experiments were using the North Hall. A total of 1080 h beam time (95 h in the first quarter and 504 h in the fourth quarter) had been shared by 12 experiments.

A new neutrino experiment was developed, fed by fast ejection based on a fast kicker plunging into the aperture once the beam was small enough at the end of the acceleration, a pulsed electromagnetic horn for efficient focusing of the parent mesons, and a new beam line. The experiment took data in the middle of 1963 and in the early part of 1964. However, it came too late to be an earnest competitor of BNL where in 1962 the discovery had been made that there are at least two neutrinos, although the AGS had only started in summer 1960.

Slow extraction into the South Hall using an integer resonance was tried in 1963 for the electronic experiments but met with little interest from the users as they were happy with the beams from the internal target. It was also difficult to implement as it required careful operator control during the ejection process. Although the experimental facilities were in a rather poor state at the beginning of 1960, their expansion in the following years was rapid. By the end of 1965 the PS was the centre of a spider’s web of beams: for the South Hall an internal target produced five secondary beams, the original fast extraction served a neutrino experiment and the (first) muon storage ring; the North Hall housed two bubble chambers (80 cm hydrogen Saclay, heavy liquid CERN) fed by an internal target; in the East Hall, available since 1963, one internal target provided a secondary beam filtered by electrostatic separators to the CERN 2 m hydrogen bubble chamber, a second internal target provided particles to three counter experiments, a slow ejected beam served two counter experiments, and a new fast-ejection fed the RF separator preceding the CERN 2 m chamber.

5 Consolidation

An impressive improvement programme for the PS was decided by Council in December 1965 together with the construction of the Intersecting Storage Rings (ISR), as shown in Fig. 12 by the radical change of the CERN site. In order to increase the average flux of protons the PS repetition rate had to be increased by a factor 2 and the PS beam intensity, $10^{12}$ protons per pulse at the end of 1965, had to be raised substantially by a new injector. In parallel, the potential of experimental facilities was also stepped up by creating a new neutrino beam and hall space for the Gargamelle bubble chamber to be constructed by CEA in France, by developing a large hydrogen bubble chamber (BEBC, see Fig. 13) in cooperation with France and Germany, and by planning a large spectrometer magnet equipped with spark chambers (Omega). BEBC and Omega were to be installed in the new West Hall.

The new main magnet power supply came into operation in 1968 providing the targeted increase in repetition rate with a more flexible control system providing a wider choice of magnet cycles, e.g., two flat-tops at different energies. The ripple voltage at the flat top was reduced from 100 V to 20 V and the reproducibility of the flat top reached $4 \times 10^{-4}$.

In order to raise the injection energy of the PS, a new 200 MeV linac and a multi-ring booster were considered. After some hesitation, it was decided in 1967 to construct a fast-cycling 800 MeV four-ring booster (PSB) which became operational in 1972. In 1973 it boosted the PS pulse intensity to $5 \times 10^{12}$ and the neutrino flux to Gargamelle by a factor 3, demonstrating that a good choice had been made, instrumental for the discovery of the neutral currents in what would become one of the most prestigious experiments of CERN (see Fig. 14).

The linac serving now as PSB injector had been upgraded in parallel to provide a pulse of 100 $\mu$s for the multi-turn injection (up to 15 turns) and a beam current of 100 mA with the repetition time halved to 0.5 s. The faithful Cockroft–Walton generator supplying the 500 kV d.c. for the proton pre-acceleration failed in 1973 and was replaced by a SAMES electrostatic generator. A new 50 MeV linac, Linac 2, was also authorized in 1973 to replace the ageing Linac 1 by a more reliable and
better performing design. Rebuilding Linac 1 was discarded as this would have led to an unacceptable interruption of the flourishing physics programme.

Although the dreaded crossing of transition energy during acceleration had turned out to be much less of a hurdle in 1959, with the prospect of higher beam intensities it was imperative to reduce the time the beam spends in this critical energy domain by rapidly changing the transition energy. Since the latter is a function of the magnet lattice configuration, pulsed quadrupoles were introduced in 1970 to produce a so-called Q-jump, resulting in a sudden rapid lowering of the transition energy. The system was replaced in 1973 by a better performing one, the so-called $\gamma_{tr}$-jump, consisting of a set of eight fast-pulsed and six slow-pulsed quadrupoles in the ring, which resulted in a further speeding up of the crossing by a factor 10 over the factor 5 obtained with the Q-jump. The new system offered the additional advantage of not affecting the focusing of the accelerator, i.e., the Q-value moved by no more than $10^{-3}$ during the crossing (see chapter Transition crossing).
The ever-increasing intensity and the inevitable losses – in particular those associated with the particle production by the internal targets – exposed some components to the limit. One of the 100 bending magnets had to be removed and replaced by a spare as early as 1967. This process has been repeated several times since, with the replaced magnet becoming a new spare after being refurbished with new coils. The radiation also reduced the reliability of the vacuum seals made of organic materials and, therefore, they were replaced by metal seals in the framework of the vacuum conversion programme which was successfully terminated in 1972. This included also the changing over from oil-diffusion pumps to sputter-ion pumps and turbomolecular pumps.

A number of new beam lines were created in execution of the 1965 plan and in view of the boosted potential of the PS:

- a new South-East neutrino beam line fed by a new fast ejection came into operation 1967 which included for the first time a so-called reflector of the parent mesons, increasing significantly the neutrino flux and being a feature of all CERN neutrino beams ever since. The beam line was used first by the CERN 1.1 m$^3$ heavy liquid bubble chamber and, from 1971 to 1975, by Gargamelle which had to share the beam with the new muon storage ring from 1974 onwards;
- a new fast ejection provided protons to the ISR which started to operate in 1971 after injection tests towards the end of 1970;
- the SPS beam line received protons from 1975 onwards created by a new fast-ejection system called Continuous Transfer. Each PS pulse was cut into five approximately equal pieces in betatron phase space at 10 GeV/c by means of a combination of a fast kicker, fast bumpers, and a thin septum in order to fill with two PS pulses 10/11ths, of the SPS circumference by boxcar stacking before trapping and acceleration in the SPS.

A considerable effort had been made in order to develop the technology of ejection components easing operation and increasing the efficiency of the ejection by reducing the losses and the concurrent radiation damage. For the slow ejection, a new magnetic septum of only 1.5 mm thickness and, later, a thin electrostatic septum of 0.1 mm thickness became available. Based on these components, a completely new slow-ejection system was developed based on a third order betatron resonance as had been in use at the AGS since 1969. It supplied from 1972 in addition to the East Hall, its traditional client, the West Hall (Omega experiment), and the South Hall with an efficiency exceeding 95% whereas the previous system only reached 70%. The beam to the West Hall was stopped in 1975. Fast-ejection had
not been neglected. A full-aperture fast kicker replacing the plunging kickers and large-aperture septum magnets had been developed, and this new system was commissioned in 1973.

This period was marked by the arrival of the new booster injector and the technological improvements but also by the intense and painstaking effort of the machine team to control the stability of the accelerated beam, gaining a detailed understanding of space charge phenomena and the beam–equipment interaction, which was indispensable for taking advantage of all the improvements. The PS ‘client’ base had been considerably expanded in this period exploiting fully the potential of the PS. The team was legitimately proud of having reached the ‘magic’ number of $10^{13}$ protons per pulse in the neutrino runs and of having indeed met the goal of the improvement programme initiated in 1965. The different steps marking the evolution of the PS complex are shown in Fig. 15.

6 Towards complexity

Although the SPS started smoothly in 1976, there was considerable activity at CERN in the middle of the 1970s after the $J/\psi$ discovery in the US in 1974, a serious miss of the ISR having been denied a $4\pi$ detector matching its potential, which unfortunately repeated itself when the Upsilon ($\Upsilon$) was discovered in 1977 at FNAL. Hence, CERN was scrutinizing how the existing facilities could be upgraded or which project would bring CERN back into the leading league. Finally, two projects were retained: converting the SPS into a proton–antiproton collider in the medium term and, as a long-term development, a Large Electron–Positron collider (LEP). Both projects had a profound impact on the PS.

The number of antiprotons which could be stored in the SPS determined the expected luminosity of the collider and this number depended on the phase space density in the antiproton beam injected. Given the low phase space density of an antiproton beam created by a primary proton beam hitting an appropriate target, it was imperative to increase this density by orders of magnitude by cooling the resulting antiproton beam in transverse and longitudinal phase space. This density increase could be achieved by one of the two cooling methods which had recently been invented: electron cooling in
Novosibirsk and stochastic cooling at CERN.

Although the stochastic cooling had been experimentally proven and resurrected in the ISR after it had nearly fallen into oblivion, a 2 GeV test ring was quickly constructed in 1977 for the Initial Cooling Experiment (ICE) with the magnets of the latest, already completed muon experiment, to demonstrate that stochastic cooling would also work at low energy and in longitudinal phase space. The ICE ring was fed from the PS South-East ejection with protons and antiprotons. This test was so successful that the decision to go ahead with only stochastic cooling was taken in 1978.

For the new mode of SPS operation, the PS had the double task of producing an intense 26 GeV/c proton beam for generating antiprotons at 3.5 GeV/c and of accelerating the antiprotons (after cooling in the Antiproton Accumulator (AA)) to 26 GeV/c for transfer to the SPS. The original idea of injecting the 3.5 GeV/c antiprotons directly into the SPS from the AA had been dropped in view of the justified fear of the SPS team that injection at this low energy would lead to a disaster.

After completion of the AA, and since the transfer channel to the ISR was ready before the beam lines to the SPS, antiprotons were first sent to the ISR and, a few months later, in July 1981, to the SPS. After the frustrating experience at the ISR, the SPS was well-equipped with modern $4\pi$ detectors leading to the discovery of the intermediate vector bosons $W$ and $Z^0$ in 1983.

From 1980 onwards, the PS produced proton pulses for the AA every 2.4 s. The particles were not grouped in 20 equidistant bunches around the circumference as usual, but were concentrated into 5 bunches matching the circumference of the AA. The intensity soon reached $10^{13}$ protons per pulse which was the limit of the target. A more cliff-hanging operation was the acceleration of the single AA bunch of $10^{11}$ antiprotons in the PS from 3.5 to 26 GeV/c, always observed by the team and the clients in the SPS under the Damocles sword of failure of some equipment resulting in the loss of the precious bunch. Their nearly daily anxiety can be understood as this number of antiprotons was the result of about 24 hours of antiproton production. Weak pilot bunches were accelerated to check the correct functioning of the whole chain. In order to minimize waste of the rare antiprotons, those bunches contained only a few $10^9$ antiprotons, which required development of dedicated instrumentation to observe them.

The ISR not only received protons and antiprotons from the PS but also light ions which entered the scene in this period. Deuterons had first been accelerated in 1964 by Linac 1 using the so-called $4\pi$-mode to deliver them at half the speed of protons [24]. This gave the PS its first taste of a new ion species. It accelerated these deuterons from 25 MeV to around 100 MeV. Since Linac 1 would be superseded by Linac 2 which was under construction, tests had been conducted since 1974 to investigate a possible future of Linac 1 as ion injector with a positive result. Hence Linac 1 was equipped with make-shift ion sources and in 1976 some $3 \times 10^{12}$ deuterons per shot were accelerated after multi-turn injection in the PS and transferred to the ISR [25], where they were collided with stacked protons or deuterons during scheduled physics runs. The sluggish deuterons were first accelerated on RF harmonic $h=40$ to an intermediate flat-top, debunched, then rebunched on the more familiar $h=20$ before final acceleration to the top PS magnetic rigidity. Similarly, by feeding the duoplasmatron source with helium instead of deuterium, shots of just a few $10^{10}$ alpha particles were also accelerated [25]. Subsequently, the introduction of stripping from $^4\text{He}^{1+}$ to $^4\text{He}^{2+}$ with a pulsed gas jet after the pre-accelerator increased the intensity to $2 \times 10^{11}$ ions per PS shot and enabled them to be stacked in the ISR [26], where $\alpha$ protons and $\alpha \alpha$ experiments were conducted. Still more intense beams of deuterons and alphas were seen in the PS in 1983 following the inclusion of the Booster in the accelerator chain for ions.

With a new 750 keV Cockroft–Walton electrostatic pre-accelerator commissioned in 1975, the new Linac 2 came smoothly on line in 1978, providing three times the normal output of Linac 1. The satisfaction of the project team was enhanced by the fact that Linac 2 was a genuine CERN design, contrary to Linac 1 which had been based on a Harwell design with the exception of electromagnetic quadrupoles in the drift tubes for the alternating-gradient focusing instead of grid-focusing.

Despite all this excitement with new beams, maintenance of the PS ring was by no means ne-
glected. For example, the pole-face windings on the bending magnets compensating the saturation effects, which distort the magnetic field in the dipole magnets, were always especially exposed to radiation, being the closest to the vacuum chamber. A replacement programme was launched in 1975 and all these windings were replaced by 1979. However, in spite of all the arsenal of new and efficient ejection methods, the internal targets could not be completely eradicated until 1980.

As described in the chapter Controls, timing and sequencing, all this multi-tasking of the PS would not have been possible without the continuous upgrading of the control system. Originally, all control by the operators was based on analogue observation and action. In 1967, an IBM 1800 was acquired to help the operator. It had its memory upgraded to 16 k words (sic) in 1968. By 1981, there was a network of computers available for the monitoring and operating of all the injectors, the main ring, and the AA including all injection and ejection lines for receiving and dispatching the various beams. Originally only one PS beam pulse could be shared between different users but the pattern was fixed for quite some time because any change was tedious with considerable risk of errors. When the ISR and the SPS had to be supplied with beams, energy and intensity had to be modulated from pulse to pulse. The sequence of pulses, called the supercycle, introduced in 1976, became even more complicated once the AA received and supplied beams, all this with tight timing tolerances of a few nanoseconds. A supercycle was typically 10 to 12 seconds long. Operators could adjust individual cycles in the supercycle, independently of each other, or work on a virtual supercycle before implementing it, which enormously facilitated operation by making it more flexible and transparent.

6.1 The versatile particle factory

The two decades which followed could be considered the golden age of the PS: the proton injection energy was brought up to 1 GeV in 1987 then to 1.4 GeV in 1999; RFQs replaced the Cockroft–Walton pre-injectors; the extracted proton intensity for SPS neutrino experiments reached its record of $3.3 \times 10^{13}$; the number of surrounding machines in the complex – injectors or users – reached ten (Linac 1 and 2, PSB, PS, AA, AC – Antiproton Collector –, LEAR, LIL-V, LIL-W and EPA); and the number of different particle types reached their paroxysm. Indeed, up to 1996, one could often find, within a single PS supercycle, the acceleration of ions for SPS fixed-target physics, of protons to the East Hall or for antiproton production in the AAC (Antiproton Accumulator Complex, e.g., the AA and the AC), of electrons and positrons for LEP via the SPS, and deceleration of antiprotons for LEAR – not to mention the odd machine development cycle to test future operations of the PS as LHC pre-injector. It is during this period that the PS complex truly earned its nickname of ‘versatile particle factory’ [27].

6.2 Upgrade of the antiproton facility

The announcement of the availability of pure antiproton beams for the needs of the collider triggered a large community of users to push for the construction of a low-energy machine, able to provide a constant flux of several $10^9$ uncontaminated antiprotons over spill times of several hours [28].

The Low Energy Antiproton Ring (LEAR ) was designed in 1980, commissioned with protons from Linac 1 in 1982, and extracted its first antiproton beams for physics in a pre-run during the summer of 1983. In order to supply LEAR with antiprotons from the AA, the PS had to assume the new role of antiproton decelerator, bringing the energy of the beam down to 180 MeV, a suitable injection value for the 78 m LEAR machine. The ejection septum was placed in straight section (SS) 26; owing to lack of space in the crowded machine, the extraction kicker had to be installed in SS28, only 1/8th of a betatron wavelength upstream. A special, low-intensity beam control, operating on harmonic 10 was designed, using a frequency programme and a phase loop [29].

Over the lifespan of LEAR, which closed in 1996, the intensities of the pbar bunch decelerated by the PS ranged from less than $10^9$ to over $10^{13}$. During the early LEAR runs, a proton deceleration cycle was always present in the PS supercycle, making sure all the necessary elements were still up and
running, to prevent the loss of a precious bunch of antiprotons. This routine was later given up as the
deceleration cycle became more reliable, the space in the supercycle more scarce, and the antiprotons
more readily available.

During 1983, the antiproton beam painstakingly accumulated overnight had to be shared by three
users: the Sp$\bar{p}$S collider, the ISR, and LEAR. Very early, it became clear that the antiproton facility,
first designed as a short-term experiment, would need an upgrade to cope with the high demand. Hence,
during a long shutdown between December 1986 and August 1987, the three-fold ACOL project took
place: increase of the PS injection energy – and thus of the PSB ejection energy – from 800 MeV
to 1 GeV; improvement of the antiproton production target area; and construction of the AC machine,
a large-acceptance, fast-cooling collector ring around the accumulator [30]. In anticipation of the syn-
chrotron radiation emitted by the future lepton beams for LEP, the vacuum chamber was also changed for
one made of high-purity, low-carbon stainless steel during the same long shutdown [31]. The necessary
adaptation and improvement of the 26 GeV/$c$ proton beam needed for antiproton production is described
in the chapter RF gymnastics.

After a short running-in period, the new AAC antiproton source rapidly reached and eventually
exceeded its goal of a ten-fold increase in accumulation rate [32], [33] and the PS supplied antiprotons
to both LEAR whose second generation of experiments had been installed in the South Hall during the
long 1986–87 shutdown [34], and the Sp$\bar{p}$S collider (see Fig. 16 for a scheme of the CPS complex in the
1990s). The SPS stopped operating as a p–$\bar{p}$ collider at the end of 1991, LEAR saw its last antiprotons
in 1996, and the AA was decommissioned the following year. However, several physics groups had
expressed interest in the possibility of keeping low-energy antiprotons at CERN after LEAR closure,
mainly for trap-based experiments on antihydrogen production and spectroscopy [35]. Hence, starting
in 1992, machine experiments took place to investigate the feasibility of antiproton deceleration in a
somewhat transformed AC ring.

The new Antiproton Decelerator (AD) was commissioned during 1999, and started operating for
physics in 2000 [36]. Nowadays the AD keeps attracting new users [37]; the machine is assuming the roles previously played by the AC, AA, PS and LEAR, albeit with a reduced antiproton flux compared to LEAR, and only available in fast extraction, unsuitable for counting experiments.

6.3 Leptons

Three more machines had to be added to the PS complex to provide leptons to LEP: the LIL-V electron linac, the LIL-W electron and positron linac, and the EPA (Electron–Positron Accumulator) storage ring. Of course the PS itself had to be somewhat modified to accelerate the new particles. However, the amount of additional hardware required to operate the 25 GeV proton synchrotron as a 3.5 GeV lepton synchrotron turned out to be relatively modest since all of its existing equipment was already compatible with the acceleration of electrons and positrons [38]. The following is described in detail in the chapter The PS in the LEP injector chain, but we will recall the main issues.

The first and only combined-function lepton synchrotron with a long acceleration cycle, the PS had to be equipped with Robinson wigglers in order to modify the damping partition numbers, keeping the beam stable and the emittances under control in all three planes. As explained in the chapter RF gymnastics, several acceleration schemes were imagined, all of which implied the use of a new 1 MV, 114 MHz RF system. Although one would have been sufficient, two new 114 MHz cavities were installed, providing the necessary redundancy. In addition to high-order mode dampers, these new cavities were equipped with moveable arms to short-circuit them during the proton cycles: and these turned out to be fragile and needed frequent interventions. The acceleration scheme also involved the regular 10 MHz cavities, operating at 3.8 MHz.

Two new injection lines had to be built to bring the electrons and positrons from EPA, injecting them respectively through septum magnets placed in sections 74 and 92, while the new lepton injection kickers were respectively placed in sections 72 and 94, one eighth of a betatron wavelength downstream.

During the first exploitation periods, four cycles – two per species – of the PS supercycle were dedicated to the acceleration and transfer of leptons to the SPS. Once it was understood that both beam currents could be increased without fear of instabilities, the number of cycles could be reduced to one per species, yielding more space for other operations in the supercycle. Each cycle featured two ejections of four bunches, spaced by 30 milliseconds. The ejection elements and transfer lines did not need any special installation since they were the same as already used for the transfer of protons and antiprotons for the SPS.

The new vacuum chamber installed during the long ACOL shutdown proved to be quite efficient in minimizing the outgassing effect of the synchrotron radiation, reducing the specific pressure rise by a factor 5, down to $5 \times 10^{-9}$ mbar [38], [39].

6.4 Ions

After the success of the ISR runs with deuterons and alphas supplied by the PS in the 1970s, the demand increased at CERN for heavier ions to be delivered as a primary beam to the SPS North experimental hall, but further advances required a substantial investment in the ion source [40].

The addition of an electron cyclotron resonance (ECR) source in collaboration with GSI, Darmstadt and of a radio-frequency quadrupole (RFQ) in collaboration with LBNL, Berkeley paved the way for fully stripped oxygen ions to be delivered by the PS as part of an SPS fixed-target programme [41]. A dedicated RF beam control operating on $h=16$ was developed in the PS for low-intensity beams. Switching to this system on a cycle-to-cycle basis meant that high-intensity operations were not precluded. It did not employ a radial loop owing to the difficulty of making a reliable position measurement at low beam current, but relied instead on an ac-coupled phase loop and an accurate frequency programme. The latter was essentially a look-up table driven by the measured dipole magnetic field in the machine. This made it adjustable according to the charge-to-mass ratio of the desired ion species (relative to that of the...
proton) by the simple expedient of scaling the magnetic field value used. A non-adiabatic bunch rotation was required before extraction from the PS in order to reduce the bunch length to fit into the 4 ns RF buckets of the client SPS machine. The PS was cycled rapidly to less than half its top magnetic rigidity allowing four such cycles to fill the SPS. In this way a total of around $2 \times 10^9$ oxygen ions per SPS shot were delivered to a variety of experiments in 1986.

One year later, sulphur ions were accelerated at CERN to a world-record energy of 6.4 TeV [42] thanks to a new 14 GHz ECR source, again provided by GSI. The accelerator chain was the same, only now the ECR source was fed with sulphur dioxide. However, oxygen ions were still produced and these constituted a 95% contamination of the total beam current. Since the relative charge-to-mass ratio difference of $^{16}\text{O}^{8+}$ with respect to $^{32}\text{S}^{16+}$ is only $-5.4 \times 10^{-4}$, the oxygen was hidden within the momentum spread of the sulphur throughout the acceleration process – with the exception of the region close to transition. It was near transition in the PS that the unwanted oxygen was eliminated. This was achieved by turning off the so-called $\gamma_{tr}$-jump to maximize the radial separation of the two species at transition and by the ad hoc addition of a small perturbation to the RF phase programme a few tens of milliseconds before the corresponding phase jump. The effect of this perturbation was to drive both species towards the outside of the machine, with the oxygen reaching the vacuum chamber first, leaving the sulphur to cross transition alone [Fig. 17, left]. The PS delivered about $2 \times 10^7$ fully stripped sulphur ions per shot. As this was barely sufficient for diagnostic purposes, setting-up was achieved by dialing in the frequency programme for oxygen so that the sulphur was lost at transition on the inner wall of the vacuum chamber [Fig. 17, right].

![Fig. 17: Separating sulphur ions from oxygen at transition in the PS. Left, the number of circulating charges dips slightly (arrowed) as the sulphur is removed. Right, the beam current drops by 95% as the small sulphur component is selected.](image)

No phase perturbation was required in this case because, as was realized later [43], the two species also separate longitudinally near transition (Fig. 18) and the phase loop competed much more strongly against any such migration of the oxygen since these dominated the pick-up signal. A phase perturbation was not required to eliminate the sulphur because the phase loop was essentially blind to the longitudinal excursion of these ions away from the programmed stable phase when an oxygen RF programme was active. But the frequency programme for sulphur was corrupted by the action of the phase loop which, as it attempted to hold the oxygen ions in place longitudinally, also reduced their radial excursion (Fig. 19) such that some could survive transition unless a phase perturbation was introduced. There were further sulphur runs in 1990 – the same year that heralded the Linac 3 project dedicated to the production of heavy ions – 1991 and 1992, after which Linac 1 was decommissioned.
The success of the oxygen and sulphur runs in the SPS pushed the users to request heavier ions. The Linac 1, whose RF fields had already been increased by 33% for the acceleration of ions of charge-to-mass ratio equal to three-eighth (O$^{6+}$ or S$^{12+}$), was reaching its technological limit. State-of-the-art ion sources were not able to deliver a high current of highly-stripped heavy ions, so a whole new project had to be devised, involving the collaboration of many external laboratories, such as GANIL and IN2P3 (France); CAT, BARC and VECC (India); INFN (Italy); IAP and GSI (Germany). CERN coordinated the project and supplied the infrastructure and the upgrades to the existing machines, while the other institutes were in charge of building the new components.

The heavy-ion facility [44] consisted of:

- a new ECR source built by GANIL, delivering Pb$^{28+}$ at 2.5 keV/u;
- a new RFQ built by the Laboratori Nazionali di Legnaro, accelerating the ions to 250 keV/u;
- a new IH structure Linac (Linac 3) built by GSI, accelerating the ions to 4.2 MeV/u;
- a debuncher built by IAP;
- the associated low- and high-energy beam transport systems built by the Italian laboratories;
- the existing CERN rings PSB, PS and SPS, respectively accelerating the ions to 95.4 MeV/u, 4.25 GeV/u, and 177 GeV/u.
The PS energy was chosen in order to minimize the SPS filling time, 4.2 GeV/u (coincidentally just below transition) being the maximum energy compatible with a cycle of 1.2 seconds [45].

Because of the low charge state provided by the source, the ions could only be partially stripped by a thin carbon foil at the exit of Linac 3, to an intermediate charge state (Pb$^{53+}$), and accelerated in the PSB and PS. Full stripping was achieved by an aluminium foil in the middle of the PS–SPS transfer line. Since no ion beam had ever been stripped at these energies before, and owing to the lack of a reliable theoretical model, several stripper thicknesses had to be tried [46], [47] before settling on the optimum value of 1 mm, a compromise between stripping efficiency on one hand, and emittance blow-up and energy straggling on the other. In order not to perturb the positron beams, the stripper had to be mounted on a mechanism to move it out of the beam path during lepton cycles.

Of course, the acceleration of partially charged ions in the PS would not have been possible without an upgrade of the vacuum quality. As the original PS seals, made with elastomer materials, had already been replaced by metal ones, the upgrade mostly consisted in the installation of Ti sublimators, whose effect brought the residual gas pressure down by approximately one order of magnitude, in the low $10^{-9}$ Torr [48]. Starting operations in 1995, the heavy-ion facility provided lead ions to the SPS until 2002 and indium in 2003 [49], [50]. However, for the needs of the LHC, the scheme had to be modified once again: in order to obtain a sufficiently high luminosity in the collider, the density of the beam needed to be increased by orders of magnitude. As several ion cooling machine experiments had already been conducted in LEAR [51], it was natural to convert the soon-to-be obsolete antiproton beam stretcher into a cooling ring for ions: the Low Energy Ion Ring LEIR (see Fig. 20). Another alternative would have been the development of a laser ion source, but the technology of a dedicated cooling ring such as LEIR was deemed more established.

![Fig. 20: The PS complex with the AD antiproton ring and LEAR converted into LEIR](image-url)
7 Into the twenty-first century

After the end of operation as LEP injector, the PS started a new period of operation in preparation as LHC injector but also for new fixed-target experiments. New PS experiments also started to run in the East area, HARP [52] (2001–2002) and DIRAC [53](2000–), whereas a new neutron Time-of-Flight (nTOF) facility [54] (2000–) was starting as the main PS user. In 2007, the MERIT experiment used the nTOF line to test the behaviour of a mercury target inserted in a 15 T magnetic field and hit by an intense proton beam, in preparation for a future neutrino factory. In 2009, amongst the different test beams, the CLOUD [55] experiment started data taking to understand the influence of cosmic rays on cloud formation.

Fig. 21: The PS complex in the twenty-first century, with the lepton injectors transformed in the CLIC test facility

The PS complex took a new shape (see Fig. 21 and the tunnel in Fig. 22), with the AA–AC area replaced by the AD and its experimental area, and the transfer line to the ISR transformed into the nTOF experimental area. The historical control room on the Meyrin site was moved to the Prévesin site in 2006, in order to centralize all the accelerator operations in a single place [56]. The 2006 restart was somewhat more difficult since the PS and SPS were stopped during the whole of 2005: during that period a good fraction of the tunnel was emptied for the magnet refurbishment, the machine was realigned, and many elements went through an exceptional maintenance. The PS operation as LHC injector started in 2008 when the first proton beam did the first turns in the LHC. Also the ion operation changed. In view of the LHC run with Pb ions, and the end of the ion fixed-target physics in the SPS, a new production scheme was adopted. The antiproton storage ring LEAR was converted into the ion storage ring LEIR. The PSB stopped injecting ions in the PS in 2004, whereas the LEIR operation started in 2005. The new Pb ion beam was commissioned in the PS in 2006, then in the SPS between 2007 and 2009. Bunches of lead ions of nominal characteristics were sent to the LHC in 2009, as a first beam following the collider repair.

Over the years the PS remained a fundamental scientific tool for beam dynamics experimental studies. In 2003, a joint group of GSI and CERN observed particle trapping in a non-linear resonance...
due to an octupolar and space-charge excitation [57] and studied the Montague resonance [58]. In the framework of the search for a novel, cleaner extraction method towards the SPS, beam trapping in stable islands created by crossing the one-third and one-fifth resonances was observed for the first time [59] in 2007.

Fig. 22: The injection region (left) and the ring with one of the LHC-type 80 MHz cavities

8 The PS as LHC injector

We made it. Protons in the LHC: complete turn with beam 1 and beam 2: this is the entry in the log book that finally celebrates the first protons injected into the LHC on 10 September 2008. Even without one of the PS extraction dipoles, out of service for a few hours, the entire world could witness the successful first turn in the LHC of the beam delivered from the injector complex.

Concerning the PS, this was the successful result of the preparation of the LHC-type beams started back in 1993, with the first injection test at 1.4 GeV [60]. Already then, it was decided that the transverse emittances of the LHC-type beam should be defined in the PSB, whereas the longitudinal structure should be the result of a very complicated series of RF gymnastic in the PS. The beam should be cleaned by eventual tails in the SPS and eventually, the longitudinal and/or the transverse emittances increased by controlled blow-ups. The nominal LHC transverse emittances could already be produced in 1999 once the 1.4 GeV injection energy had become the standard [61], whereas the different bunch splittings leading to the 25 ns time structure could be finalized in 2001, as described in the chapter RF gymnastics. During the same year, to be able to assure a continuous good quality of the LHC beams, the injection and the extraction kickers were renovated to improve the rise time but also the stability of the flat-top ripple. A transverse damper [62] was also installed to eventually control the emittance blow-up due to injection mis-steering, even though it has never been used.

After producing the 25 ns bunch spacing beam, the studies to produce other LHC-type beams started in 2002, and basically continued until 2009 with the production of the LHC beam with 50 ns and 75 ns bunch spacing by using a single injection from the PSB [63]. In the end, many different types of LHC beams are available as described by Table 1, together with the non-LHC-type beams produced by the PS.

New, adverse, beam dynamics effects surfaced with the LHC beams. During the preparation of the LHC 25 ns beam, electron clouds were observed for the first time in 1999 [64]. Even if electron-cloud-driven instabilities do not so far constitute a limitation for the production of the beam required by the LHC, it might become an issue for the future LHC upgrade [65] or if the bunch length required by the SPS were to change [66]. Studies in 2008 showed how to minimize the electron cloud formation prior to extraction of the LHC beams by a faster bunch compression [67]. Electron cloud detectors have been installed and successfully used [68] to study the creation of the cloud. Always in this framework, new techniques to stabilize high-intensity LHC-type beams were studied in 2009 [69].
Table 1: Principal characteristics of the beams produced by the PS.

| User       | PSB h | PSB Int. | Int. 10^{10} if PSB r. | nr. rings | bp 1.2 s | PS h | Tot. In. 10^{10} p | $\epsilon^*$ $\mu$rad 1$\sigma$ norm. | $\epsilon^*$ $\mu$rad 1$\sigma$ norm. | $\epsilon$ eVs inj. | Extrac. Mom. GeV/c | Use                                                                 |
|------------|-------|----------|-------------------------|-----------|-----------|------|-------------------|-------------------------------------|-------------------------------------|-----------------|----------------|-------------------------------------------------------------------|
| LHC25      | 1     | 4+2      | 160                     | 3         | 7/84      | 960  | $\leq 2.5$        | $\leq 2.5$                          | 1.3                 | 26              | LHC 25 ns bunch spacing, 12 to 72 bunches                        |
| LHC50      | 1     | 4+2      | 80                      | 3         | 7/84      | 480  | $\leq 2.5$        | $\leq 2.5$                          | 1.3                 | 26              | LHC 50 ns bunch spacing, 6 to 36 bunches, double batch            |
| LHC50+     | 3     | 3        | 160                     | 2         | 7/84      | 480  | $\leq 2.5$        | $\leq 2.5$                          | 0.9                 | 26              | LHC 50 ns bunch spacing, 12 to 36 bunches, single batch           |
| LHC75      | 3     | 110      | 3                       | 2         | 7/84      | 330  | $\leq 2.5$        | $\leq 2.5$                          | 0.9                 | 26              | LHC 75 ns bunch spacing, 8 to 24 bunches                          |
| LHC150     | 1     | 3        | 50                      | 2         | 7/84      | 150  | $\leq 2.5$        | $\leq 2.5$                          | 0.6                 | 26              | LHC 150 ns bunch spacing, 4 to 12 bunches                         |
| LHCINDIV   | 1     | 1 to 4   | 2 $\rightarrow$ 12     | 2         | 16/84     | 2 $\rightarrow$ 48 | $\leq 2.5$                          | 0.3                 | 26              | LHC individual physics beam, 1 to 4 bunches (no splitting)        |
| LHCROBE    | 1     | 0.5 $\rightarrow$ 2  | 2                       | 16/84     | 0.5 $\rightarrow$ 2  | $\leq 1$                          | $\leq 1$                          | 0.3                 | 26              | LHC probe beam for commissioning                                 |
| LHCION     | 2     | 16       | 1.25                    | 5         | $\leq 1$  | $\leq 1$                          | 0.025                            | 26                  | LHC EARLY ion beam, no splittings (from LEIR)                     |
| MDION      | 2     | 16/24    | 5                       | $\leq 1$  | $\leq 1$                          | 0.025                            | 26                  | LHC Nominal ion beam (from LEIR)                                  |
| SFTPRO     | 2     | 4        | 600                     | 1         | 8/16      | 2400 | 10                | 7                    | 1.4                 | 14              | Fixed-target physics at SPS                                     |
| CNGS       | 2     | 4        | $\geq$ 600             | 1         | 8/16      | $\geq$ 2400 | 10                | 7                    | 1.4                 | 14              | CNGS physics at SPS                                              |
| AD         | 1     | 4        | 350                     | 2         | 8/20      | 1400 | 10                | 4.5                  | 1.8                 | 26              | Antiproton prod. beam                                            |
| TOF        | 1     | 1        | 850                     | 1         | 8         | 850  | 10                | 10                   | 2.3                 | 20              | Neutron (nTOF) prod. beam                                        |
| EASTA      | 1     | 45       | 2                       | 8         | 45        | 2    | 2                 | 1.5                  | 24                  | Slow extraction to East Area North branch (T9, T10, T11)          |
| EASTB      | 1     | 4        | 2                       | 16        | 12        | 2    | 2                 | 0.3                  | 24                  | Slow ejection to East Area South branch (T8, DIRAC)               |
| EASTC      | 1     | 45       | 2                       | 16        | 45        | 2    | 2                 | 1.5                  | 24                  | Slow extraction to East Area South branch (T7 irrad., T7 second.) |

The Origins and the Evolution of the CERN Proton Synchrotron
9 Preserving the PS

After 50 years, most of the PS sub-systems have been renovated or new systems have been installed. The request for high intensity, in particular for the CNGS [70] and nTOF experiments, required a profound review of the maximum intensity deliverable by the PS but also of the impact of losses and irradiation on the machine equipment and also outside the PS tunnel. The increase of the PS Booster energy from 1 to 1.4 GeV and the Linac 2 current increase to 180 mA allowed the achievement of a new intensity record (3.3 \(10^{13}\) p/cycle circulating in the PS at 14 GeV/c) in 2000. An additional intensity increase was obtained in 2001 with a double batch injection from the PSB to the PS: 3.8–3.9\(10^{13}\) p/cycle could be accelerated to 14 GeV/c although about 20% losses were observed at low energy [71].

Before 2000, a number of studies were carried out to strongly reduce the ring irradiation [72]. It became clear that a new extraction scheme for the beams for SPS fixed-target physics was imperative, since the Continuous Transfer (CT) extraction losses (see chapter Beam extraction) where going to increase the overall dose given to the ring by a considerable amount during the CNGS run. Studies of the novel Multi-Turn Extraction based on beam trapping in stable islands had started in 2001, leading to the first extraction realised in 2008 (see chapter Beam extraction). In the meanwhile, a series of studies were carried out on the classical CT extraction to understand the source of the observed losses and to confine them in one of the better shielded straight sections of the PS [73]. This led to a redesign of the CT extraction optics, which had remained untouched since the late 1970s.

Then the transition process had to undergo an important revision. As described in the chapter Transition crossing, the PS was the first machine where transition had been crossed. Transition crossing constitutes a delicate moment in the magnetic cycle when, despite the implementation of second order gamma jump, beam instabilities can develop and spoil the beam quality. With the advent of the TOF beam, a beam break-up-like phenomenon due to a transverse mode coupling instability was observed for the first time in the PS in 2000 and could be cured by increasing the longitudinal emittance, but for single bunch intensities limited to \(7 \times 10^{12}\) protons. The studies continued, and in 2008 an experimental and simulation campaign started to better determine this instability which might constitute a limitation for the future LHC upgrade or for a general PS intensity upgrade [74]. More recent studies concerned the reduction of the losses at transition in conditions when eventual beam instabilities do not develop. The studies, started in 2006, highlighted two sources of beam losses at transition: a) a large envelope distortion induced by the gamma-jump quadrupoles [75] which could be cured by changing their powering (see chapter Powering the Proton Synchrotron); b) a large beam radial position displacement due to a lack of reaction of the radial loop. This could be corrected by a different choice of the radial loop pickups [76].

Studies concerning the injection losses from the PSB also were re-started in 2008, driven by the discovery of a too high radiation level measured outside the PS tunnel. These studies revealed that during the PS construction, some sections of the shielding were reduced. This will lead in the future to the increase of the radiation shielding of the tunnel, for the first time in the history of the PS.

Despite all these efforts, the total dose the ring is receiving is increasing every year, as shown by Fig. 23. The reason for this net increase is the net increase of the total intensity that the PS has to deliver to fulfil the physics programmes, as shown in Fig. 24. After about 40 years of impeccable operation, it also became clear that the radiation damage due to the different sources of the aforementioned losses was causing an important ageing of the main magnets: a renovation, at least of the magnets most exposed to radiation or showing evidence of decay due to the too large dose received became necessary. The lifetime of the magnets had been originally estimated to be less than 10 years and has thus been exceeded by more than a factor four. The refurbishment campaign, as described in the chapter The PS magnets, started in 2005 and concluded in 2008. In total 51 main magnet units were removed from the tunnel to exchange the main coil and the pole face-windings circuits, whereas the laminations were tightened to avoid the phenomenon of detaching observed in many magnets (see chapter The PS magnets). Figure 25 shows the difficult work of magnet replacement in the PS tunnel. Despite this renovation campaign, for the
first time in the history of the PS one of the main magnets had a high-voltage fault during a run, and had to be exchanged. A refurbished magnet, the MU25, suffered from a ground fault of the figure-of-eight loop connection in July 2008, causing the melting of a part of the circuit and damage to the main coil. Following this incident, all the magnet connections were checked and the procedure to test the refurbished magnet revised.

Always in the framework of the reduction and control of beam losses, the machine alignment again became of primary importance. Since the design of the PS, the magnet alignment has always been of great concern. In order to preserve the magnet alignment, the PS was built on a concrete beam mechanically independent of the floor of the surrounding buildings [19]. In the late 1970s, the PS closed orbit was corrected by imposing voluntary mechanical offsets to certain main magnets. In fact, more than an offset, the magnets were pivoted around their centre, either in the vertical or in the horizontal plane, to profit from the dipolar component generated by the feed-down of the combined-function magnet quadrupolar gradient. The last realignment was done in the late 1990s. More recently, and with a view to reducing to a minimum the losses during the high-intensity operation by optimizing the mechanical aperture, this procedure has been resumed. During a long injector stop in 2005, the machine was completely realigned and since 2006 the orbit has been corrected according to the aforementioned technique. The orbit is measured to compute the required magnet displacement at 10 GeV/c, an energy region for which there
are no correctors and the magnet saturation is not present. A summary of the correction results can be seen in Fig. 26. The machine alignment is also monitored during the year, since a temperature variation of the tunnel of one degree corresponds to a radial displacement of the beam support of about 1.2 mm.

**Fig. 25:** Installation of a refurbished magnet during the renovation campaign

**Fig. 26:** Evolution of the horizontal and vertical orbit for the period 2006–2008
9.1 Beam instrumentation

Most of the beam instrumentation of the PS had to undergo a review in view of PS operation as LHC injector. In particular, the emittance measurement system provided by the wire scanners (see chapter Wire scanner) and the secondary emission wires in the transfer line TT2 became fundamental to qualifying the beams for the LHC. The renovation of these two systems started in 2008, and was concluded in 2009. The LHC-like electronics was successfully applied to both systems, with a net gain in measurement efficiency in the measurement provided by the wire scanners thanks also to the new calibration procedure [77]. The tune measurement system was renovated in 2006 [78], again taking advantage of the technology developed for the LHC. The orbit measurement system was also renovated in 2009 [79].

9.2 New working point control: 5-current mode

New main magnet pole-face windings (PFW) were installed in 1979 consisting of four extra auxiliary coils per magnet moulded on a plastic support mounted on the iron poles (two coils for the focusing and the defocusing yoke). The set of coils on all focusing yokes was powered in series as well as their counterpart on the defocusing yoke. In addition, the main coil was supplemented by the figure-of-eight loop creating opposite fields in the two types of yokes. The objective was to control the working points and the chromaticities with these three correction currents. Obviously, this underdetermined system was not very effective.

More recently, in 2005 and as described in the chapter Powering the Proton Synchrotron, it was decided to renovate the PFW power converters, which became available in 2007. In particular, the four original PFW circuits were made independent and, with the addition of the figure-of-eight, five parameters became available to control the two tunes, the two chromaticities, and eventually an extra parameter, which is typically the non-linear horizontal chromaticity. Unfortunately, the relationship between current variation in the circuit and the variation of the physical parameter cannot be easily computed from a theoretical model of the main magnet. However, it can be deduced from the measurement of the variation of the working point with respect to a programmed variation of the pole face windings or figure-of-eight loop currents. The measurement campaign took place between 2008 and 2009 [80], and the matrix describing the effects of the five currents finally became available, which was quite a step forward, though further improvements on the error of the matrix elements is still needed to improve the beam control.

9.3 The future of the PS complex

After 50 years of reliable operation, the PS is still going strong and will keep supplying protons and ions, not only to the laboratory flagship, the Large Hadron Collider, for the next two decades, but also to a number of current and forthcoming accelerators and experiments. In continuation of a 50 year long tradition of attentive care, its infrastructure will have to be maintained to keep up with the ever increasing demand of high beam performance, with particular attention to controlling and reducing the irradiation. For example, as described in the chapter Powering the Proton Synchrotron, a new, solid-state, main power converter is soon to be commissioned. Also, the current proton injector will be replaced in the near future by a new 160 MeV H− linac [81], requiring the PSB to modify its injection scheme as well, and the addition of an extremely low-energy antiproton ring in the AD hall is also under study [82]. Several parts of the PS will probably have to be exchanged, improved, upgraded or modified, such as the RF systems, the instrumentation, the pole-face windings, so that the venerable old machine can stay for many more years at the heart of the CERN accelerator complex.

Long live the CERN Proton Synchrotron!
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The PS magnets

1 Introduction

The PS main magnets are — apart from the buildings — the only major components remaining from the original installation 50 years ago. Thanks to the prudent design and the intelligent choice of engineering margins, they could be operated during their remarkably long life with excellent reliability and without any significant breakdown, providing a high availability of the accelerator.

Except for a few minor modifications and upgrades, the PS main magnets remained in the original configuration up to the refurbishment programme in 2005. Until then, around 70 of the 101 main magnets were still in the original position where they had been initially installed in 1959.

This summary is dedicated to acknowledging this outstanding achievement and recognizing the excellent work of the people who were responsible for the design and engineering of the PS main magnets 50 years ago, and also the engineers and technicians who made constant efforts to reinforce and keep the magnet system in good condition over the past 50 years.

2 Decision for an alternating-gradient machine

As reported in Ref. [1], the CERN Council in May 1952 decided on the creation of a study group to explore a weak-focusing proton synchrotron. This group, led by O. Dahl, visited BNL in summer 1952 to learn about the alternating-gradient focusing principle. Although a design of a Cosmotron-like synchrotron had been worked out, it was decided after this visit to forthwith design an alternating-gradient synchrotron. The still provisional Council accepted this proposal in October 1953.

The advantage of the alternating-gradient principle was a considerable reduction in the amplitude of the excursion of the particles and consequently in the size of the vacuum chamber and the magnet gap. The cost of the magnets, their foundations, and the tunnel cross-section could be reduced dramatically. However, it made the synchrotron much more sensitive to 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, where the total weight of the combined-function magnets of the 25 GeV CERN Proton Synchrotron was fixed at 3,800 tonnes.

3 Main components of the PS magnet system

3.1 PS main magnet units

The PS main magnet system consists of a ring-shaped structure 200 m in diameter [2]. This structure comprises 100 combined-function magnet units (MU) each composed of a focusing (F) half-unit and a defocusing (D) half-unit. Between two subsequent magnet units, there is an interval called ‘straight section’, which is field-free so that the recurrent pattern is ‘FOFDOD’. The straight sections are used for placing accelerating cavities, beam diagnostic devices, injection and extraction elements, and magnetic lenses. Up to 1981, internal targets were also installed in straight sections 01, 06, and 08. A reference unit (MU 101) is located outside the tunnel in a dedicated air-conditioned room. Electrically in series with the other 100 units in the tunnel it serves to produce reference voltages for timing, beam control, and field monitoring purposes.

A half-unit is composed of five adjacent magnet blocks, each 417 mm long. A block is a straight C-shaped structure of open or closed type (Fig. 1). Employing two different types of block produces the alternation of the gradient. The magnet blocks are installed on a steel girder which rests on a reinforced concrete beam by means of a jack system. The blocks are precisely positioned
horizontally and vertically by means of adjusting screws. The ten blocks of each unit are excited by the same coil.

![Fig. 1: Open and closed blocks](image1)

There are four types of unit, identified by the position of the return yoke either inside or outside of the beam orbit and by the sequence of the half-units F and D with respect to the direction of the proton beam (see Fig. 2):

- **Type R**: Yoke outside, defocusing–focusing 35 installed in the tunnel
- **Type S**: Yoke outside, focusing–defocusing 15 installed in the tunnel
- **Type T**: Yoke inside, defocusing–focusing 35 installed in the tunnel
- **Type U**: Yoke inside, focusing–defocusing 15 installed in the tunnel

![Fig. 2: PS main magnet types](image2)

The advantages of the alternating-gradient principle are unfortunately partly cancelled by the tightness of the tolerances for the construction and layout of the magnets. Alignment errors, inhomogeneities in the magnetic field and its gradient, and imperfections in the quality and assembly of the steel must be kept down to a very strict minimum. Since the shape of the magnetic field and its possible variations in space and time had to be very accurately known, a series of models was constructed, most of them of full-scale cross-section but reduced length. It was with the help of these models that the pole profile was worked out in detail and that the effect of the magnet parameters — permeability of the steel, remanent field, end effects and eddy currents — was determined. More than ten of these models were constructed and the results obtained with them made it possible to draw up the final design of the magnet and the correct pole profile.

A large number of studies and measurements were performed to determine the main characteristics of the steel used to produce the magnet blocks. Experience gained during several years of study in the laboratories was not sufficient to decide between low-silicon steel and low-carbon steel. Finally, a steel type with low carbon content of 0.06% was chosen on account of mechanical properties, easy supply, and low cost. The steel was produced by hot rolling from an ingot, subsequent
cold rolling and annealing followed by controlled cold work, cutting into sheets, and final annealing. This process was elaborated to minimize the effects of ageing and to achieve a low as possible coercive force.

The results of experimental tests showed that, even with a careful control of the steel production parameters, it would not have been possible to construct a magnet complying with the very stringent specifications in terms of field uniformity and homogeneity. Therefore, two methods were considered to eliminate the effects of fluctuations in the magnetic properties of the steel. Firstly, the actual magnetic characteristics measured on the finished blocks were taken into account to determine the best arrangement for the blocks during the assembly of the magnet units. Secondly, constructional processes were arranged so as to incorporate laminations from every batch of steel in every block, thus decreasing variations in average performance from one block to another.

The original magnet blocks were fabricated at Ansaldo (San Giorgio, Italy) using 1.5 mm thick low-carbon steel laminations supplied by Cornigliano, Italy [Fig. 3(b)]. Each block is made of 262 ± 1 laminations. After stamping, the laminations were precisely aligned in a jig and stuck together with hot-setting Araldite (epoxy) resin type XV supplied by Ciba, Switzerland. Paper sheets are used for the insulation between the laminations. One thousand and twenty of these blocks, each weighing 2890 kg, were delivered to CERN between 1956 and 1958, and installed on the steel girders.

Each magnet unit comprises two main excitation coils: one placed around the top pole and one around the bottom pole (Fig. 4). Each of these coils consists of two pancakes, each containing five turns of conductor. The conductor is made of aluminium with a purity of over 99.74%. The conductor dimensions are 38 mm × 55 mm with a central duct of 12 mm in diameter to let the cooling water through. The pancakes are constructed differently according to the type of main unit (return yoke outside or inside).

The 412 main coils originally fabricated by ACEC in 1956 were made of aluminium bars of about 50 m in length wrapped in 0.5 mm mica-glass tape, which acts as insulator between the five turns of a pancake. The mass insulation was achieved by a 4 mm mica-glass tape vacuum-impregnated with polyester resin called ‘Thermalastic’, developed by Westinghouse. The whole pancake was then wrapped with a glass-fibre tape and painted with anti-hygroscopic paint.

The cross-section of the conductor was chosen to minimize the total cost of the magnet, coils, power supply and cooling system, as well as the cost of the power and cooling consumption over a number of years of operation. Aluminium was selected as a conductor material, because it was cheaper. The weight of an aluminium coil is low, thus making handling easier. Aluminium rods were sufficiently long that they did not require welding inside the pancakes thus reducing the risk of water leaks.

All main coils of the top poles are electrically connected in series, as well as all main coils of the bottom poles. The connections between the main coils of two subsequent units are done by so-called ‘bus bars’. The bus bars consist of two hollow aluminium conductors with a square cross-section of 52 mm × 52 mm and an inner bore diameter of 18 mm. The insulation was done by means of 4 mm resin-impregnated glass-fibre tape, similar to the insulation of the main coils. The two conductors supplying the upper and the lower coil with electricity and water are tied together with glass-fibre tapes and painted with anti-hygroscopic epoxy paint. A thin copper sheet connected to ground is installed all along the bus bar between the conductor for the upper coil and the conductor for the lower coil. Since both conductors are in close contact (only separated by the insulation) and both have the same voltage over ground but with opposite signs, this copper sheet acts as an electrostatic shield.

There are eight different types of bus bar determined by the straight section (short or long) where they are installed and by the orientation of the magnet yokes (inside or outside) that they connect.
Fig. 3(a): The magnet team of the 1950s on the PS prototype magnet in the hall of the Institut de Physique

Fig. 3(b): Lamination stacking at Ansaldo
In order to assure the correct performance of the final assembled magnet, all magnets were measured systematically (Fig. 5). The magnetic field and its gradient at all points of the useful aperture and during the whole excitation cycle were measured with an accuracy of the order of $10^{-3}$. Measurements of the static field and its gradient were carried out with rotating coils, while dynamic measurements were done with fixed coils [3]. Figure 6 shows the magnets in the assembly hall.

Fig. 4: Installation of the main coils at CERN

Fig. 5: Magnetic measurement bench at CERN

Fig. 6: Magnets awaiting installation in the tunnel
3.2 Auxiliary magnets

When the PS was installed in 1959, different lenses (quadrupoles, sextupoles and octupoles) were foreseen to correct undesired multi-pole errors (Fig. 7). The quadrupoles provided a gradient of 7000 G/cm and consisted of a laminated core made of 0.35 mm thick transformer steel laminations. Since the quadrupole lenses were excited in pulsed mode, the mean power dissipation in the coils was low and consequently no water cooling was required. The 20 lenses were subdivided into two identical groups each being supplied by an individual motor-generator set.

The maximum value of $\frac{d^2 B}{dr^2}$ in the sextupole lenses was 72 G/cm$^2$ and their effective length was 33 cm. The effective length of the octupole lenses was 43 cm and the $\frac{d^3 B}{dr^3}$ was 41 G/cm$^3$. The octupole lenses were equipped with special windings to compensate distortions in the equilibrium orbit due to remanent field errors and permeability errors. The 40 non-linear lenses were subdivided into four self-contained groups of 10 lenses (two groups of sextupoles and two groups of octupoles). All magnets in the same group were connected in series to a pulsed power supply.

![Fig. 7: Magnetic lenses in 1959...](image1)

![Fig. 8: ... and in 2009](image2)

The original lenses from 1959 were successively replaced by new magnets providing a better and more reliable performance. In addition, further magnetic elements, like bumper dipoles, kick-enhancement quadrupoles, q-tuning quadrupoles, Robinson Wiggler, were added (and also removed...
again) to adapt the PS to the more demanding operational requirements. The latest magnets, which were installed in the PS in the 2007/08 shutdown, are two octupoles for the new multi-turn extraction scheme (Fig. 8).

3.3 Pole face windings

Whereas with magnetic lenses a correction can be made at given points in the straight sections between the main magnet units, correction windings placed on the magnet poles — so called ‘Pole Face Windings’ (PFW) — act along the whole main magnet unit. The idea of these PFW is to set up a configuration of conductors (Fig. 9) on the magnet poles, creating a defined current distribution and hence an additional magnetic field of low amplitude to compensate distortions in the main field and its gradient. The performance of the PFW is nevertheless limited by the relatively low currents which can be used. Hence, it was decided to correct quadrupole and octupolar distortions with lenses installed in the straight section and to use the PFW only to correct sextupolar field components resulting from both the saturation and the leakage field at high field levels. This gave some freedom in the choice of the current distribution along the poles so that the power required for the excitation of the PFW could be kept low.

Fig. 9: Conductor positioning in the PFW (2004)

PFW can also be used to correct undesired field components at low fields, e.g., due to induced eddy currents. In such a case, the perturbing effects have roughly a constant amplitude and can consequently be corrected with constant currents in the PFW. Although the current distribution here is different from that required for high fields, the correction can be made by fitting resistors between the coils; the electric current in the coils is driven by the voltage induced by the variation of the main magnetic field and no external power supply is required. The correction current can be simply adjusted by changing the resistors. The current distribution for high fields, obtained by the active windings, is not affected by these resistors because their resistance is much higher than that of the windings.

The original PFW from 1959 [4] were manufactured by ACEC (Charleroi, Belgium). They were made of copper conductors with a cross-section of 9 mm × 2.5 mm embedded in an insulated plate of polyester resin reinforced with glass-fibre cloth. The layer was vacuum impregnated in a mould and subsequently polymerized in an oven. The space available to fit in the PFW between the pole faces of the magnet is very limited. Its construction therefore required great care, since the applied voltage reaches 2 kV. The PFW must fit exactly on the pole faces of the five adjacent magnet blocks; their shape is complicated since their skew surfaces have a double curvature. Four different shapes are necessary for focusing and defocusing half-units. The tolerance for the positioning of the conductors inside the PFW is ±0.5 mm.
4 Chronicle of the PS main magnets (1959–2003)

4.1 Magnet units

It is remarkable that up to the consolidation programme in 2003, 91 magnet units were still in their original state and 72 main units were still in the original position where they had been installed in 1959.

The following main magnet units were replaced at least once by a new or refurbished unit between the years 1959 and 2003: MU 01, MU 02, MU 06, MU 19, MU 42, MU 56, MU 64, MU 87, and MU 100. In 1966 and 1974 eight additional magnet units were assembled partly from original magnet blocks and new blocks manufactured by Siemens [13]: T 37 (1966), T 38, T 39, R 36, S 16, U 16, U 17, and U 18 (1974). Three magnets were removed from the PS and dismantled: T 30 (1966), T 37 (1970), and U04 (1970). Between 1973 and 1987 seven main units were repaired: R 06 (1973), R 15 (1974), R 23 (1982), S 06 (1987), U 03 (1975), U 09 (1973), and U 16 (1987).

Apart from the above-mentioned replacements of main units which were required mostly because of breakdowns, a number of permutations took place to adapt the PS machine to the changing requirements like the installation of new injection and extraction channels. Table 1 shows the positions after the permutations and the dates of removal.

| Ring position | Magnet unit | Ring position | Magnet unit | Date |
|---------------|-------------|---------------|-------------|------|
| MU 54         | R 02        | MU 60         | U 15        | 1963 |
| MU 42         | R 23        | MU 64         | U 03        | 1964 |
| MU 82         | R 03        | MU 58         | U 05        | 1965 |
| MU 83         | S 08        | MU 59         | T 04        | 1965 |
| MU 88         | U 11        | MU 62         | U 01        | 1966 |
| MU 22         | R 07        | MU 16         | U 04        | 1969 |
| MU 18         | U 10        | MU 48         | R 35        | 1969 |
| MU 11         | S 15        | MU 39         | T 10        | 1972 |
| MU 34         | R16         | MU 40         | U 06        | 1972 |
| MU 08         | R 01        | MU 56         | U 16        | 1980 |
| MU 24         | U 08        | MU 94         | R 12        | 1982 |

After 1987, no magnet was replaced or repaired until January 2002 when MU 01 (T 38) was removed. Although, this magnet had been operated without a problem since 1970, it was decided to replace it by a spare unit (T 39) because the main coils and the PFW insulation already showed significant signs of degradation. The magnet removal was also indispensable to re-gain the know-how of displacing a PS magnet unit, which had not been done for 15 years.

Currently, CERN owns, in addition to the 101 installed units, four fully operational spare magnets, one of each type, and one additional unit of type ‘U’ used for measurement purposes.

4.2 Degradation of the lamination bonding

As early as 1965, the main magnet started to show the first symptoms of significant ageing due to the increasing number of accelerated protons. Both the number of protons per pulse and the number of
pulses were constantly increased with the consequence of deteriorating organic materials due to a combined effect of ionizing radiation and pulsed magnetic forces. In particular the glue holding the steel lamination of the magnet blocks together started to degrade leading to a de-lamination of the blocks on the magnet extremities. In the same way the insulating materials of the PFW and the main coils were affected.

In February 1970, after a major breakdown of MU 01, it was recognized for the first time that some laminations on the extremity of the magnet blocks had become loose. The Araldite bonding had been slowly destroyed under the effect of radiation [5]. Under the influence of the pulsed magnetic forces the end laminations were bent outwards in the region of the pole tips damaging the PFW insulation and causing an electrical short-circuit [6]. Until 1977 when an overall repair was launched, some 40 blocks around the machine showed the same degradation. During several annual stops between 1977 and 1979, the pole tips of the two outer blocks (block no.1 and block no.10) on all main units were systematically equipped with fasteners [7]. These fasteners consist of two stainless-steel plates placed on the pole sides and two tie rods. A well-defined pressure was applied by means of the two pre-stressed and insulated tie rods made of copper-beryllium. In addition, wedges made of epoxy-impregnated glass-fibre laminate were mounted in the gaps between the inner blocks. In the following years up to 2003 no more problems with unbounded laminations have been reported.

During the 2002/2003 winter shutdown, a damaged fastener was found on the first block of MU 31. The copper-beryllium tie rod was broken on its threaded end and the stainless-steel plate became loose. A movement of about 25 laminations was observed when the magnet was pulsed. This moving of approximately 1 mm towards the end caps of the PFW was now enough to cause damage to the epoxy insulation of the PFW. Unfortunately, owing to the high radiation level at this position, the magnet could not be repaired and a replacement was not possible, since no operational spare magnet of this type was available at that time. In the meantime the magnet has been replaced in the framework of the PS main magnet consolidation programme.

4.3 Magnet blocks

The 1010 blocks originally produced by Ansaldo (see Fig. 10) were used to build the 101 original main units installed in the ring tunnel and in the reference room in 1959. Between 1959 and 1966 the PS ran without any spare unit; in 1966, one spare unit was assembled from the 10 additional blocks of the original production [8].

![Fig. 10: Magnet blocks ready for assembly](image-url)

A new spare blocks fabrication was launched in the end of the 1960s when the remaining stock of the original steel sheets had been used up. A total of 48 blocks were manufactured by Siemens [9] and delivered to CERN in the years 1969 to 1971. Siemens had rebuilt all necessary toolings (stamping tool, stacking tool) which were recuperated by CERN once the production had been finished. Great care was taken to ensure that the new blocks were identical to the original Ansaldo
blocks and that they had the same geometry and the same magnetic field [10]. The dimensions and the packing factor were strictly observed. The insulation between adjacent laminations was realized by a thin phosphate layer and the packing factor was corrected by inserting glass-fibre sheets. A dedicated study was launched to guarantee that the Araldite resin used for bonding the lamination could withstand a total integrated dose of 10 MGy without degradation. Nevertheless, fasteners were mounted around the pole tips as far as the blocks have been installed on the extremities of a main magnet unit.

4.4 Main coils

Degradation of the insulation on highly irradiated coils had been observed for a long time. This damage is manifested in loss of adhesion between the conductor and the insulation material thus creating bubbles on the surface. The expected lifetime of the insulation is determined by the maximum permissible integrated dose which has been estimated to be around 10 MGy.

First tests in 1965 showed that the insulation resistance had already decreased by a factor of two after five years of operation and accumulating a dose of 2 MGy. Another study on a coil after six years of operation was carried out in 1972 at CERN in collaboration with experts from ACEC [11]. This coil had accumulated a total dose of 1.5 MGy on its most exposed point. Several high-voltage tests were done and the following results obtained:

- The glass-fibre layer was completely delaminated.
- No more adhesion was present in the mass insulation either between individual layers or between mica-layer and conductor.
- The resin had changed colour and become brittle.
- The inter-turn insulation remained compact, but also changed colour.
- The mass insulation lost elasticity and became porous.
- The insulation withstood 50 kV when dry, but its insulation resistance decreased radically when the coil was sprayed with water.
- The resin, the paint, and the supporting paper for the mica foils were more or less severely damaged.

Samples of the Thermalastic insulation taken from this coil were submitted to an accelerated irradiation test in a reactor and confirmed the maximum permissible dose of 10 MGy in 1974 [12]. Nevertheless, the degradation of the coil insulation irradiated by an integrated dose significantly less than 10 MGy did not correspond to results obtained from accelerated irradiation tests. The lethal dose of 10 MGy found in these tests is rather optimistic, since it does not take account of the fact that the degradation is also a function of exposure time, temperature, and the amount of oxygen in the environment [13]–[15]. Humidity might also play an important role. Although the radiation had an obvious impact on the mechanical properties, the coil insulation was still intact from the electrical point of view. For this reason it was decided not to replace them at the time.

The state and performance of the coil are surveyed by an annual visual and audio inspection as well by a high-voltage test at 7 kV (dc) carried out regularly at the end of the run and before the machine start-up. Although the maximum voltage over ground in operation is ±3 kV, it can become as high as 6 kV over ground potential in case of a failure of the power supply. Up to 2003, the annual inspection and the high-voltage test at the beginning and the end of each shutdown rarely revealed problems with the main coil insulation. In fact, the first and only breakdown of a main coil due to a failure of the ground insulation since the installation of the PS in 1959 was recorded in 1985. From time to time a bus bar, which was accidentally sprayed with water failed and had to be replaced.

Apart from the original supply of main coils fabricated in 1956 by ACEC (101 sets installed on the original main units plus two spare sets) CERN has placed two additional orders to increase the
stock of operational spare coils: a first order in 1967 for four spare sets fabricated by ACEC and a second order in 1975 for ten spare sets supplied by Alsthom [16].

4.5 Pole face windings

Because the PFW are placed on the magnet poles close to the circulation beam, they receive a higher radiation dose than other magnet components. This circumstance reduced the lifetime of these elements and made it necessary to replace them more frequently, especially in areas of elevated radiation levels like near the internal targets, dumps, or extraction regions.

In the beginning of the 1970s CERN ordered 40 new PFW from BBC (Mannheim, Germany) to compensate for damaged and dismantled PFW and to fill up the stock of spares.

A novel PFW system applying a so-called ‘three-current’ operation was proposed in 1974 for the first time [17], [18]. The new system was provisionally implemented and successfully tested in 1976 [19], [20]. The three-current operation uses three independent powering circuits. The first circuit is connected to a so-called ‘figure-of-eight’ winding consisting of three turns of cable wound around the return yoke of a focusing half-unit in one direction and around the return yoke of a defocusing half-unit in the opposite direction, forming a figure-of-eight loop (Fig. 11). This configuration allows increasing the field gradient on a half-unit, while decreasing it simultaneously on the other half without affecting the total integrated bending field. The two other circuits power the focusing and the defocusing PFW.

![PS unit with first-generation figure-of-eight winding](image)

Fig. 11: PS unit with first-generation figure-of-eight winding

Between 1978 and 1981, the novel PFW system was consolidated several times: new power converters, specially adapted cables, automatic distribution board (‘patch panel’), and improved figure-of-eight cable windings. The upgraded system already provided the possibility of a ‘five-current’ operation which became operational only in 2006 after the installation of new power converters.

As a consequence of the new PFW system and the three-current operation, the magnetic induction in the focusing and the defocusing part of the magnet was no longer the same on account of the figure-of-eight windings. A novel B-train system adapted to the new operation mode had to be developed and was successfully installed in 1976 [21].

In 1976 an order for 486 new PFW was placed with BBC (Mannheim, Germany) to replace the PFW of the first generation which had been heavily deteriorated by ionizing radiation [22]. In three consecutive shutdowns between 1977 and 1979, the old PFW were then systematically replaced by the new type. The new PFW were fully compatible with the old type to allow for a successive replacement, but had several improvements: the windings were split into two separate electric circuits (namely narrow and wide) near to the central beam orbit to make the five-current operation possible and the copper cross-section had been increased to allow higher excitation currents. The correction of
eddy currents in the vacuum chambers had also been improved by installing new printed-circuit cards holding appropriate resistors which are connected to the auxiliary windings of the PFW.

In February 1979, after the new PFW had been completely installed, a fabrication fault was detected. Several crimped connections between the solid copper conductor and the flexible connection cable showed a bad contact resistance leading to a local overheating in the PFW [23]. A repair of 62 defective PFW had been agreed by the manufacturer, but a systematic cure for the problem was excluded since the connections are entirely potted in epoxy resin. By measuring the contact resistance each year at the beginning of a shutdown the evolution of the crimped contacts is monitored and further degradation of the contact resistance can be predicted. So the suspicious PFW can be replaced before they definitely fail. Until 1989, when the warranty period ended and the repair programme was finally stopped, the 11 defective PFW identified up until then were repaired by BBC.

The first generation of figure-of-eight windings which were installed between January 1977 and January 1978 were made of flexible copper cables with polyurethane insulation attached around the return yoke of the magnet units. The degradation of the insulation due to radiation, temperature, and oxygen made a frequent replacement of the cable necessary. In addition, the excitation current was restricted owing to heating of the conductor limiting the effect of the figure-of-eight windings due to iron saturation in particular at high energies [24]. These weaknesses finally triggered a study [25] of new figure-of-eight windings made of one turn of rigid copper conductors installed around the magnet poles thus increasing the efficiency of this system (Fig. 12). The use of glass-fibre-reinforced epoxy resin clearly improved the radiation hardness and reliability of the insulation. After a series of tests on the measurement unit U 17, the installation of the final system was completed in 1987 [26].

![Fig. 12: Schematic of new figure-of-eight winding](image)

4.6 Cooling system
The original cooling system used rubber hoses to connect the main coils and the bus bars hydraulically. In the early days of the PS these hoses had to be exchanged regularly due to radiation damage before they were finally replaced by aluminium tubes in the 1970s. Only a short connection made of rubber hoses remained between the newly installed aluminium tubes and the water supply pipework to provide electrical insulation between the coils and the cooling network.

4.7 Interlock system
A thermal interlock system is the only safety system which protects the PS main magnet coils from overheating. The initial system was installed in 1959 and used mercury temperature switches connected to a relay. The drawback of this system was that it did not trigger in case of defective or disconnected switches or defective relays.

In 1991, a proposal was made to replace the old interlock system in order to eliminate the increasing risk of malfunctioning. The new interlock system was implemented and became
operational in January 1994 [27]. It surveys the coil temperature on 202 points distributed around the machine using bimetallic thermocontacts and stops the main power supply in case of a detected overheating or a defect in the interlock system. An additional diagnosis system helps to quickly localize the fault.

In 1999, a short circuit was detected between the magnet coils and the copper plate fixed between two pancakes, which is part of the thermal interlock system. As a consequence the insulation between the coils and the copper plate was systematically reinforced.

A new, third-generation interlock system was developed in the framework of the PS main magnet consolidation programme in 2005. The copper plates clamped between the two pancakes holding the thermocontacts were replaced by special holders made of glass-fibre laminate directly fixed on the water outlet of each pancake. This now allows the monitoring not only of the temperature of each coil but of each individual pancake at the hottest spot. The new system is fully compatible with the existing one and has been installed so far on the 52 refurbished magnet units.

5 The PS main magnet consolidation programme (2003–2009)

The status of the PS main magnet system had already been subjected to a detailed study twice in the past: the first time in 1974 before the SPS was built and the second time in 1983 before LEP was built, in order to assure that the PS could serve as a pre-injector in the forthcoming periods. The outcome of these studies was published in Refs. [11] and [28].

After a relatively long period of operation without any breakdown or significant downtime, in 2001 the PS main magnets started to show alarming signs of degradation. The most recent serious accident was the breakdown of the ground insulation of two main coils during the annual high-voltage test at the end of the shutdown, which led to a delayed start up of the PS machine by two weeks in 2003. In view of the alarming number of failures, it was decided by the CERN management in March 2003 to launch a study with the following objectives:

- Analyse the present situation of the PS main magnets and their future evolution.
- Present proposals for a renovation and consolidation of the PS main magnets to assure reliable operation in the forthcoming LHC era.

5.1 Status analysis in 2003

A detailed analysis [29] of the PS main magnets after the breakdown of two main magnets in 2003 revealed that 90% of the main magnets were in their original state of the late 1950s. A relatively intensive preventive maintenance and steady efforts to upgrade and develop the system took place in the early years of the PS; but this maintenance was reduced constantly until 1987 when it was stopped completely. Since then only very minor improvements had been made and the work during the shutdowns was dedicated only to repair or replacement of faulty components in order to keep the main magnets operational.

Many magnet components had approached or were even beyond their expected lifetime and showed heavy degradation induced by radiation and mechanical fatigue due to pulsed magnetic forces, in particular the main coils. The glass-fibre insulation of many coils had deteriorated and over large areas it no longer adhered to the conductor. The ground insulation had lost elasticity and become porous. The same concerns are today still relevant for the bus bars.

The polyurethane insulation of the PFW cables gave, at first glance, the impression of being generally in good condition. However, after an inspection it turned out that the insulation was falling apart when touched (Fig. 13). This damage resulted from a combined effect of degradation of the organic material subjected to high irradiation and its poor resistance against microbes. Once a PFW cable had been moved — accidentally or intentionally during an intervention — the insulation was completely damaged and the entire PFW had to be replaced. Since almost all PFW cables are suffering from this degradation the risk of a breakdown was extremely high.
Considering all these facts, including the recent accidents, it was obvious that the reliability of the main coils and the PFW had become very low and the risk of further serious breakdowns in the near future was significant.

5.2 PS magnet consolidation 2005–2009

In summer 2003, it was decided to launch the PS magnet consolidation project to replace systematically the components with the highest risk score, namely the main coils and the PFW. The 18-month shutdown of the PS in 2005/06 offered a unique chance to repair a significant number of magnets. The most important advantage was the long cool-down period: the radiation level of the magnets was strongly reduced and, hence, the integrated dose submitted to the personnel involved in this work was minimized. An immediate repair of a maximum number of magnets became even more important in view of the increase in induced radioactivity of the PS in the forthcoming years, which is expected on account of high-intensity proton beams for CNGS.

Financial restrictions, the narrow time window, and the limited availability of human resources made it impossible to refurbish all 100 magnet units in one go. Therefore, the project had to be split into two phases. Phase I comprised 51 of the 100 main magnets units, which have now been refurbished. Of these 51 magnets, 26 high-risk magnets were repaired in the long shutdown in 2005/06 whereas magnets with a lower failure probability stayed in the tunnel and were refurbished at a rate of eight magnets per year in the following shutdowns.

Before starting the refurbishment work, a detailed campaign was undertaken to examine all 100 magnet units. The actual state of the components was determined as well as their future reliability in order to identify high-risk magnets. The magnets were categorized in several classes according to their priorities. The following criteria were applied to find the weakest magnets:

- Detailed visual inspection: significant degradation of the main coil insulation, corrosion of aluminium conductor, damaged gold plating, disintegrated rubber pads, damaged PFW cable insulation, etc.
- The total integrated dose received between 1959 and 2004: magnets close to or beyond the ‘lethal’ dose limit were given highest priority. Eighteen magnets were found to have received more than 8 MGy (Fig. 14).
- The actual radioactivity: to take advantage of exceptionally long cooling-down time, magnets with high radiation levels were given priority.
The sequence of the magnet removal and refurbishment was mainly determined by the actual radioactivity (less radioactive magnets first) and accessibility. Magnets difficult to remove or repair were dealt with when the personnel had acquired a sufficient level of experience. The minimization of the radiation doses received by the personnel involved, according to the ALARA principle, was a key issue in this project. Special tools and detailed work procedures were studied to optimize and streamline all handling and repair operations.

For the new main coils, 12 000 m (~ 64 tonnes) of hollow aluminium conductor were produced by Holton (Bournemouth, UK) in a continuous rotary extrusion process. The 232 new main coils were manufactured by BINP (Novosibirsk, Russia). The 240 PFW were produced by Sigmaphi (Vannes, France). The main concern, in addition to the tight production schedule and the complex PFW design, was to find highly flexible and radiation-resistant connection cables. A series of radiation tests led to the choice of Ultem® polyetherimid cable insulation material.

During disassembly of the first PS main magnets in May 2005, it was discovered that the degradation of the glue had advanced further. Under the influence of the pulsed magnetic forces the end laminations were bent outwards in the region of the pole tips. In particular the two central blocks were affected, since the spacers which have been put in place at the end of the 1970s had been removed again at the end of the 1980s [30] to make space for the central conductor of the new figure-of-eight windings. Without repair the moving laminations would have damaged the insulation of the central conductor and led to short circuits. Numerous repair options were studied to rescue the magnet yoke. The most promising solution found was to glue the loose laminations together and in addition bolt them with a screw. A test with 30 000 cycles at full field showed this method to be successful. The repair was applied on all refurbished magnets, but the problem of laminations becoming loose again was observed once more two years after this repair. Apparently, the problem of loose laminate remains critical and has to be observed closely to detect possible future damage.

After the repair, which involved a number of operations such as transport, removal and remounting of the vacuum chamber, installation of new coils and PFW, replacement of cables, final testing and inspection, the magnets were moved back into the PS tunnel and re-aligned. Figures 15 and 16 show one of the magnets before and after the renovation.

Every repaired magnet was tested individually before re-installation in the tunnel (hydraulic, resistance, insulation, polarity, interlock, etc.). In addition, an extended hardware test period allowed identifying and solving any possible problem before the PS start-up in 2006. The commissioning included high-voltage tests, polarity checks on all windings, and a systematic thermographic inspection (Fig. 17), to check the electrical connections and the cooling performance of all 100 main magnets. As a result, the PS startup was extremely smooth and the beam was accelerated immediately to its maximum momentum of 26 GeV/c. Phase I of the consolidation programme was continued until
2009 and covered the refurbishment of 55 magnets including 51 installed units as well as 4 spares (Table 2).

Fig. 15: PS main magnet unit before …

Fig. 16: … and after renovation

Fig. 17: Thermographic inspection of PFW
Table 2: Magnets refurbished during the main magnet consolidation programme 2005-2009

| 2005-06 | 2006-07 | 2007-08 | 2008-09 |
|---------|---------|---------|---------|
| MU 02, MU 03, MU 07 | MU 01 | MU 05 | MU 23 |
| MU 09, MU 15, MU 17 | MU 08 | MU 16 | MU 26 |
| MU 25, MU 35, MU 37 | MU 18 | MU 48 | MU 58 |
| MU 42, MU 44, MU 45 | MU 19 | MU 49 | MU 65 |
| MU 47, MU 61, MU 63 | MU 31 | MU 51 | MU 68 |
| MU 64, MU 71, MU 77 | MU 62 | MU 59 | MU 69 |
| MU 83, MU 84, MU 89 | MU 81 | MU 76 | MU 70 |
| MU 91, MU 93, MU 94 | MU 82 | MU 85 | MU 72 |
| MU 97, MU 100 | | | MU 99 |

26 units 8 units 8 units 9 units

6 Summary

To adapt the PS machine to new requirements and continuously upcoming challenges, several projects to upgrade and reinforce the original main magnet system have been proposed and realized in the past, including new PFW and new figure-of-eight windings. In addition, intensive preventive maintenance and dedicated efforts were carried out to preserve the reliability of the magnets and to keep the machine down-time low. The most recent consolidation programme which included a full renovation of 52 magnet units allows the extension of the lifetime of this remarkable machine for another decade.

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Powering the Proton Synchrotron

1 Introduction

The powering of the PS accelerator has been a challenge since the beginning. It combines high power demand and rapid cycles. Many innovative solutions had to be implemented in powering and its associated control to fulfil the requirements of the physicists. In the framework of modification and upgrade, the power converters have followed the developments in power electronics over the long life of the PS machine [1]. This section will present the history and major evolutions in the powering of the PS. The main focus will be on the evolution of the specific equipment used to power the magnets.

1.1 Powering the main magnets

One of the first challenges in the history of the PS was the design of the main magnets. This new magnet type combines the dipole and quadrupole magnetic fields in one magnet. The one hundred and one units are placed in series producing an impedance of 0.9 H / 0.3 Ω with a nominal current of 6 kA at 28 GeV/c.

To make the required cycles, a voltage of 5 kV has to be applied to the magnets resulting in a peak power demand of 30 MW during the ramp to the flat-top current. When the current returns to zero, the peak power is inverted. This type of cycle is repeated every ~3 s. In 1957 the electrical network was not able to accept such peak-power variation. The solution was to use a dedicated motor-generator set to supply the main magnets. The first rotating machine was from Brown Boveri (BBC, see Figs. 1–3).

For the PS upgrade in the 1960s, this machine was replaced by a new one able to double the power provided to the magnets [2]. The new power system, still in operation in 2009, was able to apply 10 kV during the ramp of the current to 6 kA. Siemens won the call for tenders in 1965. Since 1968, the PS has been powered by this new rotating machine. The principle of this type of power system is rather nice.
The system consists of an exchange of energy between the rotor and the magnets. The losses in the system (magnet resistive losses and power converter) are made up by the motor, while the magnetic energy of the magnet (12 MJ of a 26 GeV/c cycle) is exchanged with the rotor. A motor with a limited power (7 MW) drags a heavy rotor of a high-power generator (95 MVA). At the nominal speed of 1000 rpm, the kinetic energy of the rotor is 220 MJ. During the ramp of the current, the speed of the rotor will decrease when the motor reaches its maximum power. The rotor speed decreases by 4% for a 26 GeV/c cycle. The motor generator set is still the original one (shown in Figs. 4 and 5), except for the rotor which had to be replaced in 1977 due to degradation of the insulation material. This power system did more than 200 million cycles, which is exceptional. This long life can be explained by the excellent mechanical construction of the rotor and by the civil engineering around the rotating machine. To limit the vibration during the fast torque inversion (when the magnet current decreases), the rotating machine was set on a floating concrete platform placed on shock absorbers with springs. Any cycle can be felt by a human standing on this platform.

At the time, the rectifiers which transform the AC voltage to DC made use of mercury valves. In 1965, the thyristor was not considered a mature enough technology to be used for the new PS power system. The mercury valves were replaced by thyristors only in 1979 and these are still in operation.
A fire broke out on 29 August 1975 in the South Hall extension. The fumes of hydrochloric acid arising from burning PVC cable insulation damaged a lot of equipment including the old BBC machine which was dismantled afterwards (see Fig. 6). Nevertheless, the PS restarted after only four weeks. Also in 1975, a contractor’s employee, from the cleaning service, was killed in an electrical accident on the main power supply.

Many developments of this power system and its control system have occurred during these 40 years of operation. Principally, the protection and control systems went from relays to programmable logic controllers (PLC) and the excitation and motor control were replaced. From the operational point of view, the voltage controlled loop was replaced in 1998 by the Bdot (dB/dt) controlled loop and then in 2009 by the B controlled loop (see Fig. 7) [3]. The PS is the first CERN accelerator to be directly controlled in the magnetic field. Usually, the power converters are controlled in a current loop which generates problems for a rapid cycling machine with different energy levels due to hysteresis and saturation of the magnets. With the magnetic-field controlled loop, any cycle can be produced one after the other.

In 2005, a fan blade of the generator rotor broke and the first rotor kept as a spare was installed in the generator. Unfortunately, it broke after one month of operation due to the degradation of the insulation material. All the fan blades were replaced by Siemens on the second rotor and the rotating machine
restarted six weeks later (see Figs. 8–10). This event showed that the situation of the PS powering was fragile and, in 2007, the CERN Director-General R. Aymar approved the replacement of the existing power system with a new one as the PS has to operate for at least the next fifteen years. This new power system, called POPS (POwer for PS), will be put into operation in 2011 and is based on the same principle of energy exchange. For POPS, the energy is stored in capacitors and the power semiconductors are press-pack insulated-gate bipolar transistors (IGBT) [4].

1.2 Powering the pole face windings and the figure-of-eight loop

A second very particular system in the PS is the pole face windings (PFW) and figure-of-eight loop. These windings are placed inside the gaps of the PS main magnets (a scheme of the circuits and their installation are shown in Figs. 11 and 12) and are used to adjust the tunes ($Q_h, Q_v$) and the chromaticities ($\xi_h, \xi_v$) of the machine.

At first, the PFW windings were powered by rotating machines and then in 1978 these windings were replaced and powered by new thyristor converters. At this time, a new layout of the PFW was proposed to control it in 3- or 5-current mode. In the 3-current mode, the induced voltages of the main magnets are compensated by putting in series circuits with opposite induced voltages. In the 5-current mode, each circuit is independent. This mode is difficult to implement because the power converter has to reject the induced voltage of the main magnets. Only the 3-current mode was used until 2007. In 2005, a project for the replacement of the power converters was launched with the proposal to work in 5-current mode [5]. In 2007, the new switched-mode power converters were in service and the 5-current mode operational [6] (see Figs. 13 and 14). The advantage of the 5-current mode is to have five independent power converters controlling four machine parameters ($Q_h, Q_v, \xi_h, \xi_v$). This mode simplifies the adjustment of the machine working point and reduces the complexity for the accelerator operation [7].
At the same time, the figure-of-eight loop was powered by a new switched-mode power converter featuring 1 MW peak power (1600 A/600 V). It was the first time at CERN that this type of power converter was used for this level of power.

![Fig. 13: New PFW converters](image1)

![Fig. 14: Open PFW converter](image2)

2 Powering the auxiliary magnets

Another system which presented challenges for its powering was septum 57 (SMH57). This septum requires a high current (13 kA) in pulsed operation with a very low ripple. The chosen solution in 1968 was to associate a thyristor rectifier with transistors in linear mode in series. As there was no high-current transistor, the solution was to place more than seven thousand transistors in parallel, as presented in Fig. 15 [8]. All these transistors were placed on water-cooled plates creating a very nice-looking power converter mechanics. This power system was replaced in 2006 by a 10 kA LHC-type power converter [9]. This converter is identical to the ones used in the LHC but it was the first LHC converter to be put into operation for physics. This converter can be used with its limited voltage of 8 V because of the reduction of the DC cabling. Initially, the converter was in building 359 (PS ‘Centre Anneau’). The new converter is now located in building 356 (Fig. 16), closer to the septum magnet (see Fig. 17).

![Fig. 15: Old SMH57 converters](image3)
The last special system which will be described below is the gamma transition. These quadrupole magnets are used to change the optics of the machine when crossing the transition at 6.02 GeV/c. In the 1970s, these systems were powered by capacitor discharged converters [10]. In 2007, the PS started with a new circuit layout (four power converters for the doublets and two for the triplets, see Figs. 18 and 19) and with new power converters [11]. These converters have to generate a pulse current shorter than 100 ms, and for the doublets which are the most critical, the current has to be inverted from 500 A to −500 A in 500 µs. These two types of converter are switched-mode converters with pulse-width modulation control at 10 kHz. It was the first time that such converters could be used for such a function.

3 Conclusions
To conclude, the Proton Synchrotron machine was and still is a challenging machine to power. It requires innovative solutions to fulfil the physics requirements and during its long life the solutions followed the evolution of power electronics. It started with rotating machines, went to thyrister converters and transistor-regulated amplifiers and ten year ago went to switched-mode power converters with IGBT
semiconductors. The PS required a lot of developments for its powering and the story still goes on with
the new PS power system for the main magnets which will come into operation in 2011. Other
consolidation work is already planned or will be required in the coming years.

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1 Introduction

The CERN PS machine is the first synchrotron where transition had to be crossed. This occurred for the first time during the night of 24 November 1959, when a beam with an intensity of \( \approx 10^{10} \) protons per pulse was accelerated through transition up to the top energy of 25 GeV. However, between the day when the beam made its first turn, on 16 September 1959, and this famous night, more than two months elapsed, during which the machine specialists oscillated between a few triumphant moments and most of the time discouragement. It seemed as if the protons just did not want to be accelerated through transition. Eventually, the breakthrough, and the relief of all the PS early workers, came from Wolfgang Schnell and his famous Nescafé tin. The idea was to use the radial-position signal from the beam to control the RF phase instead of the amplitude. With this system, the sign of the phase had to be reversed at transition, and, in his haste, Schnell had built this part into a Nescafé tin, the only thing of the right size [1]. A similar phase-control system would then be used in the AGS a few months later, and in all the subsequent synchrotrons where transition had to be crossed.

The increase of energy in a medium energy proton synchrotron such as the CERN PS has two contradictory effects: (i) an increase of the particle velocity and (ii) an increase of the length of the particle trajectory. According to the variations of these two parameters, the revolution frequency evolves differently. Below a certain energy, called transition energy, the velocity increases faster than the length: the revolution frequency increases. Above transition energy, the opposite is true (at very high energy the velocity reaches the speed of light and does not change anymore): the revolution frequency decreases. At transition energy, the variation of the velocity is compensated by the variation of the trajectory, i.e., a variation of energy does not modify the revolution: this is the isochronous condition. The ratio between the beam energy at transition and the rest energy of the particles, called \( \gamma_t \) (relativistic mass factor at transition), is independent of the particle mass. Its value depends only on the machine optics and geometry and is given by

\[
\gamma_t = \frac{1}{\sqrt{\alpha_p}} \text{ with } \alpha_p = \frac{dC/C_0}{dp/p_0},
\]

where \( C_0 \) is the path length of a particle with nominal momentum \( p_0 \) on the reference orbit (the parameter \( \alpha_p \) is called the momentum compaction factor). In the case of a regular lattice, the value of \( \gamma_t \) is close to the horizontal tune, \( \gamma_t \approx Q_x \). This is the case in the PS where the horizontal tune is \( Q_x \approx 6.25 \) and \( \gamma_t \approx 6.1 \). In fact, owing to the transverse space-charge force, which modifies the tune of each individual particle, \( \gamma_t \) depends on the azimuthal beam density. Therefore all the particles do not cross transition simultaneously. However, this so-called Umstätter effect [2, p. 285] is usually negligible if the transition energy is much bigger than the injection energy. The chromatic non-linearities also produce a spread in the \( \gamma_t \) value of the particles, which is known as the Johnsen effect [2, p. 285] and can be reduced using sextupole families.

Crossing transition changes the sign of the slip factor (which relates the frequency spread in the beam to its momentum spread) given by

\[
\eta = \alpha_p - \frac{1}{\gamma_t^2} = -\frac{\Delta f/f_0}{\Delta p/p_0},
\]

where \( f_0 = \Omega_0/2\pi \) is the revolution frequency of a particle with nominal momentum on the reference orbit. As the small-amplitude (in one RF bucket) synchrotron angular frequency is given by

\[
\omega_s = \Omega_0 \left( -\frac{e\bar{V}_{RF}h\eta \cos \phi_s}{2\pi \beta^2 E_{total}} \right)^{1/2},
\]
where $e$ is the elementary charge, $\hat{V}_{RF}$ the peak RF voltage, $h$ the RF harmonic number, $\phi_s$ the synchronous phase, $\beta$ the relativistic velocity factor, and $E_{\text{total}} = \gamma E_{\text{rest}}$ the total energy of the synchronous particle having the rest energy $E_{\text{rest}}$, the sign of $\cos \phi_s$ has to be changed to keep $-\eta \cos \phi_s > 0$ and maintain the longitudinal phase stability. This means that, as a first consequence of transition crossing, the synchronous phase has to jump rapidly from $\phi_s$ to $\pi - \phi_s$.

2 Numerous unfavorable effects

2.1 Non-adiabatic region

Because of its dependence on $\eta$, the synchrotron frequency slows down near the transition region, and the adiabaticity condition

$$\frac{1}{\omega_s^2} \left| \frac{d\omega_s}{dt} \right| \ll 1,$$

where $t$ is time, is not satisfied anymore, which results in a non-adiabatic synchrotron motion. The non-adiabatic, also called characteristic, time is defined as [3]

$$T_c = \left( \frac{\beta^2 E_{\text{rest}} \gamma^4}{4\pi f_0^2 \hat{V}_{RF} |\cos \phi_s|} \right)^{1/3},$$

where $\dot{\gamma} = d\gamma/dt$. The physical meaning of it is that when the time is close enough to transition, the particle will not be able to catch up with the rapid modification of the bucket shape. It can be shown analytically that the bunch length reaches a minimum right at transition (see Fig. 1), which is not zero as could be deduced from the adiabatic theory (see also Fig. 3), while the momentum spread reaches a maximum and can become so large that it exceeds the available momentum aperture, causing beam losses [3–5]. As the product of the bunch length and momentum spread in Fig. 1 is not constant it can already be anticipated that the longitudinal phase-space ellipse is tilted near transition, as confirmed in Fig. 2 for the case of the PS nTOF bunch (see Table 1) [6], for which the non-adiabatic time is $T_c \approx 1.9$ ms. It is worth emphasizing that all the curves are symmetric with respect to the transition time.

2.2 Non-linear synchrotron motion

A second effect arises from the non-linearities in the slip factor. The first definition of the slip factor gives only the linear dependence of the orbit length on momentum offset. In the general case, it should be extended to [3]

$$C(\delta) = C_0 \left[ 1 + \alpha_0 \delta + \alpha_1 \delta + \alpha_2 \delta^2 + \ldots \right],$$
where $\delta = \Delta p/p_0$ and $\alpha_1, \alpha_2, \ldots$ are called the high-order components of the momentum compaction factor. Thus the slip factor $\eta$ now also becomes momentum-spread dependent and this raises another non-linear problem in synchrotron motion. To characterize this non-linear synchrotron motion, a non-linear time $T_{nl}$ can be defined as the time when the phase slip factor changes sign for the particle at the maximum momentum width of the beam [4]. Within $\pm T_{nl}$, some portions of the beam could experience unstable synchrotron motion.
2.3 Longitudinal mismatch

A third adverse effect comes from the longitudinal Space Charge (SC). As it is defocusing below transition and focusing above, the equilibrium bunch length below transition is longer than without SC, while it is shorter above (see Fig. 3, which has been obtained by solving numerically the longitudinal envelope equation near transition). Therefore there is an intensity-dependent step in the equilibrium bunch length at transition that leads to a longitudinal mismatch and subsequent quadrupolar oscillations when transition is crossed (see Fig. 4) [7]. If these bunch shape oscillations are not damped they will eventually result in filamentation and longitudinal emittance blow-up. It is worth mentioning that in the case of Fig. 4, the minimum of bunch length is not reached right at transition anymore, but after about one non-adiabatic time, i.e., after \( \approx 2 \) ms in the present case. Moreover, it should be noted that the same kind of mechanism appears also in the case of an inductive (only) longitudinal Broad-Band (BB) impedance (see Fig. 5). The difference with the case of SC, is that the equilibrium bunch length is now shorter (than without impedance) below transition and longer above transition, i.e., it is the opposite of SC (an inductive impedance can compensate the SC effect). Furthermore, the minimum bunch length in this case is reached right at transition. Measuring the evolution of the bunch length near transition in a machine (with both SC and BB impedance) can provide some information about the inductive part of the machine BB impedance as both effect just add (in fact subtract). However, as the BB impedance of a machine

![Fig. 3: Evolution of the full bunch length vs. time for the case of the adiabatic theory without space-charge, and for the non-adiabatic theory with and without space-charge in the static case (i.e., without crossing transition), applied to the PS nTOF bunch.](image1)

![Fig. 4: Evolution of the full bunch length vs. time for the case of the non-adiabatic theory with and without space charge in the dynamic case (i.e., crossing transition), applied to the PS nTOF bunch.](image2)
also has some real part, the previous analysis is valid only below a certain intensity threshold, as above it a longitudinal coherent instability will develop.

Fig. 5: Evolution of the full bunch length vs. time for the case of the non-adiabatic theory with (only) and without an inductive Broad-Band impedance (BB) in the dynamic case (i.e., crossing transition), applied to the PS nTOF bunch. Here a BB impedance of $Z_{BB}/n = j \times 20 \Omega$ has been used.

### 2.4 Head–Tail instability

A fourth impediment to transition crossing with high-intensity beams comes from the transverse head–tail instability. If the sign of the chromaticity (which is equal to $\approx -1$ for an uncorrected machine like the PS) is not changed (in both transverse planes) above transition, a (single-bunch) head–tail instability may develop [8–10]. This instability can be damped through Landau damping using octupoles, which introduce some amplitude detunings. This method was first used in the past to stabilize the PS beams. However, the better method of changing the sign of the chromaticities (and keeping them to small positive values, usually between $\approx 0.05$ and $\approx 0.1$) by acting on the optics with sextupoles was then adopted, and it has been a routine operation at the CERN PS for many years.

### 2.5 Negative mass and microwave instabilities

Finally, since the frequency spread of the beam vanishes at transition energy, there is no (or little, depending on non-linearities) Landau damping of the longitudinal and transverse microwave instabilities which can lead to emittance growth and/or huge beam losses [2, p. 119]. It was Lee and Teng who first pointed to the importance of the microwave (negative mass) instability [11].

### 3 Remedies

To avoid all the above unfavourable effects, it is appealing to eliminate transition crossing. Nowadays, an accelerator lattice can be designed in such a way that the momentum compaction factor $\alpha_p$ is negative (as for instance the CERN LEAR machine), and thus the beam never encounters transition energy. This is called the Negative Momentum Compaction (NMC) or the ‘imaginary $\gamma_t$’ lattice. The NMC modules were invented by Teng [12] and were later pushed by Trbojevic et al. [13].

On the other hand, the $\gamma_t$ value of existing machines such as the PS cannot be changed by a large amount without changing the ring geometry. Many compensation methods have been studied in the past [2, p. 285], such as for instance the ‘triple switch’ scheme [14], where the RF phase is switched back and forth three times to try and cure the bunch tumbling from the longitudinal SC (see Fig. 4). The idea is that after switching the phase from $\phi_s$ to $\pi - \phi_s$ at the transition time $x_1 = 0$, the bunch tries to adjust itself to fit the configuration of shorter bunch length. At some time $x_2$ before the undershoot, the phase...
is switched back to $\phi_s$. The bunch is then at an unstable fixed point and it will try to lengthen. The phase is finally switched back to $\pi - \phi_s$ at the time $x_3$, chosen such that the bunch lengthening cancels the undershoot thus damping out the oscillations and eventual filamentation. However, this method has not been successfully implemented in the CERN PS because it does not work at high intensity, by principle, due to the spread in $\gamma_t$: the required precision on the different timings $x_{1,2,3}$ can be achieved for a group of particles but not for all of them. Moreover, the negative mass instability (and probably also the head–tail instability) was still a pending issue. Note that a feedback device can also be used to damp out the longitudinal quadrupolar oscillations, but as was seen previously, many other effects are detrimental.

3.1 $\gamma_t$ jump

If transition crossing cannot be avoided, the $\gamma_t$ jump is the only (known) method to overcome all the intensity limitations resulting from the above-mentioned phenomena. It consists in an artificial increase of the transition crossing speed by means of fast pulsed quadrupoles. The idea is that quadrupoles at non-zero dispersion locations can be used to adjust the momentum compaction factor $\alpha_p$.

The change in momentum compaction (called $\gamma_t$ jump) depends on the unperturbed and perturbed dispersion functions at the kick-quadrupole locations. These schemes were pioneered by the CERN PS group [15–17]. Such a $\gamma_t$ jump scheme makes it possible to keep the beam at a safe distance from transition, except for the very short time during which the transition region is crossed at a speed increased by one or two orders of magnitude (see Fig. 6). The required jump amplitude and speed depend on the beam intensity. In the present case of the PS, the transition crossing speed without the $\gamma_t$ jump is $\dot{\gamma} = 49.9 \text{ s}^{-1}$ whereas the effective crossing speed $\dot{\gamma}_{eff} = \dot{\gamma} - \dot{\gamma}_t$ in the presence of the $\gamma_t$ jump becomes $\approx 50 \dot{\gamma}$, i.e., about 50 times faster than without jump. The amplitude of the $\gamma_t$ jump is $\Delta \gamma_t \approx -1.24$ and the jump time is $\Delta t_{jump} \approx 500 \mu$s (see also Fig. 7).

Looking at Fig. 4 clearly reveals why an asymmetric jump was proposed in the past [16] to damp the longitudinal quadrupolar oscillations arising from the SC-induced mismatch: the idea is to jump rapidly from an equilibrium bunch length below transition to the same value above. The amplitude of the $\gamma_t$ jump is defined by the time between the same equilibrium bunch length below and above transition. The minimum amplitude of the jump corresponds to the case represented with the dashed blue line starting right at transition. However, in this case the initial longitudinal phase-space ellipse is tilted (see Fig. 2), while the final one is almost not, which is not ideal. One might want therefore to start the jump earlier, when the longitudinal phase space is almost not tilted, for instance at $x = -2$, which requires a larger jump (see the dashed orange line in Fig. 4). Finally, taking into account the longitudinal and transverse microwave instabilities, whose intensity thresholds are proportional to $|\eta|$ [18], even larger jumps might be required. The evolution of $\eta$ near transition crossing with the present PS $\gamma_t$ jump is depicted in Fig. 7. As can be seen, a minimum value of $|\eta_{min}| \approx 5 \times 10^{-3}$ is always obtained except for the very short time
of the jump, i.e., during $\Delta t_{\text{jump}} \approx 500 \mu s$. In the absence of the $\gamma_t$ jump, $|\eta|$ would have been smaller than $|\eta_{\text{min}}|$ during $\approx 25$ ms.

![Fig. 7: Evolution of $\eta$ near transition crossing with the present PS $\gamma_t$ jump (upper), and zoom (lower)](image)

3.2 Review of the PS $\gamma_t$ jump schemes [19]

A non-zero tune shift was tolerated at the CERN PS between 1969 and 1973 with the so-called $Q$-jump scheme [15,16], using a set of six quadrupoles more or less regularly spaced around the ring with identical strengths and polarities. A tune change of $\Delta Q_x = 0.25$ was required to obtain $|\Delta \gamma_t| = 0.3$.

In 1970, a scheme was proposed for the FNAL Booster using twelve regularly spaced quadrupoles with equal strengths but alternating polarities [20], yielding $|\Delta \gamma_t| = 1$ at the expense of only $\Delta Q_x = 0.1$. It was again Teng who pointed out that one can/should change $\gamma_t$ without changing $Q_x$, which led to the birth of the $\gamma_t$ jump. The idea was enthusiastically taken up by Hardt and collaborators and the scheme for the PS conceived.

Since 1973, a large $\gamma_t$ jump ($|\Delta \gamma_t| \approx 1.2$) with (almost) zero tune shift is obtained in the PS by grouping 16 quadrupoles (with two strengths $\pm K1$ and $\pm K2$) together in doublets. The use of quadrupole pairs separated by $\pi$ in the betatron phase advance (called $\pi$-doublets) gives zero tune shift and avoids crossing non-linear betatron resonances. Note that during the $\gamma_t$ jump the dispersion function has the tendency to increase. This can lead to an increase of the horizontal beam size and a subsequent beam loss. The optical design of a $\gamma_t$ jump scheme should therefore aim at a large $\Delta \gamma_t$, while keeping the maximum dispersion and betatron functions below reasonable values, and the tune shift should be as small as possible. Transition crossing with a $\gamma_t$ jump has become a routine operation at the CERN PS, where the present scheme is shown in Fig. 8 [21, 22]. However, even in the presence of this $\gamma_t$ jump, together with the proper shift of the synchronous phase and change of the sign of both chromaticities when transition is crossed, a fast vertical single-bunch instability is observed with the nTOF bunch when no longitudinal blow-up is applied before transition (see Fig. 9) [18, 23]. Figure 9 reveals that the head
of the bunch (on the left) is stable and only the tail is unstable in the vertical plane. The particle loss in the tail of the bunch can be seen from the hole in the bunch profile. The remedy that was found and applied since then is to increase the longitudinal emittance from $\approx 1.5 \text{ eV s}$ to $\approx 2.1 \text{ eV s}$ for an intensity of $\approx 7 \times 10^{12} \text{ p/b}$ [23]. However, this can only be done because the longitudinal emittance is not a critical parameter for this beam. If one would have no margin in the longitudinal emittance the $\gamma_t$ jump should be improved with a larger amplitude and an increased speed. A possible alternative could be to not only change the sign of the chromaticities as proposed in Refs. [8–10] for (slow) head–tail considerations but to correlate the variation of the chromaticity with the one of the slip factor, for (fast) head–tail considerations this time [24].

**Fig. 8:** Present transition crossing scheme in the PS

**Fig. 9:** Single-turn signals from a wideband pick-up in the CERN PS in 2000 with the nTOF bunch. From top to bottom: $\Sigma$, $\Delta x$, and $\Delta y$. Time scale: 10 ns/div.
4 Lessons learned from the PS

Since the bunch length becomes naturally very short near transition, operating synchrotrons under an isochronous or quasi-isochronous condition has been proposed to achieve very short bunches in numerous future projects. These designs require both an accurate control of the first high-order component of the momentum compaction factor $\alpha_1$ (using sextupoles) to provide the necessary momentum acceptance and effective ways to damp all the collective instabilities.

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RF gymnastics

1 Introduction

During its remarkably long life as a high performance accelerator, the PS has demonstrated an outstanding flexibility to adapt to the varying and continuously more demanding needs of physics. In many cases this was made possible by innovative RF gymnastics, manipulating the RF parameters to change longitudinal beam characteristics in ways that had not even been envisaged by the initial designers. Besides the importance of the quality and performance margin of the major long-lived equipment, the continuity of demand, effort, and support played a crucial role. The systematic programming of upgrade projects led to regular machine experiments which allowed for a detailed understanding of the accelerator limitations and to in-depth training of accelerator staff. Corrective measures could then be designed and implemented, increasing the performance level and the potential of the whole accelerator.

Time and space do not allow for an exhaustive description of all the gymnastics which have been implemented (and even less for the ones only tested!) since the PS was started. More modestly, this section is focused on the description of representative examples drawn from the period 1970–2000, and used for the proton–antiproton programme, for LEP, and finally for the LHC.

The link is made with the progressive improvement and sophistication of the high-power and low-level RF systems summarized in Tables 1–3, which rendered the most recent gymnastics feasible.

2 The infancy of RF gymnastics in the PS (1959 ~ 1975)

When the PS started in 1959 it was equipped with 16 ferrite-loaded cavities operating at the same frequency, on harmonic \( h=20 \) [1]. A programmed RF source was used for beam capture and the early part of the cycle. In the course of acceleration, a phase loop and a radial loop were activated to avoid longitudinal dipolar oscillation and keep the beam centred in the vacuum chamber. For unexplained reasons, probably hardware-specific, the first attempt with a radial loop acting upon the total acceleration voltage, by modulating the phase difference between the cavities divided in two groups [2], was not successful. The operation of the first beam control allowing for acceleration of a proton beam through transition in an alternating-gradient synchrotron was finally brilliantly demonstrated on 24 November 1959 [3] using a radial loop acting upon the accelerating phase [4].

This RF system was later used for basic RF gymnastics like bunch rotation, triggered by a fast longitudinal mismatch (typically a voltage step), and debunching, obtained by a reduction to zero of the RF voltage at constant B field (‘flat top’) [5].

The CERN Improvement Programme, launched in 1965, set the challenge at a ten-fold increase of the beam intensity (from \( 10^{12} \) to \( 10^{13} \) protons/pulse) thanks to injection at 800 MeV from an additional four-ring synchrotron, the PS Booster (PSB). The development of a new RF system was hence required; this replaced the initial one in 1972 and became the ‘workhorse’ of the PS [6]. High-voltage relays were installed on all cavities to minimize their impedance when not in use by short-circuiting their gaps.

The decision to build the SPS, taken in 1972, significantly increased the requirements on the PS, needing the reliable delivery of a high-intensity beam (>\( 10^{13} \) p/p) at 10 GeV/c, bunched at the SPS frequency of 200 MHz. In a first step, the beam has to be debunched on the high energy flat top to remove its \( h=20 \) time structure and make it continuous. In a second step, rebunching has to take place, which requires a 200 MHz RF system. Eight cavity/amplifier assemblies were ultimately installed [7].

A sketch for one cavity is shown in Fig. 1. Each cavity is equipped with three damping lines terminated in 50 \( \Omega \) loads which allow their Q and impedance to be reduced by more than an order of magnitude when they are not in use (in practice most of the cycle). Before applying RF power and getting voltage across the gap, damping is suppressed by short-circuiting the resistive loads with PIN
diodes. When driven by the RF amplifier, the equivalent impedance of the cavity is minimized by adjusting the length of the feeder line.

Tests with beam quickly revealed an unacceptable longitudinal blow-up during debunching, later diagnosed as due to a longitudinal microwave instability [8]. It was soon realized, however, that the newly installed 200 MHz cavities could provide a mitigation measure. Driving a few of them with a phase modulated signal at an harmonic of the accelerating RF frequency, the longitudinal emittance of the bunches could be blown up in a clean and controlled way during the early part of the acceleration cycle to keep the beam below the instability threshold [7].

To increase the number of protons per pulse beyond $10^{13}$ p/p, numerous phenomena were encountered and diagnosed [9]. Concerning the $h=20$ RF cavities, feedforward was implemented to reduce their apparent impedance and allow operation at reduced voltage [10], as required for a matched longitudinal capture at injection and for quasi-adiabatic debunching at 10 GeV/c.

3 SPS and the proton–antiproton programme

The proton–antiproton programme, officially starting in 1979, made difficult demands on the existing accelerators, and especially on the PS:

- for production, because the flux of antiprotons is directly proportional to the proton intensity on target, and the duration of the proton pulse cannot exceed the revolution period of the Antiproton Accumulator (AA) or approximately one quarter of the PS;
- for acceleration and transfer of antiprotons to the SPS, because of the large bunch emittance and the need to prepare it for capture in a single 5 ns long SPS bucket.

3.1 RF gymnastics for antiproton production

Multiple techniques were tried to maximize the proton flux on the AA target by recombining beams from the PSB. Vertical recombination at injection worked, but was abandoned because of the excessive beam loss due to the large transverse emittance of the recombined beam in the PS.

Longitudinal recombination using ‘slip stacking’ was attempted between beams of two PSB rings with slightly different energies [11]. The principle is sketched in Fig. 2. Two different RF frequencies $f_1$ and $f_2$, corresponding to the energies of the PSB beams, are simultaneously applied in the PS, splitting the C10 RF cavities into two groups of five. With a frequency difference $f_2 - f_1 \approx 5f_s$, where $f_s$ is the synchrotron frequency in the centre of an unperturbed bucket of one family, two families of buckets coexist which keep the beam bunched and slip past each other because of their
frequency difference. Therefore the separation between the two sets of bunches decreases until they are superimposed in azimuth. If the RF is then suddenly switched to the average frequency \((f_1 + f_2)/2\) on both groups and the voltage increased by a large enough factor, pairs of bunches can be recombined in the corresponding large buckets.

\[
h_0 f_{REV} \quad +\Delta f \quad + \quad -\Delta f \quad -
\]

2 n bunches separated in energy and azimuth

**Fig. 2:** Slip stacking

Capture on \(h_0\) of 2 bunches/bucket

Figure 3 shows a mountain range display of a typical result with a total injected intensity of \(10^{13}\) p/p. Feedforward beam loading compensation was essential for a correct RF operation at such a high intensity. However, this process also suffered from excessive beam loss, probably due to the presence of a large proportion of particles with very large emittances after filamentation and to limited acceptances at low energy.

**Fig. 3:** Mountain range display of longitudinal recombination by slip stacking at 800 MeV

Hence a similar but much more sophisticated process was successfully implemented at 25 GeV and used until 1989. Again two RF groups are necessary. Combining four cavities operating at the same peak voltage \(\hat{V}\), with two cavities on \(h=20\), one on \(h=19\) and one on \(h=21\), each of these groups generates a 100% amplitude modulation at the revolution frequency \(\omega/2\pi\) of a carrier on \(h=20\). Indeed:

\[
V_{total} = \hat{V} \cos(19\omega t) + 2\hat{V} \cos(20\omega t) + \hat{V} \cos(21\omega t)
\]

\[
\Leftrightarrow V_{total} = 2\hat{V} \cos(20\omega t) \cdot [1 + \cos(\omega t)]
\]

\[
\text{Carrier on } h=20 \quad \text{Peak amplitude modulation at the revolution frequency}
\]

With a proper phasing of the different harmonics with respect to the beam, the maximum amplitude of a group can be centred onto a set of five bunches. Starting with two sets of bunches diametrically opposite in the PS, each set ‘sees’ a maximum voltage from its RF group and a minimum from the other one. This situation is illustrated in Fig. 4. Separate beam controls can hence handle both sets separately, giving them a difference in energy, and ‘slip stacking’ begins.
In that case there is no need to recapture pairs of bunches in the same bucket: the beam is simply ejected onto the target when both beam sets are azimuthally superimposed. The mountain range display in Fig. 5 shows a typical result at $10^{15}$ p/p.

The practical implementation of this process was rather complex. Controls and low-level RF had to provide all the necessary signals, and the ferrite cavities had to operate in three groups tuned at different frequencies and with different voltage programmes. Gap relays were momentarily activated on the four cavities used on h=19 and h=21 at the beginning of the flat top to reduce their impedance when they were changing tune.

Another strongly non-adiabatic technique was successfully applied for a few years, in combination with the previous one. With a specially designed RF deflecting dipole in the transfer line between the PSB and the PS, bunches of two PSB rings were interlaced (Fig. 6) so that each PS bucket captured two of them [12]. This ‘funnelling’ process is intrinsically imperfect, both in the transverse phase plane because all particles in a bunch do not get the same deflection, and in the longitudinal phase plane because capture is strongly non-adiabatic, triggering an intense filamentation and a large blow-up. An acceptable operational compromise was nevertheless found — adjusting the distance between bunches to optimize the overall result and minimize beam loss (Fig. 7).
Fig. 6: ‘Funnelling’ with an RF dipole in the PSB–PS transfer line

Fig. 7: Average and peak beam current during a complete acceleration cycle with the RF dipole

The needs of the upgrade programme launched in 1983 and based on the Antiproton Collector (ACOL) could, however, not be met with the previous methods of preparation of the antiproton production beam. Bunch rotation of the antiproton bunches entering ACOL was indeed foreseen, to quickly reduce their energy spread by a large factor, without resorting to any cooling. Hence the proton bunches had to have a reproducible and as short as possible bunch length. A two-step quasi-adiabatic process was therefore proposed, using bunch merging and batch compression [13].

Merging pairs of bunches is obtained at constant B field by changing the RF voltage seen by the beam from h=20 to h=10, with the h=10 stable phase centred in the middle of the h=20 buckets (Fig. 8).
If the rate of voltage changes is slow enough, the time structure on h=20 disappears progressively, being replaced by an h=10 periodicity. This process can then be quasi-adiabatic and preserve longitudinal emittance. It was successfully implemented on an intermediate flat top (3.57 GeV/c), dividing cavities into two groups, and adiabaticity was indeed obtained, as illustrated in Fig. 9.

Fig. 9: Mountain range display of merging at 3.57 GeV/c

After acceleration on h=10 up to the 25 GeV flat top, the five bunches resulting from merging still occupy one half of the PS circumference. Batch compression is then applied to concentrate them in one quarter of the circumference. This is obtained by increasing the harmonic of the RF seen by the beam in five steps of two units, to finally cover the range from h=10 to h=20. At each step, two RF groups are active, one on \( h_0 \) and the other on \( h_0 + 2 \). The voltage on \( h_0 \) is slowly ramped down to 0, while the voltage on \( h_0 + 2 \) is increased to maximum. Phasing is such that bunches converge towards the centre of the batch. The principle of such a step is shown in Fig. 10, and the complexity of the practical implementation of the complete process is illustrated in Fig. 11.

Fig. 10: Principle of a single step of batch compression

Fig. 11: Voltage and harmonics of the three groups of cavities during batch compression (h=10 \( \rightarrow \) h=20)
In practice, cavities have to be split into four groups, operating at three different frequencies: one group of four cavities is at 0 V, while three other groups of two cavities are controlled as in Fig. 11. The low-level RF has to be able to provide all these harmonics with the correct phasing. Even though gap relays are repeatedly activated to short-circuit gaps when cavities are at 0 V, the voltage induced by the beam when cavities are at low voltage is a major source of imperfection. It was impractical to implement feedforward beam loading compensation in that context. An upgrade programme was therefore launched for reliably reducing the impedance of all cavities, independently of their tune, implementing a fast RF feedback [14][15]. That implied the modification of the high-power amplifier of every cavity (Fig. 12). Beam performance in these conditions was much better than with funneling by means of the RF dipole. A typical result at $1.6\times10^{13}$ p/p is shown in Fig. 13.

![Fig. 12: Fast RF feedback on a PS ferrite-loaded cavity](image1.png)

However, transient beam loading remained a source of imperfection because the equivalent filling time of the feedback-equipped cavities is of the order of 300 ns, which makes the first bunches experience a different beam-induced voltage than the last ones. This was addressed with a one-turn delay feedback [16] which further decreased impedance by a factor four in a limited bandwidth of ±3 revolution frequency harmonics around the cavity tune. The reduction of transient beam loading on a cavity with five bunches on h=20 (end of the batch compression process) is shown in Fig. 14.

![Fig. 13: Mountain range display of batch compression (h=10 → h=20) at 25 GeV](image2.png)

![Fig. 14: Beam-induced voltage in a cavity without (top) and with (bottom) one-turn delay feedback](image3.png)
All these measures and renewed low-level electronics are nowadays combined to provide the performance regularly achieved for the Antiproton Decelerator (Fig. 15).

Fig. 15: Mountain range display of batch compression ($h=8 \rightarrow h=20$) at 25 GeV for the AD

3.2 RF gymnastics for antiproton acceleration

The main difficulty with the acceleration of antiprotons in the PS resulted from the large longitudinal emittance of the bunch. To maximize the RF bucket acceptance, $h=6$ was therefore used as the lowest harmonic number compatible with the tuning range of the ferrite cavities. However, it remained insufficient for a ‘conventional’ non-adiabatic bunch rotation to provide a bunch shorter than 5 ns at 25 GeV that could fit into a single 200 MHz RF bucket in the SPS. That was solved with a more involved gymnastics combining RF on $h=6$ and $h=12$ and varying amplitudes and phase during bunch rotation to linearize the focusing voltage only over the instantaneous length of the bunch (Fig. 16). Synchronization with the SPS revolution frequency to about 0.5 ns remained a demanding challenge because of the large voltage and phase transients due to the voltage and phase manipulations required by the bunch rotation gymnastics.

Fig. 16: Bunch at end of bunch rotation on $h=6$ (left), $h=6+12$ (right) at 25 GeV
For LEAR, the PS had for the first time to decelerate beam from 3.57 GeV/c down to 609 MeV/c. To stay within the tuning range of the ferrite cavities, the RF system had to operate on h=10 instead of h=6. To deal with very low bunch intensities, the beam control was based on an accurate frequency programme and an AC-coupled phase loop, without radial loop.

4 Electrons and positrons for LEP

In the context of LEP, the suggestion was made in 1980 [17], and quickly adopted, to modify the SPS and PS as electron–positron injectors. The PS was charged with accelerating the electrons and positrons provided by the EPA from 500 MeV up to the energy of 3.5 GeV at which they could be transferred to the SPS [18]. A new RF system with two cavities operating at 114 MHz was therefore installed in 1986 [19]. To preserve the capability to accelerate high-intensity proton beams, these cavities were equipped with HOM dampers and short-circuited by copper bars moved during the dead-time between lepton and proton cycles (Fig. 17).

Contrary to most other lepton synchrotrons where damping times are short so that bunches reach their equilibrium size soon after injection, the low radiation loss in the PS made bunches keep a ‘memory’ of the early part of the cycle. Special gymnastics were implemented taking into account this effect [18] to tailor the bunches to the needs of the SPS by the combined action of RF and of two Robinson wigglers controlling the damping partition numbers. Without these wigglers the horizontal betatron oscillations would be antidamped (J_x = -1) as the PS has a combined-function lattice [20]. One scenario was to use the 114 MHz system alone on h=240: at the end of acceleration, bunches needed ‘expansion’ to the proper emittance which was obtained by reducing the damping partition number J_x by 3.8 units. Another scenario was based on acceleration with the ferrite cavities on h=16 or h=8: at 3.5 GeV, bunches needed compression which was obtained by a quasi-adiabatic increase of voltage at 114 MHz and a small reduction of J_x by 0.9 unit. The scenario finally preferred in operation used the same J_x as in the expansion case, but it provided bunches twice as long, focusing the beam with one quarter of the RF voltage at 114 MHz and accelerating it on the crest of a 200 kV, h=8 RF at 3.8 MHz.

The two 114 MHz cavities were removed after the end of LEP, in December 2000.
5 Protons for the LHC

The luminosity goals in the LHC require proton beams with a brightness exceeding the existing capabilities of the Linac2–PSB–PS–SPS cascade. An upgrade was therefore launched [21] based on three main ingredients: (i) division by 2 of the beam brightness in the PSB by the use of two pulses to fill the PS, (ii) division by 1.5 of space-charge tune spread in the PS by increasing the injection energy to 1.4 GeV, and (iii) suppression of the transition bottleneck in the SPS by injecting at 25 GeV. The longitudinal stacking of two PSB batches in the PS is made possible by having a single bunch in each PSB ring, operating the RF on h=1, and changing to the beam transfer scheme sketched in Fig. 18. The harmonic number also had to be changed in the PS, and the initial choice was for h=8.

![Fig. 18: PSB–PS beam transfer before and after modification for the LHC](image)

Single-batch filling of the PS remains possible, with two bunches per PSB ring (RF on h=2) and RF on h=8 in the PS. Once implemented at the beginning of 1998, all beams delivered by the PS had to be modified to operate with new harmonic numbers and revised gymnastics [22]. In particular, the inverse process to merging pairs of bunches, splitting bunches into two, became routine operation [23].

Beyond beam brightness, the PS also has to give its final time structure to the proton beam, for example transforming it into a 40 MHz bunch train (25 ns spacing between bunches) in the nominal case. Debunching on h=16 followed by rebunching on h=84 (40 MHz) at 25 GeV was the process initially foreseen for that purpose (Fig. 19) [21]. A fixed-tune 40 MHz RF system was therefore built and installed in the PS in 1996 [24]. It was complemented in 1998 with an 80 MHz RF system [25] to allow for the bunch rotation necessary to reduce bunch length down to 4 ns, as required by the SPS. All of these cavities are equipped with a telescopic mechanical short-circuit which almost perfectly closes their gaps when they are not in use (Fig. 20). Although opening and closing take approximately one second, movements are planned to take place only a few times per day, immediately before and after filling the LHC. In addition, a fast RF feedback is implemented on both systems to minimize impedance when the gap is open.
However, it quickly proved impossible to achieve the necessary emittance and bunch length after recapture [26], even after the removal of the 114 MHz cavities. A new process was then proposed [27] which avoids debunching, provides a large flexibility in the beam time structure, and allows for the preservation of a gap where the extraction kicker can rise, avoiding particle loss. It is based on multiple successive splittings, including one splitting into three (‘triple splitting’). In a slight variant with respect to the scheme initially foreseen and sketched in Fig. 18, six bunches delivered in two batches by the PSB are captured on harmonic $h=7$ in the PS. Each bunch is then split into 12 in two steps, as shown in Fig. 21.
Fig. 21: Multiple splitting scenario for the nominal bunch distance of 25 ns for the LHC

Triple splitting is started as soon as the second batch is received, which provides 18 consecutive bunches on $h=21$. The beam is then accelerated on this harmonic up to the 25 GeV flat-top, where each bunch is twice split into two to give 72 consecutive bunches on $h=84$. This leaves a 320 ns gap in the bunch train for the rise-time of the ejection kicker. Triple splitting requires three simultaneous RF harmonics ($h=7$, $h=14$ and $h=21$) which can be provided by the ferrite cavities divided in three different tuning groups. The relative phases between harmonics are such that a stable phase on $h=21$ and an unstable phase on $h=14$ coincide with the stable phase on $h=7$. Starting with $h=7$ alone, the effect of increasing the voltages on $h=14$ and $h=21$ is to flatten the bunch ($t=7$ ms in Fig. 22). In phase space, two new stable points emerge close to the initial one, encircled by three buckets. Using numerically determined laws of variation, these three areas are kept equal throughout the process so that layers of increasing emittance in the initial bunch are progressively peeled off and accumulated evenly into the three new buckets. Provided that the rate of change of the voltages is sufficiently slow, the particles of the initial bunch are gradually captured in the new buckets whose area grows as the voltage decreases on $h=7$ and increases on $h=21$ ($t=14$ ms). Three equal bunches are finally obtained, each with the same distribution of particle density as the initial one ($t=25$ ms). The low-level RF generates the different harmonics, precisely controlling their relative phases. A beam phase loop is active throughout the process, controlling the sum of all harmonics whose relative phase is rigidly fixed. A typical result at the nominal intensity for the LHC is shown in Fig. 23(a).
Quadruple splitting [Fig. 23(b)] at 25 GeV is obtained by cascading two double-splitting steps. Three groups of cavities are also employed, operating on harmonics 21, 42 and 84 respectively. Getting voltage on $h=42$ required the installation of an additional RF system operating at 20 MHz [28].

![Fig. 23: Mountain range displays when generating a bunch train at the nominal intensity for the LHC, with the nominal 25ns bunch distance](image)

The relative phase between harmonics is rigidly fixed and a beam phase loop suppresses collective oscillations with respect to the RF sum voltage. Simulation predicts that the longitudinal emittance will not increase, and this is also observed in practice, as long as the beam is kept stable at the beginning and during the process. At the end of the splitting process at 25 GeV, bunches are rotated by raising quickly to full voltage, first the 40 MHz ($h=84$) system, then, 180 $\mu$s later, the 80 MHz ($h=168$) system [Fig. 24(a)]. The resulting bunch [Fig. 24(b)] is then ready for transfer to the SPS.

![Fig. 24: Rotation of a nominal bunch for the LHC at 25 GeV](image)
The combination of the successive splittings from \( h=7 \) to \( h=84 \) with this bunch rotation provides the nominal bunch emittance and length, while avoiding beam loss at PS ejection during the rise-time of the ejection kicker. It has been adopted as the basic operational scheme for the generation of the proton beam for the LHC.

An additional advantageous feature is that it easily allows for having gaps in the bunch train by sending no beam from certain PSB rings, or for having a 50 ns time interval between bunches by removing the last splitting step at 25 GeV.

Using the same kind of gymnastics with different sets of harmonics, a 75 ns time interval between bunches is also available. Starting from six bunches on \( h=7 \), as in the nominal case, two splittings into two are applied. The first one is at injection energy (1.4 GeV), giving 12 bunches on \( h=14 \) which are then accelerated on that harmonic up to high energy. The second splitting takes place at 25 GeV, giving 24 bunches on \( h=28 \) (13 MHz). The whole process is sketched in Fig. 25. The RF system that provides voltage at this frequency is the same one that can operate at 20 MHz [28]. This scheme is also operational and typical results are shown in Fig. 26. Beam can even be delivered every 2.4 s by the PS, using a single batch from the PSB.

(a): Splitting in two at 1.4 GeV  
(b): Splitting in two at 25 GeV

**Fig. 25:** Generation of a bunch train with 75 ns between bunches

**Fig. 26:** Mountain range displays when generating a bunch train at the nominal intensity for the LHC, with a 75 ns bunch distance
6 Heavy ions for the LHC

For ions heavier than protons, the beam for the LHC does not pass through the PSB. It is prepared in the Low Energy Ion Ring (LEIR) which sends it directly to the PS. The role of the PS is to accelerate and adapt the beam from LEIR to the needs of the downstream machines, imposing the 100 ns bunch spacing required by LHC experiments and the bunch charge, bunch length, and bunch frequency which are acceptable to the SPS.

For that purpose ‘batch expansion’, the reverse process to ‘batch compression’ applied to the AD production beam, is applied twice at an intermediate energy, separated by a splitting into two [29]. Starting from two LEIR bunches captured and accelerated on $h=16$ up to a magnetic plateau, the bunch spacing is increased during the first batch expansion by progressively decreasing the harmonic number from $h=16$ down to $h=12$. Bunches are then split into two on $h=24$. The correct spacing between bunches is finally obtained by a second batch expansion decreasing the harmonic number to $h=21$. This full process was demonstrated experimentally in August 2009 (Fig. 27).

Additional gymnastics take place at top energy (86.7 Tm), after acceleration on $h=21$ through transition. First, the four bunches in consecutive $h=21$ buckets are transferred from the ferrite cavity system to the fixed-frequency 80 MHz one ($h=169$), to precisely set a distance between bunches that corresponds to SPS buckets. Optionally, if space charge proves problematic at injection energy in the SPS, bunches could be split into two to fit into pairs of consecutive 200 MHz buckets. The final bunch pattern sees 5 ns between the ‘bunchlets’ of each pair and 95 ns between the nearest neighbours of consecutive pairs.

![Batch expansions and splitting of lead ions](image)

Fig. 27: Batch expansions and splitting of lead ions

7 Summary

The PS has progressed remarkably in capability since its start, fifty years ago. It is nowadays equipped with a total of five multi-cavity RF systems (Table 1) which provide the means to cover a broad range of harmonic numbers at high beam intensity (Table 2). The low-level RF and the overall
control set-up (timings, voltage waveform, etc.) are of an unprecedented complexity (Table 3). It took fifty years of dedicated efforts to gain the experience and knowledge required to design and master such an involved set-up. With its sets of gymnastics in regular use, the PS can reasonably be claimed to have today the most sophisticated and complex mode of RF operation ever implemented in a synchrotron.
### Table 1: High power RF systems

| Name      | Cavity type                                  | Frequency range | Tuning                                                  | Number of cavities | Voltage / cavity | RF power / cavity | Date of installation | Date of removal |
|-----------|----------------------------------------------|-----------------|--------------------------------------------------------|--------------------|------------------|--------------------|----------------------|-----------------|
| Marelli   | Ferrite-loaded coaxial resonator             | 2–10 MHz        | Fast over the full range (ferrite bias)                | 16                 | 8 kV             | > 5 kW             | 1959                 | 1973            |
| C10       | Ferrite-loaded coaxial resonator             | 2.6–9.5 MHz     | Fast over the full range (ferrite bias)                | 11                 | 20 kV            | 90 kW              | 1972                 |                 |
| C200      | Pill-box with ceramic gap                    | 200 ± 0.5 MHz   | Slow (piston with stepping motor) on all cavities + Fast (piston with linear actuator) on two cavities | 8                  | 30 kV            | 20 kW              | 1977–1979            |                 |
| C114      | Evacuated with nose cones                    | 114.511 MHz     | Slow (piston with stepping motor)                      | 2                  | 500 kV           | 50 kW              | 1986                 | 2001            |
| C40       | Evacuated with capacitive loading            | 40.055 MHz      | Slow (piston with stepping motor)                      | 2                  | 300 kV           | 400 kW             | 1996                 |                 |
| C80       | Evacuated with capacitive loading            | 80.100 MHz      | Slow (piston with stepping motor)                      | 3                  | 300 kV           | 400 kW             | 1998                 |                 |
| C20       | Ferrite-loaded coaxial resonator             | 13.3 + 20 MHz   | Slow (HV switch) + fast over limited range (ferrite bias) | 2                  | 20 kV            | 50 kW              | 2002                 |                 |
| Starting year | Operation | Main users | RF systems running simultaneously |
|---------------|-----------|------------|----------------------------------|
|               |           |            | Systems | Harmonics | Freq. groups | Ampl. groups |
| 1959          | Acceleration on h=20 | Experiments ISR | 16 × Marelli cavities | h= 20 | 1 | 1 |
| 1978          | Controlled longitudinal blow-up | High intensity users | 1–4 × C200 cavities | h= n × 20 (21<n<24) | 1 | 2 |
| 1978          | Debunching on h=20 + rebunching on h=420 | SPS fixed target | 10 × C10 cavities | h= 20 | 1 | 3 |
|               |           |            | 4–8 × C200 cavities | h= 420 | 1 | 1 |
| 1978          | Longitudinal recombination at 25 GeV | AA | 10 × C10 cavities | h= 19 + 20 + 21 | 3 | 3 |
| 1979          | Acceleration on h=20 to 3.5 GeV/c and on h=6 to 25 GeV + bunch compression | SppbarS | 10 × C10 cavities | h= 20 + 6 + 12 | 3 | 3 |
| 1981          | Acceleration on h=20 to 3.5 GeV/c and deceleration on h=10 to 609 MeV/c | LEAR | 10 × C10 cavities | h= 20 + 10 | 2 | 2 |
| 1985          | Bunch pair merging and batch compression | AC | 10 × C10 cavities | h= 10 + 12 + 14+ 16 + 18 + 20 | 4 | 4 |
| 1986          | Acceleration on h=16 + 240 (e+/e-) | LEP | 10 × C10 cavities | h= 16 | 1 | 1 |
|               |           |            | 2 × C114 cavities | h= 240 | 1 | 1 |
| 1998          | Acceleration on h=8 to 3.57 GeV/c + splitting to h=16 + acceleration on h=16 to 25 GeV + rebunching on h=84 + bunch compression | LHC | 10 × C10 cavities | h= 8 + 16 | 2 | 2 |
|               |           |            | 1 × C40 cavities | h= 84 | 1 | 1 |
|               |           |            | 2 × C80 cavities | h= 168 | 1 | 1 |
| 1999          | Capture on h=7 + triple splitting at 1.4 GeV (→ h=21) + acceleration on h=21 to 25 GeV + quadruple splitting (→ h=84) + bunch compression | LHC | 10 × C10 cavities | h= 7 + 14 + 21 | 3 | 4 |
|               |           |            | 1 × C40 cavities | h= 84 | 1 | 1 |
|               |           |            | 2 × C80 cavities | h= 168 | 1 | 1 |
Table 3: Means of impedance reduction / beam loading compensation

| Name   | Frequency    | Beam loading compensation / impedance reduction scheme                                      | Date of installation | Date of removal | Ref. |
|--------|--------------|---------------------------------------------------------------------------------------------|----------------------|-----------------|------|
| Marelli| 2–10 MHz     | None                                                                                        |                      |                 |      |
| C10    | 2.6–9.5 MHz  | Gap short-circuit with HV relays (when not in use)                                          | 1972                 |                 | [6]  |
|        |              | Feedforward beam loading compensation                                                       |                      |                 |      |
|        |              | Wide-band feedback                                                                         |                      |                 |      |
|        |              | One-turn delay feedback                                                                    |                      |                 |      |
|        |              | Date of installation: 1972, Date of removal: 1988, Reference: 10                          |                      |                 |      |
| C114   | ~200 MHz     | De-Q-ing with resistive loads using PIN-diode switches (when not in use)                    | 1977                 |                 | [7]  |
|        |              | Driver mismatch                                                                            |                      |                 |      |
| C200   | ~200 MHz     | Short-circuit arm (when not in use)                                                         |                      |                 |      |
|        |              | HOM dampers                                                                                |                      |                 |      |
|        | C114 114.511 MHz | Short-circuit arm (when not in use)                                                        | 1986                 | 2001            | [19] |
| C40    | 40.055 MHz   | Telescopic short circuit (when not in use)                                                  | 1996                 |                 | [24] |
|        |              | HOM dampers                                                                                |                      |                 |      |
|        |              | Wide-band feedback                                                                         |                      |                 |      |
|        |              | Date of installation: 1996, Date of removal: 2001, Reference: 24                          |                      |                 |      |
| C80    | 80.100 MHz   | Telescopic short circuit (when not in use)                                                  | 1998                 |                 | [25] |
|        |              | HOM dampers                                                                                |                      |                 |      |
|        |              | Wide-band feedback                                                                         |                      |                 |      |
|        |              | Date of installation: 1998, Date of removal: 2001, Reference: 25                          |                      |                 |      |
| C20    | 13.3 + 20 MHz| Gap short-circuit with HV relays (when not in use)                                          | 2002                 |                 | [28] |
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Beam extraction

1 Introduction

In the first years of the PS, secondary beams for the physics experiments were generated from targets introduced inside the machine vacuum chamber. This straightforward method had three drawbacks: a) the irradiation of the machine became severe as the intensity request thanks to new physics discoveries went up; b) the production angle could not be made small; c) the optics of the secondary beams was deteriorated by the traversal of the highly non-linear fringe field of the PS main magnet placed after the target.

As the demand for secondary beams increased, it became necessary to overcome these difficulties by extracting the beam from the machine in a controlled manner and sending it to external targets. For counter experiments, the particle spill had to last for several hundred milliseconds, adapted to the magnetic flat-top length available at the chosen extraction energy, the so-called slow extraction. For experiments with bubble chambers and, later, for neutrino physics, the extraction of the whole beam or a limited number of bunches within one turn was desirable, i.e., a fast extraction.

2 Fast extraction

Even though nowadays the fast extraction of a particle beam is a very well established technique that is routinely used in circular accelerators, this was not the case at the time of the design of the PS machine. The first study dates back to 1954 [1], but one had to wait until 1963 to implement the first system for extracting the beam over one turn [2–5].

Fig. 1: Example of the trajectory of a fast-extracted beam towards the East Hall [4]
An example of an extraction trajectory dating from 1969 is shown in Fig. 1, where the beam was delivered to the experimental East Hall. The kicker magnet was placed in SS97 and the extraction septum magnet in Straight Section SS58. Extraction of protons from SS58 was operational from 1965 to 1982 and went on afterwards for antiprotons and electrons towards the SPS. Fast extraction from SS74 was used from 1967 to 1980 for the neutrino, g–2 and ICE experiments. Nowadays, the only remaining fast extraction is performed in SS16 towards the Super Proton Synchrotron (SPS), the AD machine and the n-TOF experiment. The full-aperture kicker magnets are located in SS71 and SS79, while the long extraction septum magnet is located in SS16.

2.1 Fast kickers

The initiating element for fast extraction is the kicker which imparts a horizontal betatronic oscillation to the bunches to be ejected. They are then deflected out of the circulating orbit by a downstream septum magnet. In addition, local bumps are needed at the extraction septum.

Kicker rise and fall times must be less than 80 ns for clean extraction of a limited number of beam bunches. This is obtainable from single-turn magnets, usually of travelling wave type, operating at high voltages and currents. Switch jitter must be low and reliability high.

In its 50 years the PS has known three kickers, two were successes and one a failure. The first, installed in the early sixties, was of limited aperture and was hydraulically positioned after beam acceleration. It used lumped element pulse forming networks (PFNs), spark gap switches, and electrolytic terminating loads. The system operated successfully for over 10 years but the movement into the beam line after acceleration imposed operational restrictions. A full-aperture (FAK) system was proposed to succeed it and the project started in 1964.

At the heart of the FAK was the use of ferrite rings left over from the PS cavities. These would serve as magnet yoke, the dielectric for the magnet capacitance, and also form an important part of the vacuum envelope around the beam. To make them impervious they were pre-impregnated with epoxy resin before assembly into two glued back-to-back 2 m stacks. Fortunately, prior to final assembly it was shown that a continuous ferrite stack does not behave like a travelling wave magnet. To make it do so, alternate ferrites were replaced by Araldite rings. The completed magnet was successfully laboratory tested prior to installation in SS66 where disaster struck. The residual electric charge on the epoxy surfaces after a single kicker pulse prevented further 50 MeV injection for several minutes. With a provisional semiconducting Mylar tube in the aperture the FAK worked as designed, but that was not a long-term solution. The FAK was removed to the museum and deemed a failure because of trying to get too much out of a stack of surplus ferrite rings.

The need for a new kicker for the PS remained. To meet future operations this had to be full-aperture and be able to eject any number of bunches up to six times per machine cycle at intervals down to 50 ms. A single-module kicker of 80 ns rise time would require a PFN voltage close to 1 MV so the new system would require at least 10 modules and 20 or 30 switches depending on whether the pulse fall used a ‘tail-biter’ (see Fig. 2). Clearly, the choice of switch would be critical; spark gaps could handle the voltage, current, and jitter initially but their long-term maintenance in such numbers could pose a serious problem. An alternative would be the hydrogen thyratron developed for military radar but never operated at dI/dt rates needed for kickers. The first step was evaluation of thyratron dI/dt capability. Six tubes were tested in the laboratory, switching 15 ohm cables charged to 80 kV. Provided that the cables were charged in a few ms from pulsed resonant supplies, the average switch dI/dt was 100 A/ns, easily maintained over 100 million pulses in a yearlong test, with jitter smaller than 5 ns. The thyratron option was therefore chosen. Very-low-attenuation 15 ohm SF₆ pressurized polythene tape PFN cable would be charged to 80 kV in under 4 ms by a resonant supply. Cable discharge would be by thyratrons at each end, their relative timing controlling the kicker pulse duration. No tail-biter would be needed because of the
high-quality cable used for the PFN. The magnet would be a 15 ohm delay-line, installed in machine vacuum using ferrite only as the magnet yoke. Interleaved high-grade-finish aluminium alloy plates would provide the needed capacitance, the dielectric being the machine vacuum. The total system would comprise 12 modules, nine in SS71 and three in SS79 [6].

The initially authorized project was for SS71 only, possibly due to some lingering doubts after the failure of KFA66. Construction went without surprises and after laboratory testing nine modules were installed in 1973 in SS71. They functioned correctly and were joined a little later by the three modules of SS79. After 36 years of service the system is still in use. There have been no high-voltage breakdowns and thyratron switching is trouble-free, average life exceeding 20 000 hours. Overall system availability has been high. After the failure of KFA66, the new version KFA71+KFA79 has been a success.

2.2 Extraction septa

The first septum magnet was installed in SS01 in 1963. A first neutrino experiment had been set up in the South Hall with the CERN heavy liquid bubble chamber, a spark chamber experiment, and in the end the Ecole Polytechnique heavy liquid chamber. The hope was that CERN might beat BNL on the ‘2 neutrinos’ question, but they were faster by a few months.

The next operational septum magnet was installed in 1964 in SS58 for the East Area bubble chambers. The South-East Area was then specially built for the neutrino beam in 1965 and extraction from SS74 was installed with hardware transferred from SS01. Then came the long septum 16 for extraction towards the ISR and bubble chambers at the end of the West Area. Since the vacuum required in the PS at that time was not very high, the septum yokes were built of packets of laminations glued together with Araldite [7].

Later on, since lead ions required better vacuum, new models were developed in the early 1990s without organic materials. Standard 0.35 mm thick steel laminations with a 3% silicon content were used, insulated on both sides with an inorganic coating [8].

The cooling circuit comprises two thin-walled stainless steel tubes embedded (and brazed) in pre-machined slots in the septum conductor. This reduces erosion of the cooling circuit caused by the high water speeds of up to 10 m/s.
The tanks are cylindrical, bakeable, and equipped with RF beam screens to insure the continuity of the RF impedance. The magnets can be moved remotely in the radial and angular directions, while their vacuum tanks remain fixed.

For SMH16 (Septum Magnetic Horizontal in SS16, see Fig. 3), the maximum field is 1.2 T for a pulsed current of 28.5 kA. The fringe field measured is less than 1/1000 of the gap field at a 50 mm distance from the septum conductor.

![Fig. 3: Extraction septum magnet 16 (photo taken in 1994)](image)

These thinly laminated magnets need to be baked out to obtain the required vacuum. Therefore infra red lamps are installed under vacuum to heat up the magnet, while keeping the vacuum vessel and vacuum seals at acceptable temperatures. After the bake-out cycle, consisting of a quasi linear temperature increase to 200 °C over 18 hours, a 24-hour flat top at 200 °C, and an exponential temperature decrease of approximately 72 hours, a vacuum of $6 \times 10^{-10}$ to $4 \times 10^{-9}$ mbar is achieved in the tank.

3 Slow extraction

A slow extraction over thousands of turns obtained by pushing the beam away from the centre of the vacuum chamber toward a septum magnet would not work. The order of magnitude of the beam size is 20 mm and an extraction over approximately 200 000 machine revolutions was needed: the jump of particles per turn at a first septum location would then be $1/10 \mu$m, far less than the thinnest feasible septum (at the PS a 100 µm electrostatic septum is used). In this context, the use of transverse resonance can enormously increase this jump, which is also called spiral pitch.
3.1 Integer resonance extraction

3.1.1 Principle

The first use of resonances for extraction from a particle accelerator dates from the early 1950s at the
University of Chicago ‘Fermi’ synchrocyclotron. It was later proposed for the first time for a synchrotron
in 1961 for the PS machine [9, 10]. The scheme was based on integer extraction.

The radial betatron wavelength of the machine, which is normally about 6.25, is reduced to 6 by
energizing one or more quadrupoles and some sextupoles. A stable area in the transverse phase space
appears, surrounded by unstable phase space (see Fig. 4). Extraction is achieved by pushing the beam out
of the stable area so that particles move away along the single separatrix. They are then captured and
extracted by a septum magnet. In theory the method has a high efficiency and produces an extracted beam
with a small emittance and narrow energy spectrum, without raising any impossible technical problems.

![Fig. 4: Example of typical phase-space diagram for integer resonant slow extraction](image)

3.1.2 Implementation

The first tests at the PS were conducted in 1964 [11]. The beam was extracted from SS01 (see Fig. 5,
left), the main, long, straight section used for beams into the South experimental hall. Conditions for
ejiction were achieved by pulsing sextupoles in SS25, 55 and 75 with currents of one polarity, sextupoles
in SS15, 35, 65 and 95 with currents of opposite polarity, and also a quadrupole in SS99 located 1/8
betatron wave-length upstream from the septum magnet at SS01.

The septum magnet, designed with a different ejection system in mind had an aperture of 28 mm
wide by 30 mm high, the effective septum thickness being 4.5 mm. From the standby position at the
outside of the CPS vacuum chamber it was plunged to its working position in about 150 ms.

Originally a distance of 25 mm between the central orbit and the nearby edge of the septum was
specified. This was changed afterwards to 20 mm (Fig. 5, right). The 5 kA power supply, a six phase
mercury vapour rectifier, produced a field ripple of several per cent, the exact value depending on the
particular current pulse used. This ripple could be reduced by an order of magnitude through insertion of a
9 mH choke of low resistance (a spare CPS magnet unit, no. 102) in the circuit. However, as the cooling
capacity of the septum magnet was limited, the longer current rise-time produced by the choke led to a
shortening of the usable flat top in the septum currents. Therefore half the choke inductance was sometimes used.

Fig. 5: Left: the extraction area. Right: beam and septum magnet positions.

The efficiency of extraction during the first tests was of the order of 50%, limited by the thickness of the septum of the extractor magnet. However, the resonant extraction was shown to be possible and it was decided to implement it towards the East Hall. The time structure of the burst was still poor owing to the imperfect regulation of power supplies at that time. The oscillogram of the spill and other relevant parameters is shown on Fig. 6.

Fig. 6: Oscillogram of beam burst for SS01 integer extraction

In 1965 an integer resonance extraction was installed with an extraction septum in SS58, shared with the fast extraction. One year after, the system was overhauled and the extraction septum was installed in SS62. The efficiency had improved but was still lower than 80%, causing heavy losses on the septum. The external target 64 soon disappeared and physicists received their particles from external targets.

In 1967, the efficiency was further improved by means of the installation of a thin septum magnetic lens, 0.2 mm thick, in SS79.
A last improvement came in 1971 with the use of a first-stage separation of the extracted beam through an electrostatic septum. Efficiency could now reach values exceeding 90%.

3.2 Third-integer resonance ‘Square’ extraction

3.2.1 Choice of the resonance

In the late 1960s it was decided to build the West Hall. A new extraction scheme had to be developed to provide for East or West area extractions whilst sharing with internal targets. The choice of the third-order resonance was made for several reasons. Three separatrices allow the possibility for three times more extraction straight sections [12]. Moreover, efficiency when sharing with an internal target is better than with integer resonance extraction. The final proposal was made in 1971.

3.2.2 Implementation

Commissioning of the Square, Semi QUAdrupole Resonant Extraction, from SS16 or SS62 took place in 1972 (see the layout in Fig. 7) [13, 14]. Sharing was possible with internal targets 1 or 8, and later on with 1 alone.

Three septa were used for each extraction: an electrostatic in SS83 for the first step (0.1 mm width), a thin magnetic septum in SS85 for the second stage (1.5 mm width), and thick magnetic septum (6 mm width) for the final extractions in SS16 or SS62 (in this last case there were even two extraction magnets in SS61 and SS62).

![Diagram of the Square extraction](image)

**Fig. 7:** Layout of the equipments for the Square extraction in the late 1980s

The resonance was driven by a standard quadrupole in SS23 and a non-linear magnet called semi-quadrupole, located in SS53. A cross-section of this magnet, which is essentially one half of a Panofsky quadrupole, is shown in Fig. 8. The main coils create the non-uniform field and dipole coils compensate the dipole component of the field at the centre.
A certain amount of ‘Q-gymnastics’ is necessary to prepare the ejection. The beam is first brought to the inside half of the vacuum chamber, then the horizontal tune is increased from its normal value of about 6.25 to about 6.36 by means of an auxiliary quadrupole. Finally the semi-quadrupole is switched on and, after de-bunching, the particles are split by a negative slope on the main field flat-top. The reason for this is that the negative chromaticity requires that the resonance be approached from higher Q values so that the beam is pushed into the extraction toward the outside.

![Diagram of semi-quadrupole and its magnetic field](image)

**Fig. 8:** The semi-quadrupole and its magnetic field

The phase space plots in Fig. 9 show the way the beam flowing out in the separatrices is split at the electrostatic septum and how it behaves at the entrance of the thin septum magnet.

![Phase space plots](image)

**Fig. 9:** Left: phase space plot at ES83. Right: phase space plot at TSM85.

Sharing was used essentially with internal target 1 until all physics experiments disappeared from the South Hall in 1981. All internal targets were thus suppressed to avoid excessive irradiation of the machine components. Efficiency for extraction 62 alone reached 93%, losses being shared on the electrostatic and first magnetic septum.

De-bunching was and still is performed before extraction. It has several advantages: it eliminates the accelerating frequency structure, precludes any interaction with beam controls loops, and allows the enlargement of $\Delta p/p$ which decreases the sensitivity to low-frequency ripples. In 1987, the maintenance of
the semi-quadrupole began to raise problems and it was exchanged for a quadrupole and two sextupoles which gave about the same effect so that the extraction performance was not altered.

3.3 Third-integer resonance SE61 extraction

3.3.1 Reasons for a new extraction system and its principle

In the late 1980s, the requirements for slow extraction had changed:

- There was no more extraction towards the West Hall.
- There were no more internal targets.
- The PS was accelerating leptons for LEP on certain cycles and the electrostatic and even the magnetic septa placed towards the outside of the machine orbit suffered from synchrotron radiation during there cycles.
- It was desirable to have fewer septa to save space in the machine and reduce the maintenance effort.
- Better vacuum was necessary to prepare for ions, so that organic material was banished in vacuum.
- The septum magnets had aged.
- The systematic losses on magnetic septa were excessive.

A new extraction scheme was developed to fit these requirements and benefit from the less stringent specifications (no more West Hall and internal targets) [15–17]. Its main characteristics are:

- Protection of the septa from synchrotron radiation during lepton cycles since they are placed towards the inside of the machine or are outside vacuum.
- Reduced number of septa for less maintenance (only one septum magnet in vacuum instead of three before).
- Improved vacuum (required for ion acceleration): the thin septum magnet can be baked out, the tank is made of vacuum fired 316LN stainless steel, and there is no organic material in vacuum.
- Systematic losses due to chromatic effects at the thin septum magnet are avoided through adjustment of local dispersion coefficients at the electrostatic and thin magnetic septa.

3.3.2 Layout of SE61

The new extraction was commissioned in March 1992 and regular operation could start immediately [18]. The elements installed in the PS machine are (Fig. 10):
— Quadrupoles (in SS29 and SS87) to raise $Q_h$ from 6.2 to 6.33, increase $\beta_h$ at the septa, and decrease the horizontal dispersion at the electrostatic septum and increase it at the first magnetic septum.

— Sextupoles (one in SS7 and two in SS19) to provide the 19th harmonic defining the stable and unstable phase areas, and the zero harmonic to decrease the horizontal chromaticity $|\xi_h|$. 

— One electrostatic septum in SS23 on the machine centre side (Fig. 11, left).

— One magnetic septum in SS57 under vacuum on the machine centre side (the only magnetic septum under vacuum) (Fig. 11, right).

— One magnetic septum in SS61 outside vacuum (Fig. 12, left).

— Bumpers in SS19 and 27 to approach the electrostatic septum.

— Bumpers in SS53, 59, 61 (septum type, Fig. 12, right) and 67 to approach the beam to both magnetic septa.

Fig. 10: Layout of the elements for SE61
In 2007, the sextupoles in SS19 had to be displaced to free the straight section in conjunction with the installation of the multi-turn extraction (MTE). They were first placed in SS03 but it turned out that the separatrices were curved and that the efficiency was lowered and losses increased (parenthetically, the initial performance was restored by using octupole magnets to re-shape the separatrices at large amplitude). Nevertheless, to ease operation, it was decided to find a better place for the sextupoles, which were then moved again to SS01 and the efficiency returned to its previous value.

The phase plane plots at the electrostatic septum 23 (Fig. 13, left) and thin septum 57 (Fig. 13, right) show the main difference with the Square extraction. The improvement of the systematic losses on the first magnetic septum (thin septum) is obvious when the plots at the thin septa are compared (Fig. 9, right and Fig. 13, right). By a proper choice of the horizontal dispersion at the electrostatic septum and at the first magnetic septum, the separation between ejected and circulating beam was enlarged, the magnetic septum thickness could be enlarged, resulting in a welcome increase of its deflection angle. Therefore only one extractor magnet was needed and it could even be installed outside the vacuum enclosure.
The de-bunching is kept unchanged from the Square extraction. When the beam reaches the flat top, the radial position is changed, using an offset on the beam control radial loop, so as to place the beam just outside the resonance. In order to suppress the RF component in the spill and enlarge $\Delta p/p$ (to lower the effect of the low frequency ripple), de-bunching is then done as seen on Fig. 14. Starting from the stable beam in longitudinal phase space (a), the RF phase is changed by 180° during about 500 $\mu$s so that bunches stretch along separatrices (b), then the phase is changed back to the initial value (c) so that bunches rotate during about 3 ms after which the RF power is turned off and cavities are short-circuited (d). A careful tune of these parameters results in a nearly homogeneous distribution of $\Delta p/p$ and therefore a regular spill with almost rectangular shape versus time.

Fig. 14: The RF gymnastic for de-bunching
3.3.3 **Performance of the SE61 extraction**

Owing to East Area radiation limitations, the intensity is restricted to $2 \times 10^{11}$ protons per pulse (ppp) per each of the two external targets. The particle momentum is 24 GeV/c in normal operation, but other energies are also possible. When carefully adjusted, the efficiency can reach values above 95%. Losses are practically limited to the electrostatic septum straight section. For a $3 \times 10^{11}$ ppp beam, the typical physical emittance of the extracted beam is 0.1 $\pi \mu$rad in the horizontal plane and 0.8 $\pi \mu$rad in the vertical plane. The instantaneous momentum spread $\Delta p/p$ is 0.08% and the total $\Delta p/p$ is 0.3%. The maximum spill length is 500 ms, the standard value being 400 ms.

3.3.4 **Ripple correction**

The residual undulation on the power supplies was responsible for a ripple in $Q_h$ which induced a ripple in the extracted beam intensity. The frequencies were usually 100, 300 and 600 Hz. Physicists often required a cure for these intensity fluctuations.

A servo-system had already been used with the Square extraction to overcome this problem. A monitor in the extracted beam gives the intensity of the spill. It is compared with a fixed reference, the difference undergoes various corrections through filters and it is fed through a wide-band power amplifier to a quadrupole. Only the lower frequencies could be corrected this way owing to the slow response of the extraction to a change in $Q_h$. This is due to the great number of revolutions in the machine before a particle is ejected.

Another, more successful way to correct the low frequency ripple is the feed-forward method, as shown in Fig. 15.

![Fig. 15: Left: spill and circulating current without correction (1997). Right: spill (PE.MLSDSESPILL) and circulating (PE.TRA345E11) current after correction of the mains harmonics 2, 3, 4, 6, 8, 12 of 50 Hz.](image_url)

An air quadrupole is installed in the machine at a high $\beta_h$ location. An audio-frequency amplifier feeds it with the harmonics to be corrected. They are synthesized with a function generator, synchronized with the mains, variable in phase and amplitude. The optimization was done manually, optimizing the Fourier transform from cycle to cycle. This was a long process, since 7 frequencies were involved: 50, 100, 150, 200, 300, 400 and 600 Hz. The optimization had to be performed from time to time because of ageing and detuning of the various power supplies or changes in mains phase.

A third possibility is the phase displacement (empty bucket channelling) method [19]. The beam is displaced away from the resonance and then de-bunched. RF cavities are excited at a harmonic of the revolution frequency corresponding to the position of the resonance. This increases $dQ/dt$ of the particles which squeeze in between the empty buckets, and thus decreases efficiently the low-frequency ripple (Fig. 16). The latter is traded against a strong RF component. This method was tested experimentally only
with 200 MHz cavities but was not put into operation since the RF cavities were not available in normal operation.

Nowadays, the regulation of the power supplies for the main magnets as well as for the pole face windings has made such progress that their residual ripples have become quite negligible. All these compensation systems are therefore no longer in operation.

All in all, slow extraction has been provided to the CERN PS physicist clients for 45 years. There was a time when a good part of the relevant physics research was performed on secondary beams from external targets fed this way and sometimes even directly on the extracted protons. Nowadays the emphasis is on colliding beams, but slow extraction in the East Area of the CERN PS is still busy with tests on the various types of equipment for LHC physics, and some interesting experiments such as DIRAC studying the strong force and CLOUDS which will investigate the possible influence of galactic cosmic rays on the Earth’s clouds and climate.

4 Continuous Transfer or CT extraction

This original extraction method was driven by the need to fill the CERN SPS as uniformly as possible [20–27]. The SPS circumference is eleven times that of the PS, hence the SPS could be filled by extracting the beam over several turns from the PS machine.

Such an approach would lengthen the duration of the beam, but it would also provide a natural way of manipulating the transverse emittance of the extracted beam. This is certainly an interesting feature for overcoming potential aperture bottlenecks in the receiving machine.

The principle itself [20–24] is based on a careful choice of the horizontal tune of the PS machine and on a variable-strength closed bump. On a turn-by-turn basis the beam is pushed towards an electrostatic septum: the beam in the septum gap will be deflected and will oscillate around a fraction of the machine circumference. A magnetic septum will then provide the necessary deflection for the beam to leave the machine and enter the transfer line.
After the proposal, an experimental test was set up [25]. In order to re-use a maximum of existing equipment, the layout of the slow bump used to approach the electrostatic septum and the fast bump to shave the beam was not that of the operational configuration. The test layout is shown in Fig. 17.

![Fig. 17](image.png)

**Fig. 17:** Sketch of the experimental set-up for the first tests with an eleven-turn CT extraction (from Ref. [25])

The initial tests provided an extracted beam at 10 GeV/c over ten or eleven turns. The latter case is shown in Fig. 18 where the circulating intensity, the extracted intensity, and the strength of the staircase kicker are reported.

The longitudinal structure of the beam has no impact on the extraction proper, only the losses at extraction being different due to the finite rise time of the kickers used to generate the fast bump. Both bunched and de-bunched beams were considered during the ejection tests reported in Ref. [25].

Of course, the eleven-turn extraction was not adapted to the injection in the proposed SPS, as there was no place to accommodate the rise time of the injection kicker. Therefore, the ten-turn version became the nominal configuration for a while [26], typically for intensities up to about $7 \times 10^{12}$ protons. Already at that time it became clear that for higher intensity operations, a new variant was needed providing more protons. In fact, the solution found, and in operation to date, is the filling of the SPS by means of two consecutive PS extractions over five turns. In addition, the extraction energy was increased to 14 GeV/c. The layout of the hardware required and installed in the PS ring is shown in Fig. 19 from Ref. [25], where the issue of controlling the overall extraction system is addressed in detail.

![Fig. 18](image.png)

**Fig. 18:** Experimental results of the setting up of an eleven-turn CT extraction from Ref. [25]. The circulating intensity (left), the extracted intensity (centre), and the staircase current (right) are shown.

In the latter scheme the horizontal tune of the PS machine is set to the value 6.25 just prior to extraction. At the same time the closed-orbit is modified by means of two dipoles that generate a closed bump around the electrostatic septum located in section 31 of the PS circumference. In addition, a second bump centred on the electrostatic septum is generated by two kickers so that by selecting its amplitude, a different portion of the beam is cut off. Because of the value of the horizontal tune, four slices are shaved...
off and extracted as a continuous ribbon over four turns. Therefore, only a fraction of the beam core remains in the machine and is extracted last, during the fifth turn, by changing the beam trajectory, so as to jump over the septum blade. This shaved beam receives a horizontal kick by the electrostatic septum that produces the necessary displacement to jump over the thicker blade of the magnetic septum located in section 16 of the PS ring (see Fig. 19).

![Fig. 19: Sketch of the CT extraction from Ref. [27]](image)

To amplify the effect of the kickers and septa on the beam trajectory, the optics of the machine is perturbed by means of the so-called kick enhancement quadrupoles (QKE16), namely two quadrupoles located in SS05 and SS25, as can be seen in Fig. 20 (top). They increase the horizontal beta-function at the location of the electrostatic septum so as to reduce the local beam density and hence the losses on the device. At the same time, the value of the horizontal dispersion function is reduced at the electrostatic septum, thus making the whole extraction process less sensitive to the intrinsic momentum spread of the beam. In 2007, during a campaign of extraction loss studies, the quadrupoles in SS05 were displaced to SS73. The new optics, shown in Fig. 20 (bottom), displaced the losses produced by particles scattered by the electrostatic septum in better shielded zones of the tunnel.

From the principle it is clear that the five extracted slices have different extraction conditions, i.e., positions and angles at extraction and have different shapes and emittances in transverse phase space. During normal operation, the difference in extraction trajectories is corrected by means of dedicated kickers installed in the TT2 transfer line, the DFAs, also called Emittance Reduction Dipoles (ERDs). It was already mentioned that one of the aims of CT extraction is to reduce the extracted beam emittance. Nevertheless, it is worth noting that the extraction shaving occurs in the horizontal plane, while the aperture limitation in the SPS is mainly in the vertical plane. Therefore, a special optics insertion was added in the TT10 part of the PS–SPS transfer line in order to exchange the transverse plane and hence increase the usefulness of the emittance reduction [28].
Fig. 20: Optical parameters for the PS ring when the beam is sliced for CT. The standard optics is perturbed by means of special quadrupoles, the QKE16 (top, original extraction optics, bottom, optics used for the loss displacement).

A typical time profile of the CT ejection is shown in Fig. 21, from the 2008 SPS physics run. The intensity is measured at injection in the SPS by means of a fast beam current transformer. The first injected batch (left part) remained in the machine for 1.2 s while waiting for the second batch.

It is clear, however, that a number of drawbacks are present, namely: i) beam losses, especially at the electrostatic septum, are unavoidable. They amount to about 10–15% of the total beam intensity; ii) the extracted slices do not match the natural structure (circles) in normalized horizontal phase-space, thus generating a betatronic mismatch. This, in turn, induces emittance blow-up in the receiving machine; iii) the extracted slices have different horizontal transverse emittance. A detailed analysis of the properties of the extracted slices can be found in Ref. [29], where computation of the mismatch parameters for the CT as a function of the slicing was performed. For the CT extraction, the optical parameters and the beam emittance are different for the five slices, thus generating different emittance blow-up at SPS injection. Furthermore, because of the fancy shape of the slices, the mismatch can be rather large.

The optical properties of the five extracted slices of the CT can be derived by performing integration over the beam distribution taking into account the shape of the slice due to the interaction with the electrostatic septum. Knowing that the relative position between the septum and the beam can be controlled on a turn-by-turn basis, it is rather straightforward to compute all relevant quantities for each slice (in some cases it is even possible to derive analytical expressions of the optical parameters vs. the septum position). Two approaches have been followed, corresponding to the equalization of the beam intensity or of the extracted emittance. The first approach corresponds to what is done in reality when
tuning the beam. The second one cannot be applied in practice on account of lack of an appropriate instrument to measure the beam emittance of each extracted slice.

Fig. 21: The two-batch injection in the SPS using a five-turn CT extraction from the PS. The beam intensity is measured with a SPS fast beam current transformer. The width of the line is due to the overlay over seven injections. The beam is then accelerated and extracted towards the CNGS target.

As expected, it turns out that the two approaches are not compatible with each other. In other words, making the intensity equal generates very unequal emittances and vice versa. This fact is visualized in Fig. 22, where the shape of the five slices is shown for the two approaches. The difference is clearly visible.

Fig. 22: Shape of the five slices for the present CT in normalized phase space \((x, x')\) according to whether intensities (left) or emittances (right) have been equalized. The solid circle has a radius of \(\sqrt{14e}\) where \(e\) is the r.m.s. beam emittance before slicing.

5 Why replace the CT?

In the framework of the activities to prepare the future high-intensity proton beam for the CERN Neutrino to Gran Sasso (CNGS) Project [30], a critical review of the key processes used to generate such a beam was carried out [31], in view of a possible upgrade beyond the present nominal intensity value of about
3.3×10^{13} protons per PS batch. Among other issues, efforts were devoted to the improvement of the present extraction scheme from the PS to the SPS, the Continuous Transfer.

In the framework of the High Intensity Protons Working Group (HIP-WG) [32] a detailed analysis of the losses for the beam for CNGS was performed [33]. The outcome is rather striking: for an overall intensity of about 4.5×10^{19} protons/year required by the neutrino experiments, approximately 1.7×10^{19} are lost in the accelerator chain, corresponding to about 40% of the total intensity. A large fraction of beam losses, namely 0.7×10^{19}, or 40% of the total intensity lost occurs in the electrostatic septum of the PS ring used to slice the beam.

In the quest for an improved extraction mode, a novel approach was proposed, named multi-turn extraction (MTE). In the new scenario the beam is separated in transverse phase space by generating stable islands inside the region where the beam sits and by slowly (adiabatically) moving them towards higher amplitudes. By doing this, particles may get trapped inside islands thus generating well-separated beamlets [34]. This method is potentially superior to the present one as no intercepting device is used to split the beam; hence particle losses are limited to the fraction of the beam improperly deflected during the kicker rise time. Furthermore, the extracted beam should better match the phase space structure.

6 Novel Multi-Turn Extraction

6.1 Principle

The novel technique relies on the use of non-linear magnetic fields (sextupolar and octupolar) to generate stable islands in the horizontal phase space [35]. By means of an appropriate tune variation, a specific resonance is crossed, the fourth-order in the case under study, and the beam is split by trapping inside the stable islands moving from the origin of the phase space towards higher amplitudes [34]. A good model consists in choosing a simple FODO cell with a sextupole and an octupole located at the same longitudinal position, both represented in the single-kick approximation [36]. An example of the change of the phase space topology during resonance crossing is shown in Fig. 23.

![Fig. 23: Topology of the normalized phase space during resonance crossing](image)

The evolution of the beam distribution during the resonance crossing is shown in Fig. 24.
Fig. 24: Evolution of the beam distribution during resonance crossing. The initial state is represented by a bi-Gaussian beam (left), at resonance crossing some particles are trapped inside the moving islands (centre), at the end of the process, the particles trapped in the islands are moved towards higher amplitudes (right).

When the tune is changed, the islands move through the phase space region where the charged particles sit and some are trapped inside the islands. At some stage a complete separation between the beamlets and the central core occurs and the distance between the beamlets can be increased at will by simply acting on the tune. It is worth while stressing that the beam after trapping has a peculiar structure, i.e., it is made of two disconnected parts: the beamlets, which are indeed one single structure closing up after four turns around the machine (see Fig. 25), and the central core.

The idea behind this process is that such a beam splitting in the transverse phase space can be used to perform multi-turn extraction. In fact, once the various beamlets are separated, the whole structure can be pushed towards an extraction septum by means of a closed slow bump. Then, kicker magnets generate a fast closed bump and one island jumps beyond the septum blade so that the beamlets are extracted out of the machine in four turns. The fifth beamlet, i.e., the beam core, is extracted using a classical single-turn extraction. The advantage of this approach is that, at least for the first four turns, the optical parameters are, by definition, the same. This is intrinsic to the method, as the same stable island is used to extract the beam.

It is worth stressing that numerical simulations are performed by crossing the resonance from above: this is the opposite of what is done in the experimental tests, where the resonance is crossed from below. The choice of the resonance to be crossed is completely arbitrary as the use of a fourth-order resonance is dictated only by the CERN-specific application (see Refs. [37, 38] for a generalization to other types of resonance and to injection, respectively).

6.2 Measurement results

6.2.1 Overall measurement strategy
In parallel with the computational and theoretical analysis, an intense experimental campaign was launched at the end of 2001 on the CERN PS (see Ref. [39] for the final account of the results achieved). This entailed the development of new measurement systems, such as the turn-by-turn orbit measurement system [40, 41], as well as the installation of sextupoles and octupoles to generate the stable islands.
The magnetic elements and the beam instrumentation used in the experimental campaign are shown in Fig. 26 (left). The tune is changed by means of the two families of focusing and defocusing quadrupoles, normally used to control the machine at low energy. Sextupoles and octupoles are used to generate the stable islands; the fast-extraction kicker is used to displace the beam and induce betatron oscillations for phase space measurements; a wire scanner [42] is used to measure the horizontal beam profile (see Fig. 26 – right – for details on the installation); two pick-ups are used to record the betatron oscillations.

Trapping measurements with a high-intensity beam represented the most important test for this novel approach. A sequence of transverse beam profiles during the splitting process is shown in Fig. 27 (upper part) together with the best result achieved (lower part). The intensity as a function of time is shown (lower left). The injected intensity is slightly above $6 \times 10^{12}$ protons and small losses are visible up to transition crossing (second vertical red line). Then, the intensity stays remarkably constant up to extraction, which is performed by means of a kicker in a single turn after having merged back the beamlets in order to reduce the beam size in the horizontal plane to match the septum acceptance. The beam distribution as measured in the transfer line downstream of the extraction point from the PS machine is shown in Fig. 27 (lower right). Optical Transition Radiation (OTR) [43] is used to record the two-dimensional beam distribution in physical space. The peculiar shape of the beam distribution is clearly visible: the two lateral peaks represent the projection in physical space of the beamlets.

A final test was performed to increase the fraction of particles trapped inside the islands. For this study, a special setting of the octupoles was programmed: instead of keeping their strength constant all along the resonance-crossing phase, the current was suddenly increased just before resonance crossing and then gradually reduced. This should generate large islands at small amplitudes thus trapping more particles from the region where the density is high, and then keeping almost constant the island’s size. The results are shown in Fig. 28, where the current as a function of time for both the sextupoles and the octupoles is shown (left) as well as the measured horizontal beam profile (right).
Under these new conditions it was indeed possible to increase the fraction of particles inside the islands, achieving a value of 18% against a previous value of about 13%. It is worth while mentioning that for the optimal performance of the SPS machine, the tolerance for the fraction of particles in each beamlet is (20±5)%. Therefore, if this needs to hold for the central core, then, the four beamlets should satisfy the tighter limit (20±1)% as any deviation in beamlets intensity is reflected on the core amplified by a factor of four. However, the price to pay was the presence of slightly higher losses during resonance crossing up to the level of 2%–3% of the total beam intensity.

The main parameters of the single-bunch beams used in the experimental campaign are summarized in Table 1.

**Table 1:** Parameters of the single-bunch beams used for the experimental tests of the novel multi-turn extraction. The emittance is the normalized, one-sigma value.

| Parameter                          | Intensity (protons/bunch) | $\hat{\varepsilon}_H (\sigma)$ (\(\mu\)m) | $\hat{\varepsilon}_V (\sigma)$ (\(\mu\)m) | $\Delta p/p (\sigma)$ \(10^{-3}\) |
|-----------------------------------|---------------------------|---------------------------------------------|---------------------------------------------|---------------------------------|
| Low-intensity, pencil beam        | $5\times10^{11}$          | 2.3                                         | 1.3                                         | 0.25                            |
| Low-intensity, large horizontal emittance | $5\times10^{11}$          | 6.2                                         | 1.6                                         | 0.25                            |
| High-intensity beam               | $6\times10^{12}$          | 9.4                                         | 6.4                                         | 0.60                            |
Fig. 27: Sequence of beam profile during splitting (upper) and best result achieved with a high-intensity beam, whose intensity as a function of time (lower left). Two-dimensional beam distribution in physical space of the beam in the transfer line downstream of the PS extraction point (lower right).

Fig. 28: Current as a function of time for the sextupoles and octupoles as used in the special test to increase the fraction of particles trapped in the beamlets (left). The resulting horizontal beam profile after splitting is also shown (right). The profile is not centred at zero due to an instrumental offset of the wire position.
7 Implementation of MTE at the CERN PS

7.1 Design principle

The experimental campaign was completed at the end of 2004. The analysis of the required modifications to implement the proposed multi-turn extraction took place during the 2005/2006 long shutdown of the PS machine. The conceptual design of the proposed multi-turn extraction can be sketched as follows (see Ref. [44] for more details and Ref. [45] for a complete account of the hardware commissioning):

- Beam splitting: two pairs of two sextupoles and one octupole each will separate the initial single beam into the five beamlets prior to extraction. Contrary to the experimental set-up, where only one set of two sextupoles and one octupole was used, the choice of two pairs is mainly dictated by the need to control and adjust the phase of the islands at the extraction point.

- Extraction: the extraction point is in SS16, where the magnetic septum for the beam extraction towards the SPS is located. In the proposed scheme, the electrostatic septum, currently used to slice the beam in the context of the CT extraction in SS31, is not required, thus simplifying the overall scheme. Two bumps will be used to displace the beam towards the magnetic septum blade (slow bump) and to extract the beamlets over five turns (fast bump).

- Slow bump: a set of dipole magnets (bumpers) will be used to generate the slow bump around the magnetic septum. Currently, four bumps powered with a series/parallel circuit are used to extract the beams towards the SPS. In the proposed scheme, six independently powered magnets are foreseen. The large number of bumpers is imposed by the aperture constraints, as it will allow a careful shaping of the bump to overcome the potential aperture bottlenecks.

- Fast bump: three new kickers will generate the fast bump used to displace the beam beyond the blade of the magnetic septum. The pulse length should correspond to five PS turns. Since the centre core of the beam needs to be ejected, an additional kick will have to be imparted at the fifth turn. For this the fast extraction kicker will be used.

- Trajectory correction in the transfer line towards the SPS: even though the extraction conditions for the novel multi-turn extraction do not change from turn to turn, as one single island is used to extract the beam, the feed-down effects of the machine non-linearities (particularly from the pole face windings in the main magnets) due to the extraction bumps could generate turn-by-turn variation of the beamlet position at PS extraction. Such an effect could have a negative impact on the emittance after filamentation in the SPS. Hence two kickers capable of generating deflection changing from turn to turn will be used in the TT2 transfer line to correct for the variation in the extraction conditions (position and angle). These two devices are already being used for the CT extraction mode.

7.2 Implementation

The implementation of MTE required different interventions, such as design, production, and installation of new octupoles; construction of new power converters for the new extraction bump; design, construction, and installation of new vacuum chambers for increasing the beam aperture in particular in the extraction region; construction of new extraction kickers and their Pulse Forming Network (PFN). A large fraction of the PS circumference was affected by those interventions, summarized in Fig. 29, and...
they were done over two consecutive winter shutdown periods 2006/2007 and 2007/2008, the peak of activities occurring during the 2007/2008 shutdown.

Fig. 29: Summary of the hardware interventions related to the MTE installation

7.2.1 Slow bump

The original version of the slow bump in section 16 was made of four magnets located in SS12, 14, 20, and 22. The elements in SS12 and 22 were connected in series as well as those in SS14 and 20, the two groups being then connected in parallel to a single power converter.

Fig. 30: Amplitude of closed bump 16 all along the circumference of the PS machine for both the original version based on the use of four dipoles and the current one based on six dipoles

For MTE the layout of the slow bump 16 was modified so that six magnets (those already installed plus two in SS15 and in SS18) will each be powered by a dedicated power converter. The shape of the
bump in its present configuration and in the proposed one is shown in Fig. 30. The non-closure of the original version of the slow bump is corrected by the larger number of independent correctors.

It is worth mentioning that the new version of the slow bump entails a number of changes also at the level of the power converters [44].

7.2.2 **Fast bump**

The MTE scheme is based on a fast bump around the magnetic septum in SS16 (see Fig. 31, top).

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**Fig. 31:** Top: PS Complex layout, indicating the location of the fast pulsed magnets (red dots) and the magnetic septum in SS16 (blue dot) implied in the new PS multi-turn extraction scheme. The elements named DFA correspond to the devices called ERD. Bottom: Example of the bump generated by the new kickers for the extraction of the fifth turn, i.e., the beam core.
Fast pulsed magnets (kickers), to be located in SS13 and SS21, will create a nearly closed bump for the beamlets in the first four turns. To close it perfectly, an existing kicker in SS09 will be used. The core beam needs to be moved out by more than twice the distance of the other four beamlets. One additional kicker, to be located in SS04, in conjunction with the existing KFA71–79 system will kick out the remaining beam in the fifth turn. Two existing emittance reduction fast dipoles in the TT2 transfer line will be used to correct the trajectory of the beamlets. As an example, the fast bump generated by the kickers for the extraction of the fifth turn is shown in Fig. 31 (bottom).

The turn-by-turn variation of the extraction conditions will be corrected by dedicated kickers in the TT2 transfer line. The new system re-uses a maximum of existing de-commissioned and reserve equipment to minimize delays and reduce the cost.

A summary of the main parameters of the PS ring kickers is given in Table 2.

Table 2: Required kicker strength and rise time values (10% and 90%). The strengths are computed for a beam rigidity of 46.68 Tm.

| Turn | BFA9 (mrad) | KFA13 (mrad) | KFA21 (mrad) | KFA71 (mrad) | KFA4 (mrad) |
|------|-------------|--------------|--------------|--------------|-------------|
| 1    | -0.114      | 1.839        | 1.887        | 0            | 0           |
| 2    | -0.114      | 1.839        | 1.887        | 0            | 0           |
| 3    | -0.114      | 1.839        | 1.887        | 0            | 0           |
| 4    | -0.114      | 1.839        | 1.887        | 0            | 0           |
| 5    | -0.114      | 1.839        | 1.887        | -1.834       | -0.400      |

Rise time (ns) 340 350 350 70 80
Maximum strength (kV) 35 80 80 9×80 80

### 7.2.3 Sextupoles and octupoles

The creation of stable islands is possible by setting the linear and non-linear magnetic components in the PS ring. This is achieved by acting on the pole-face windings, figure-of-eight loop, plus four sextupoles and two octupoles dedicated to MTE operation. Whereas the four sextupoles already existed, three new octupoles, two operative magnets plus one spare, have been designed, constructed, magnetically measured, and then installed. The octupolar gradient difference between the three magnets is well below the 0.3%, as shown in Fig. 32 (left), where also the octupolar gradients versus current are presented. The magnet saturation occurs at about 500 A. Two octupoles have been installed, one in SS39 and the other SS55, in a tightly packed installation together with two sextupoles, shown in Fig. 32 (right).
7.2.4 Optimization of the aperture

A crucial issue for the implementation of MTE is the available mechanical aperture. On account of the principle, once the beam is split, there will be five beamlets circulating in the ring with different closed orbits. This increases the required aperture, in particular in the extraction region.

The changes implemented during the installation of MTE are concentrated in straight sections in the neighbourhood of SS16 and they are aimed at accommodating the five beamlets without any beam losses. As an example, the original and the new layout of the vacuum chamber installed in the magnet unit 16 are shown in Fig. 33. The main improvement refers to the increase of the cross-section for the part of the vacuum chamber dedicated to the circulating beam. Furthermore, the longitudinal extension of the region where circulating and extracted beams share the same aperture was increased.

Fig. 33: Layout of the new vacuum chamber in magnet unit 16 (lower part). The chamber originally installed is also shown (upper part).

The available aperture in the extraction region is shown in Fig. 34. In the upper part the cross section of the new vacuum chamber in magnet unit 15 is shown together with the beam envelope at 3 $\sigma$, represented by the rectangles, with the slow and fast bumps switched on. In the lower part the same situation is represented as a function of beam trajectory.
After the completion of the installation phase during the winter shutdown 2007/2008, the hardware and beam commissioning started in the 2008 PS run. Here, the milestones will be recorded, the details being available in Refs. [45–47].

The first half of 2008 was devoted to the hardware commissioning and the setting up of the beam splitting with the new hardware [45].

The first MTE extraction was performed on 1 August 2008, when a single-bunch beam of about $3 \times 10^{12}$ protons was sent to an external dump in the PS–SPS transfer line.

Figure 35 (left) shows the measured horizontal beam profile of the beamlets in the PS at the end of the splitting process and prior to extraction. A fit of the five beamlets is also superimposed. Figure 35 (right) shows the intensity signal of a pick-up in the PS–SPS transfer line of the extracted beam. Each of the five peaks corresponds to a beamlet extracted over a single turn. The distance between them corresponds to the PS revolution time of 2.1 μs. As expected, the five peaks feature about the same intensity, a clear sign that the equally populated islands were correctly extracted.
Fig. 35: Transverse profile of the beamlets before extraction (left) and intensity signal of a pick-up in the PS–SPS transfer line of the extracted beam

The rest of the commissioning period in 2008 was devoted to the preparation of the operational magnetic cycle, the study of the extraction with multi-bunch beam, and the determination of the most suitable longitudinal structure to be injected in the SPS. This has been another crucial point of the study. The beamlet formation, in fact, is not sensitive to the number of bunches in the machine, but it is sensitive to the beam momentum spread, since via chromaticity a large momentum spread creates a large tune modulation, inducing trapping/de-trapping phenomena and reducing the capture efficiency. The losses at extraction, however, depend on the bunch spacing due to the finite rise time of the kickers. In particular, the kicker rise time is longer than the $h=8$ PS bunch spacing, the rise time being about 350 ns and the bunch spacing about 260 ns. This implies that a fraction of the beam will be intercepted by the extraction septum during the kicker rise. The situation becomes worse if the $h=16$ harmonic is preferred or if the beam is de-bunched: the losses are nearly doubled going from 0.6% of the circulating intensity for $h=8$ up to 0.9% and 1% for the $h=16$ and de-bunched cases, respectively [44]. A detailed series of studies has been made by injecting a beam in the SPS with different longitudinal structures from the PS and assessing the dependence of the losses as a function of the harmonic number and of the RF voltage at extraction. The conclusion was that a de-bunched beam is the most suitable for the SPS, even if this choice does not minimize the losses in the PS. Hence, a MTE de-bunched extraction, see Fig. 36 (left), was prepared after the end of the 2008 SPS run, increasing the extracted intensity to $1.4\times10^{13}$ protons. The extraction efficiency, expected to be up to 97–98%, turned out to be on average about 93%, but with peaks up to 99%. These fluctuations were correlated with beam instability due to a slightly negative value of the chromaticity just prior to the resonant crossing. For the nominal extraction case, with an efficiency of about 98%, the beam loss pattern was compared with the five-turn extraction currently in use [48]. As expected, (see Fig. 36, right), the MTE beam losses are concentrated in the extraction region, whereas for the CT, losses of typically 5–6% of the circulating intensity are spread out over the entire machine circumference [48]. These losses are generated by the interaction of protons with the blade of the electrostatic septum in SS31. Moreover, particles scattered at the septum generate losses in the region between SS40–45 and SS72–76.

During the last part of the CNGS run, it was possible to inject a MTE, $h=16$ bunched beam in one of the CNGS SPS cycles. The total intensity injected was about $1.4\times10^{13}$ protons. The two batches, each of about $0.7\times10^{13}$ protons, had the last PS ejected turn with a larger intensity than the other four. The proton beam in the SPS could be injected, accelerated, and extracted towards the CNGS target. Neutrinos were also produced during the last night of the 2008 CNGS run.
The target for the 2009 physics run was to complete the commissioning, in particular cure the instability and the ensuing emittance blow-up, prepare a debunched version of the MTE beam, and improve the beam sharing among the five beamlets. In the second half of the 2009 run it was possible to deliver a beam to the SPS for one of the CNGS cycles. The intensity delivered was about $1.6 \times 10^{13}$ p per PS extraction. By the end of the 2009 CNGS run about $4.7 \times 10^{17}$ p were delivered via the MTE beam.

The intensity sharing was improved continuously during the 2009 run, introducing the correction of the non-linear coupling generated by the MTE octupoles, using the string of octupoles normally used to combat beam instabilities. Then, the last bit was achieved by means of the transverse damper that improved the sharing so that the target of 20% was reached. In Fig. 37 the impact of the beam excitation via a signal generated synthetically and sent to the damper kicker is clearly seen.

![Fig. 36: Intensity of a MTE de-bunched beam extracted over five turns measured by a transformer in the PS–SPS transfer line (left). Beam losses at each PS straight section for the MTE beam compared to a CT extracted beam (fixed target physics) for the same intensity (right). The sizeable reduction is apparent.](image)

![Fig. 37: Extracted spill profile for no beam excitation, excitation with a single frequency at the tune value, excitation at the tune value with noise. The difference is apparent.](image)

It is worth mentioning that a number of instabilities (microwave, and coupled-bunch longitudinal of quadrupolar mode) were observed during the MTE commissioning in 2009. The first one required the beam to be debunched only at the very end, just prior to extraction, as can be seen in Fig. 38.
Fig. 38: Magnetic field (black) and RF voltage (h=8, blue; h=16, red) for the whole magnetic cycle. The shaded area corresponds to the transverse splitting gymnastics.

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1 Brief overview of the chain of LEP injectors

LEP was an electron–positron storage ring of 26.7 km circumference with four collision points and an initial beam energy of about 46 GeV, sufficient for the production of the neutral boson $Z^0$ but not for that of the charged boson pair $W^\pm$. The LEP storage ring was designed to have the potential to reach a beam energy of about 100 GeV provided that a superconducting radio-frequency (RF) system was developed. The magnets were designed for a beam energy of 125 GeV.

The LEP injector chain and LEP storage ring are shown in Fig. 1. The first part of the chain of injectors, the LEP pre-injector (LPI), consisted of two LEP injector linacs (LIL) and an electron–positron storage ring (EPA). A 200 MeV high-intensity electron linac (LIL-V), fed by an electron gun, produced positrons in a tungsten converter target for LEP positron filling. The electron beam for LEP electron filling was deflected through a hole beside the target to avoid crossing it. Further lepton acceleration followed in a 600 MeV low-intensity electron–positron linac (LIL-W). The linac pulses were then stored sequentially in eight buckets of the 600 MeV electron–positron accumulator (EPA). The eight positron bunches, and 1.2 s later the eight electron bunches, were ejected to the PS (once every PS supercycle) and accelerated to 3.5 GeV with a 114 MHz RF system. While the eight electron bunches were collected within one PS basic period of 1.2 s, it took a full PS supercycle to accumulate in EPA the same quantity of positrons [1, 2].

Fig. 1: Schematic view of the LEP injector chain of accelerators and the LEP storage ring [3] with the four experiments ALEPH, DELPHI, L3, and OPAL.

The PS being a combined-function machine, horizontal betatron oscillations were excited by synchrotron radiation at higher beam energies, though the energy oscillations were strongly damped. This damping behaviour would have led to a little energy spread, inadequate for beam stability in the
PS and for SPS injection. To modify and control the damping partition, Robinson wigglers had to be installed in the PS. Since the electron–positron emittances were smaller than the proton emittances, the leptons could be accepted by the SPS at a fairly low energy of 3.5 GeV. However, to prevent instabilities and beam losses, the total charge accelerated per pulse had to be spread over many bunches. This was the reason for choosing eight bunches throughout the injector chain as the basic mode of operation.

Next, the eight positron bunches were transferred to the SPS in two batches of four bunches (spaced by 30 ms) via the existing proton beam line TT10, and the eight electron bunches were similarly sent the SPS in two batches of four bunches through the past antiproton beam line TT70. The leptons were originally accelerated to 20 GeV in the SPS with an extra 200 MHz RF system consisting of 32 single-cell cavities and, after extraction the SPS, they were sent to LEP via two new transfer lines.

The lepton beams were injected in the arcs of LEP, where the dispersion function was non-zero. The circulating beam was brought close to the septum by means of a closed-orbit bump so that the incoming beam then followed an orbit similar to and near to that of the circulating beam. So, the injected bunch could be stacked in either betatron phase space (large-amplitude betatron oscillations about the central orbit integrating the stored beam density after synchrotron radiation damping) or synchrotron phase space (large-amplitude synchrotron oscillations about an off-momentum orbit, reaching the stored beam density after damping, as the dispersion function was non-zero at injection and the incoming lepton energy was a bit lower than the tuned LEP energy) next to the already circulating bunch of LEP. The same injection equipment was used for both betatron and synchrotron phase space stacking schemes, the preference among the two depending on the LEP operation mode.

Quite wide-ranging modifications had to be made to use the PS as a 3.5 GeV electron–positron synchrotron. Almost all the existing equipment of the PS machine was compatible with the acceleration of electrons and positrons. However, the vacuum chamber was entirely changed; electron and positron transfer lines from EPA to PS and injections into the PS were added. New 114 MHz RF cavities, Robinson wiggler magnets, and some instrumentation were added too. The new injection system was installed without compromising the performance with proton beams. The extraction channels were the same as for proton–antiproton operation. Since the PS is a combined-function lattice synchrotron and has a long acceleration cycle, the implementation of Robinson wigglers to ensure the stability of the beams was essential. The wigglers also helped to match the longitudinal bunch size to the SPS.

In 1986 leptons were injected and accumulated in the EPA at 500 MeV instead of 600 MeV as initially planned. Since then, 500 MeV remained the nominal lepton energy in EPA. First injection in the PS of electrons at 500 MeV and acceleration was achieved in 1986. By 1987 electron and positron beams were ready.

2 Operating modes of the PS and SPS injectors

In the early years for the basic mode of operation the electrons or positrons were accelerated in the dead-time of the SPS; but in place of one acceleration cycle, four 1.2 s lepton magnetic cycles were inserted between the proton cycles to decrease the intensity of the lepton beams in the injectors for beam stability reasons. Positrons were accelerated in the first two cycles and electrons in the second two, which led to the PS and SPS supercycle pattern \{p e^- e^- e^-\}. Both LEP beams consisted of four bunches. Figure 2 shows the magnet supercycle pattern of the SPS and PS, and the total beam intensity in the EPA. PS and SPS supercycles were made of various magnetic cycles, one or several cycles being allocated to each user [4].

Within a SPS 14.4 s supercycle time period, the positrons were accumulated in the EPA during the quite long SPS proton cycles due to the low positron intensity of the linac (LIL-W). The linac
operated with a repetition frequency of 100 Hz, and each pulse was put one at a time into another one of the eight EPA stockpiling buckets by stacking the pulse in betatron phase space close to the stored bunch (the elapsed time between two injections into the same bucket was 80 ms). Hence, after the required beam intensity was reached, each of the eight positron bunches was moved onto a thin electrostatic septum which cut in half the bunch in betatron phase space and ejected one half to the PS on the first positron cycle. The remaining eight halves stayed in EPA waiting for the second positron cycle to be transferred to the PS. The eight bunches injected into the PS were then accelerated to 3.5 GeV and ejected to the SPS, accelerated to 20 GeV and sent to LEP. Once the positrons were extracted from EPA the linac began to inject electrons and filled up the eight EPA bunches to an intensity equal to half that of the positrons. The eight electron bunches were then transferred through the PS and SPS to LEP like the positrons. After the second electron cycle, the linacs resumed positron injection into the EPA. All circular injector accelerators ran with eight bunches to lessen the charge per bunch.

![Fig. 2: The 14.4 s PS and SPS supercycles and the EPA total beam intensity. Positrons and electrons were accelerated on the four last consecutive 1.2 s cycles of the PS supercycle](image)

Variant operating mode schemes were examined to cope with possible constraints due to the stability thresholds. Had the thresholds been less favourable than expected, the PS and SPS bunch intensity would have had to be decreased by a factor of, say, two and the number of cycles doubled. The EPA electrostatic septum would have cut the eight positron bunches such that one quarter of the initial intensity was extracted each time. The eight bunches remaining for the last positron cycle would have been transferred to the PS via standard extraction. The electrons would have been handled in the same way as in the basic scheme, except that there would have been four electron transfers during the supercycle instead of two.

Later, once the new 100 MHz RF cavities were installed in the SPS, allowing the bunch intensity to be increased, a new mode of operation using only two magnetic cycles per PS supercycle was feasible, the first cycle for positron acceleration and the second for electron acceleration.

### 3 Lepton injection into the PS

The ratio of the PS and EPA circumferences was chosen to be equal to the integer 5, and since the bunches were equidistant in EPA and PS the eight EPA bunches could be injected within a single turn of the PS. Single-turn injection was desirable because it makes the beam transfer very fast so that a slowly rising PS magnetic field could be allowed. The design of the PS injection channels took into account the constraints imposed by the position of the EPA and the operation of the PS with proton beams. Symmetric injection trajectories into the PS were chosen to standardize equipment, with a large angle of incidence of 160 mrad to reduce the magnet stray field effect. The injection positron septum was located in straight section SS92, that of the electron septum in SS74. Enough space was left in the straight sections for the installation of a vertical correction dipole and a position monitor [1].

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The injection positron kicker was located in SS94 and the electron kicker in SS72. The kicker fall-time was less than 250 ns, corresponding to less than one eighth of the PS circumference. The kick strength (9 mrad) was strong enough that no slow injection bump was necessary. Single-turn injection was achieved through the electron (positron) injection channel by means of a fast kicker magnet one eighth of a betatron wavelength downstream of a pulsed septum magnet. There was no closed orbit bump in the injection area so as to avoid aperture restrictions.

Chromaticity adjustments were performed with a small damping change at injection using the PS auxiliary windings. A small energy damping partition number change of \( \Delta J_e = -0.5 \) was obtained through an unbalanced combined-function bending magnet field using the PS auxiliary winding figure-of-eight loop. The ensuing tune change was cancelled by powering the focusing and defocusing pole-face-winding coils. The sextupolar component of these coils modified the chromaticities and made them positive in both planes, as required to avoid head–tail instabilities.

4 Emittance control of the PS lepton beams using a Robinson wiggler

In 1958, Robinson of the Cambridge electron accelerator (Massachusetts) proposed that a gradient wiggler magnet be used to stabilize naturally unstable electron and positron beams in combined-function machines. In 1986 such a method was applied in the PS so that it could serve as an accelerator in the LEP injector chain. A prototype wiggler magnet was designed and constructed at CERN. As predictions were confirmed by measurements carried out in the PS with electrons and in the DCI (LAL, Orsay, France) with positrons to check the damping variations produced by this wiggler, three wiggler magnets were installed in the PS as it was part of the LEP injector chain [5].

A Robinson gradient wiggler magnet consists of an even number of combined dipole–quadrupole magnet blocks of identical pole profile. The orientation of the pole profile is the same in all four blocks with field and gradient of alternating polarity. The overall beam deflection is cancelled by powering the half of the blocks with opposite polarities. To first-order this restricts the closed-orbit perturbation and offsets the quadrupole focusing.

The damping of betatron and energy oscillations is proportional to the damping partition numbers \( J_x, J_y, J_e \) which can be expressed in terms of synchrotron radiation integrals \( I_2 \) and \( I_4 \) where \( D_x \) is the dispersion function, \( B_y \) the magnetic field, \( \rho_x \) the curvature radius, and \( k_x = -(B_y \rho_x)^{-1} \partial B_y / \partial x \) the normalized gradient

\[
J_x = 1 - \frac{I_4}{I_2} \quad J_y = 1 \quad J_e = 2 + \frac{I_4}{I_2}
\]

with (assuming a planar ring and wiggler sector magnets for simplicity)

\[
I_2 = \oint \frac{ds}{\rho_x} \quad I_4 = \oint \frac{d\rho_x}{\rho_x^7} (1 + 2\rho_x^2 k_x) \, ds.
\]

An individual wiggler magnet adds a contribution \( \Delta I_4 \) to \( I_4 \) and a small positive amount \( \Delta I_2 \) to \( I_2 \)

\[
\Delta I_4 = 2 \int_{\text{wiggler}} \frac{d\rho_x k_x}{\rho_x} \, ds \quad \Delta I_2 = \int_{\text{wiggler}} \frac{1}{\rho_x^3} \, ds.
\]

If the gradient wiggler is such that field and gradient are of opposite sign (i.e., \( B_y \partial B_y / \partial x < 0 \)), its contribution to \( \Delta I_4 \) is negative and consequently \( \Delta J_x \) is positive (though \( \Delta I_2 > 0 \) slightly lessens the positive change of \( J_x \)) and damping is increased in the horizontal plane. Hence the gradient wiggler magnet increases the damping of radial betatron oscillations and decreases the damping of energy oscillations (\( J_e = 2 + I_4/I_2 \)).

Equilibrium transverse emittances and energy spread are reached when the mean quantum excitation rates are equal to damping rates.
\[
\frac{\sigma^2}{E^2} = \frac{C_q y^2}{J_x \rho_x} \quad \epsilon_x = \frac{C_q y^2 I_5}{J_x I_2} \quad \epsilon_y = \frac{C_q y^2 (\rho_x^{-3})}{2J_y (\rho_x^{-2})}
\]

for a planar ring, where \( C_q = 3.8319 \times 10^{-13} \) for electrons–positrons, and

\[
I_5 = \int (\beta_x D_x^2 + 2\alpha_x D_x D'_x + \gamma_x D_x^2) (\rho_x^{-3}) ds.
\]

The PS gradient wiggler magnet consisted of four consecutive blocks of identical pole profile open to the outside of the machine (see Figs. 3–5), powered either as a FDDF or DFFD structure. Both configurations provided the same damping and focusing changes, but the former produced in the wiggler a local closed-orbit bump to the outside of the machine whereas the latter produced a local orbit bump to the inside, the two outer blocks producing about the same deflection as the inner ones.

**Fig. 3:** Schematic representation of the four Robinson gradient wiggler blocks

**Fig. 4:** One of the four identical PS wiggler blocks before end shimming

**Fig. 5:** A wiggler installed in a PS straight section

The wiggler was installed in a straight section of the PS together with a correction dipole to compensate for residual horizontal orbit distortion and with a correction quadrupole to reduce the
betatron tune changes. The wiggler polarity was such that the local closed-orbit bump in the magnet was to the outside of the PS. Closed-orbit distortion and betatron tune changes induced by the wiggler were measured as a function of energy.

The wiggler was then transferred and installed, together with an adapted vacuum chamber on the bottom ring of DCI (LAL, Orsay). Its polarity was such that the local bump in the wiggler was towards the outside of the machine. Measurements of the bunch length (by means of the digitized signal from a PU electrode) and the horizontal profile (by means of synchrotron light monitors) were carried out for various wiggler excitations. The longitudinal and horizontal partition numbers were deduced from the measurements. Figure 6 shows the effect on the horizontal beam size when the wiggler is excited.

![Fig. 6: Horizontal positron beam profile in DCI (a) without the wiggler, (b) when the wiggler was excited](image)

Measurements with a proton beam in the PS showed that the wiggler magnet behaved as expected as far as beam optics are concerned. Measurements with a positron beam in the DCI showed that damping changes expected were obtained in both the horizontal and longitudinal planes. In the PS a maximum change of $\Delta J_x = 1.6$ could be produced by such a wiggler. Following these results, three magnets of this type were installed in the PS in 1986 to provide the required damping changes and enable this machine to play its role in the LEP injector chain.

Because of the combined-function magnets in the PS, the longitudinal and horizontal damping partition numbers were $J_x = 4$ and $J_x = -1$, so electron acceleration was anticipated to be horizontally unstable. Thus in all three modes the damping partition numbers, and hence the longitudinal and horizontal beam emittances, had to be controlled by Robinson wigglers (in particular, getting $J_x > 0$ was essential to ensure beam stability).

5 Synchrotron radiation and vacuum

The synchrotron radiation did not penetrate the wall of the PS vacuum chamber at 3.5 GeV. The critical energy of the photons was only 1.4 keV, and the photons were absorbed upon traversing a few micrometres of metal. With $8 \times 10^{10}$ particles circulating in the PS on the 3.5 GeV flat-top the power lost in the vacuum chamber around the bending magnets was about 1 Wm$^{-1}$ so that no noticeable heating of the vacuum chamber occurred.

Concern had been expressed early on about the amount of synchrotron-radiation-induced gas desorption in the PS due to the acceleration of positrons and electrons. Extrapolations from measurements made on the DCI (LAL, Orsay) in 1984 showed that the initial increase in outgassing rate due to synchrotron radiation would have been more than one order of magnitude above the actual outgassing level with protons and what had been initially assumed for electrons–positrons. Experimental data on the molecular yield $\eta$ (number of molecules produced per incident photon) on stainless steel at PS conditions had been obtained from a test of a typical chamber in a beam line of the DCI ring [1].

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Results showed that from an initial value of $10^{-8}$ mbar, the mean pressure grew to $2 \times 10^{-7}$ mbar ($1.5 \times 10^{-7}$ Torr) with four nominal electron cycles in a 14.4 s supercycle. The lowest mean dynamic pressure registered in the ring under nominal conditions was $4 \times 10^{-7}$ mbar ($3 \times 10^{-7}$ Torr). Comparison of initial molecular yields of the EPA ($\eta = 1.2 \times 10^{-5}$) and of the PS ($\eta = 2.5 \times 10^{-3}$) showed a noticeable difference in the surface state of these two stainless steel chambers, which could not be explained only by the photon energy (the PS critical energy 1.4 keV at 3.5 GeV, EPA 200 eV at 500 MeV). The better EPA performance was thought to be caused by the 950°C vacuum firing applied as the last step in the chamber preparation sequence. This had reinforced the expectation of a radically reduced pressure increase with the new PS vacuum chamber, which was submitted to the same treatment.

So, after the mid 1980s an improvement programme for the PS vacuum system was carried out. All 100 magnets received new vacuum chambers made out of vacuum-fired stainless steel. Almost all seals used were by then made from metal; lead, aluminium, or copper. Most of the big equipment tanks for septa or kickers were equipped with rectangular covers with vacuum seals made out of a diamond-shaped aluminium extrusion. The total installed pumping capacity with some $80 \times 200$ l/s and some $40 \times 400$ l/s gave an average pressure in the $10^{-8}$ mbar region under static conditions. By then intensities of the lepton beam had also increased such that the created desorption due to synchrotron radiation gave rise to pressure flashes and increases up to a factor of three.

### 6 Beam stability

The main, risky, single-bunch instabilities were the fast-growing turbulence effects driven by mode coupling via the broad-band impedance, mainly harmful at injection where the beam energy was low. The RF parameters of the EPA accumulator had to be properly chosen so that the bunch energy spread was adequate and the peak current stayed below the threshold in the receiving PS machine. Hence the PS acceleration mode was strongly conditioned by beam stability considerations at injection in the SPS. In order to obtain a sufficient energy spread at PS injection, the lattice of the EPA had a reduced damping partition number $J_\varepsilon$. Estimations were based on the longitudinal low-frequency impedance of $|Z/n| = 20 \, \Omega$ in the PS and the SPS, as indicated by measurements with proton beams. The high-frequency impedance was assessed by extrapolation using a resonator model with a resonance frequency at 1.3 GHz [1].

For possible multi-bunch instabilities driven by the low-frequency impedance, the proton feedback systems would have helped. Good control of chromaticity was necessary so that the growth rate of the head–tail modes was minimized.

### 7 Instrumentation and controls

At the EPA–PS hand-over point a beam-position monitor, a beam-profile monitor, and a beam-current transformer measured the incoming beam characteristics. Matching of both injected beams was measured by a single set of three beam-profile monitors.

The electronics of the forty PS beam-position monitors (electrostatic pick-ups) also used for the proton orbit measurement were adapted to the very short electron–positron bunches by properly shaping the electrode signal with a filter. The surface of the electrodes was not exposed to synchrotron radiation, except for one monitor located in the enlarged vacuum chamber. Since the pick-ups are located in the fringe field of the main magnet, the secondary electrons were trapped before they could harm the signals of the electrodes. New beam-position monitors were installed to measure the
amplitude of coherent betatron oscillation and the mean radial position at injection. Also, electron–
positron beam intensity, bunch length, and bunch structure measurements were available for beam
diagnostics. Significant amounts of new equipment had to be installed in the PS control system to
manage the electron–positron operation, which differed in some ways from the proton operation.
Software and controls hardware were developed, mostly to handle speed and sequencing problems [1].

8 PS lepton acceleration schemes
As part of the LEP injector chain, the PS (i) received electrons and positrons from the EPA using a
bunch-into-bucket transfer scheme, where the PS RF system was locked to that of the EPA; (ii)
accelerated them either with the usual 10 MHz ferrite cavities, driven on h = 16 or h = 8, or with the
new 114 MHz cavities on h = 240; (iii) accurately positioned the bunches at high energy for correct
bunch-into-bucket transfer to the SPS; (iv) shaped the bunches so that they were stable in the SPS
using one of the three techniques envisaged: ‘bunch compression’, ‘bunch expansion’ or ‘long bunch
expansion’.

8.1 Bunch requirements
Bunch length and energy spread were chosen carefully to avoid transverse and longitudinal single-
bunch instabilities (turbulences) associated with high peak currents in the SPS. In particular, the
bunches had to have the right longitudinal dimensions at peak energy in order that they be trapped by
the SPS RF system without instabilities. Analysis of the beam dynamics in the combined-function
lattice of the PS showed that this requirement was fulfilled after the damping partition numbers were
changed using Robinson wigglers.

The following nominal beam parameters are those of the 1983 LEP design status [6].

The maximum bunch length allowed at 3.5 GeV injection in the SPS was derived from
conditions on longitudinal matching and plausible ratio between the SPS bucket height and the bunch
energy spread $\sigma_e$ (r.m.s. bunch height), leading to a combined condition on the bunch length so as to
fit the bunches into the SPS bucket with a large enough margin

$$\sigma_s \leq \frac{\lambda_{RF(SPS)}}{nn^2} \sqrt{1 - \frac{\pi}{2} \phi_s} \tan \phi_s$$

where $\sigma_s$ is the r.m.s. bunch length, $\phi_s$ the stable phase angle, $n \geq 5/2$ and $\lambda_{RF(SPS)} = c/f_{RF(SPS)}$, $c$ being
the speed of light.

For a small value of the stable phase angle, the latter condition reduces approximately to $\sigma_s \leq \frac{c}{(n\pi f_{RF(SPS)})}$, yielding $\sigma_s \leq 0.16$ m (assuming $n = 3$) considering the operational SPS 200 MHz RF
system ($f_{RF(SPS)} = 200$ MHz).

It can be shown that the minimum relative energy spread $\sigma_e/E$ required to inject at 3.5 GeV in
the SPS above the longitudinal and transverse turbulence threshold is

$$\left(\frac{\sigma_e}{E}\right)^2 \geq \frac{c}{2\pi^{3/2}} \frac{N_p|Z/n|}{\sigma_e\alpha_pE} \frac{\sigma_e}{E} \geq \frac{k}{f(\sigma_e)} \frac{N_p\epsilon}{R\alpha_pE}$$

where $R$ is the mean SPS radius.

The first equation refers to the longitudinal threshold, the second to the transverse one, with $k =
2.26 \times 10^3$, $f(\sigma_e) \sim 18.1 \times \sigma_e$ for $\sigma_e \geq 0.07$ m, $N_p$ being the number of particles per bunch, $\alpha_p$ the
momentum compaction factor, $Z/n$ the SPS wall impedance, and $\epsilon$ the electron charge.

Figure 7 shows the turbulence threshold where the forbidden regions are shaded. It can be seen
that transverse stability imposes more strict constraints than longitudinal stability. With these
constraints an operating point (Ej) at PS ejection with a small energy spread and a long bunch length was chosen because it minimized the wiggler strength and the required RF voltage in the PS. Its coordinates defined the longitudinal beam dimensions at PS ejection: $\sigma_s = 0.16 \text{ m}$, $\sigma_{e/E} = 10^{-3}$ (yielding a longitudinal bunch area of $\sigma_s \times \sigma_{e/E} = 1.6 \times 10^{-4} \text{ m}$), at an intensity $N_b = 0.8 \times 10^{10}$ particles per bunch. These values were the nominal characteristics of bunches necessary for proper injection and trapping into the SPS 200 MHz RF system at 3.5 GeV. The number of particles per bunch was assumed to be raised without trouble up to $N_b = 10^{10}$.

![Fig. 7: Constraints at SPS injection (shaded) and location of the operating ejection point Ej](image)

Rephrasing the single-bunch transverse stability criterion in terms of longitudinal bunch area amounts to saying that $\sigma_s \times \sigma_{e/E} \geq 1.6 \times 10^{-4} \text{ m}$. The bunch was then assumed to be longitudinally stable provided it was transversally stable. The PS without any modifications ($J_e = 4$) could have supplied at 3.5 GeV: (i) a bunch of length $\sigma_s = 0.46 \text{ m}$ and a longitudinal bunch area of $\sigma_s \times \sigma_{e/E} = 0.1 \times 10^{-4} \text{ m}$ with the 10 MHz RF ferrite cavities tuned at 7.6 MHz; (ii) $\sigma_s = 0.05 \text{ m}$ and $\sigma_s \times \sigma_{e/E} = 0.1 \times 10^{-4} \text{ m}$ with the 200 MHz RF cavities. In the first case the bunch was too long, and in both cases the bunch area was too small to avoid turbulences in the SPS.

Besides beam acceleration the PS RF system had to compensate for the synchrotron radiation energy losses at high energy, equal to about 200 keV per turn at 3.5 GeV, and to provide an RF bucket sufficiently large for a satisfactory lifetime in the presence of quantum fluctuations.

### 8.2 Bunch shaping methods

Two techniques mixing the effects of RF and wigglers were initially proposed for matching the PS bunches to the SPS demands: the ‘bunch compression’ and the ‘bunch expansion’ shaping [1, 4, 7].

#### 8.2.1 Bunch compression

The ‘bunch compression’ method made use of the PS 10 MHz ferrite cavity system tuned at 7.6 MHz ($h = 8$) as the accelerating system. This low-frequency RF system yielded a large bunch area, but with a too long bunch. So, when the beam reached the 3.5 GeV flat-top, a second RF system composed of two 114 MHz cavities ($h = 240$), yielding 1 MV of peak RF voltage [8], was adiabatically turned on to compress the bunches, the bunch length being expected to shorten as the voltage rose from 5 kV to 1 MV (fast regarding the radiation damping time $\tau_e \sim 24 \text{ ms}$), keeping the large bunch area conserved. With this bunch shaping technique the damping partition number $J_e = 3.1$ was foreseen to be close to its natural value $J_e = 4$, a single Robinson wiggler was thus necessary, yielding $\Delta J_e = -0.9$ (Table 1).

The acceleration rate was $dE/dt = 2.1 \text{ GeV s}^{-1}$ ($dB/dt = 0.1 \text{ T s}^{-1}$) during the first 50 ms after injection and $dE/dt = 11.2 \text{ GeV s}^{-1}$ ($dB/dt = 0.53 \text{ T s}^{-1}$) for about the next 250 ms before the 3.5 GeV
flat-top was attained. After the lepton beam reached the required energy spread along the flat-top a first batch of four bunches was ejected. The second batch of four bunches waited for the reloading of the kicker magnets before it was ejected. During the kicker reloading time, the blow-up of the bunch dimension due to the quantum excitation was less than 5%.

The ‘bunch compression’ shaping method was tested. However, it was discarded as a result of the overheating of the ferrites at this 7.6 MHz frequency and due to the relative complexity of the method compared to other bunch shaping techniques.

Table 1: ‘Bunch compression’ method – parameters at injection and on the 3.5 GeV flat-top before and after compression (1983 status)

| $N_b$ | $E$ (GeV) | $\sigma_s$ (m) | $\sigma_e/E$ | $J_e$ | $V_{RF(1)}$ (kV) | $f_{RF(1)}$ (MHz) | $V_{RF(2)}$ (kV) | $f_{RF(2)}$ (MHz) |
|-------|-----------|----------------|-------------|-------|----------------|-------------------|----------------|----------------|
| Injection | $10^{10}$ | 0.6 | 0.5 | $0.6 \times 10^{-3}$ | 3.1 | 120 | 7.6 (h = 16) | – | – |
| Before compression | $10^{10}$ | 3.5 | 0.5 | $0.3 \times 10^{-3}$ | 3.1 | 220 | 7.6 (h = 16) | 5 | 114 (h = 240) |
| After compression | $10^{10}$ | 3.5 | 0.5 | $10^{-3}$ | 3.1 | 220 | 7.6 (h = 16) | 1000 | 114 (h = 240) |

8.2.2 Bunch expansion

In the ‘bunch expansion’ method, the same 114 MHz RF system of two cavities (h = 240) accelerated the beam from 500 MeV at injection to 3.5 GeV, the acceleration rate being the same as for ‘bunch compression’. Unlike the ‘bunch compression’ mode only a single RF system was necessary. The required energy spread $\sigma_e/E = 10^{-3}$ was obtained at the end of the acceleration by adjusting the longitudinal damping partition number from its natural value $J_e = 4$ down to $J_e = 0.2$ with two Robinson wiggler magnets, each making changes $\Delta J_e = -1.9$.

The required bunch length of $\sigma_s = 0.16$ m was achieved by setting at about 950 kV the total accelerating voltage of the two 114 MHz cavities on the 3.5 GeV flat-top. At this energy the longitudinal damping time was 200 ms. As the bunch energy spread at the beginning of the flat-top was smaller than the equilibrium energy spread, $\sigma_e/E$ and $\sigma_s$ slowly expanded to the required values until the proper longitudinal emittance was reached (see Table 2 and Figs. 8 and 9).

Table 2: ‘Bunch expansion’ method – parameters at injection and at 3.5 GeV before ejection (1983 status)

| $N_b$ | $E$ (GeV) | $\sigma_s$ (m) | $\sigma_e/E$ | $J_e$ | $V_{RF(1)}$ (kV) | $f_{RF(1)}$ (MHz) | $V_{RF(2)}$ (kV) | $f_{RF(2)}$ (MHz) |
|-------|-----------|----------------|-------------|-------|----------------|-------------------|----------------|----------------|
| Injection | $10^{10}$ | 0.5 | 0.2 | $0.6 \times 10^{-3}$ | 0.2 | 40 | 114 (h = 240) | – | – |
| Ejection | $10^{10}$ | 3.5 | 0.16 | $10^{-3}$ | 0.2 | 950 | 114 (h = 240) | – | – |

Fig. 8: Electron cycle with the ‘bunch expansion’ mode (time-scale 100 ms/div):

a) circulating beam current, b) detected wideband pick-up electrode, c) dB/dt
These two acceleration modes were expected to give different transverse emittances as the horizontal partition number $J_x$ was very different in the two cases. Calculations led to $\varepsilon_x = 0.04 \ \mu m$ for ‘bunch expansion’, with $J_x = 2.8$. In the case of ‘bunch compression’ the emittance was larger, $\varepsilon_x = 0.22 \ \mu m$ for the first batch and even enlarged $\varepsilon_x = 0.32 \ \mu m$ for the second batch, with $J_x = -0.1$ (negative as the wiggler was weak). The horizontal, uncoupled emittance of the second batch being too large for the SPS electron injection channel, strong coupling between the horizontal and the vertical planes had been produced by powering the existing skew quadrupoles in the PS. This would have brought the emittances at transfer to $\varepsilon_x = \varepsilon_y \leq 0.11 \ \mu m$ and $\leq 0.16 \ \mu m$ for the first and second batch, which suited the SPS.

‘Bunch expansion’ was estimated to have the potential to reach higher energies and intensities provided wigglers and RF cavities were added. However, ‘bunch expansion’ would have needed strongly excited Robinson wigglers and operation with a very small $J_y$. This shaping method was also tested, but not regularly put into operation because the next bunch shaping scenario allowed the acceleration and ejection of doubly more populated bunches to the SPS.

8.2.3 Long bunch expansion

A third method of bunch shaping was also worked out, the ‘long bunch expansion’ mode, which took advantage of the use of the new SPS 100 MHz RF system for trapping the PS bunches, rather than the 200 MHz RF system. However, like the ‘bunch compression’ mode it required a double RF system: a single 114 MHz ($h = 240$) RF cavity (0.5 MV of peak voltage) to accelerate the beam and the 10 MHz ferrite cavity system tuned at 3.8 MHz ($h = 8$) (200 kV of peak voltage) as compensation to energy loss during bunch shaping. This frequency was chosen to avoid the ferrite overheating at the higher 7.6 MHz frequency ($h = 16$) as in the ‘bunch compression’ mode.

With this scheme, bunches with the same $\sigma_e/E$ but with bunches twice as long ($\sigma_s = 0.32 \ m$) could thus have a double intensity and be safely injected into the SPS (constraints $\sigma_s, \sigma_e$ and $\sigma_s/E$ of Fig. 7 had to be recomputed for a double longitudinal acceptance, with $f_{RF(SPS)} = 100 \ MHz$). Like in the ‘bunch expansion’ mode, the longitudinal damping partition number was tuned to $J_e = 0.2$ but the 114 MHz RF voltage was reduced down to about 250 kV before extraction to arrive at the 0.32 m bunch length. Unfortunately, the 250 kV supplied an RF bucket too small to give enough quantum lifetime for synchrotron radiation loss compensation. So, to enlarge the 114 MHz bucket, the 10 MHz ferrite cavity system on $h = 8$ and properly synchronized to the 114 MHz system, was powered at 200 kV too. Thus, during the whole cycle, the required RF voltage never surpassed 500 kV, allowing the use of a single 114 MHz cavity (see Fig. 10). The ‘long bunch expansion’ shaping-mode was finally retained as the preferred bunch shaping scenario.
8.3 Observation of collective effects

For the nominal bunch characteristics and the PS wall impedance as assessed from earlier measurements with proton bunches ($Z/n = 18\pm5 \, \Omega$), the 3.5 GeV electron beam did not suffer any significant potential well bunch lengthening. Nonetheless, measurements on short dense bunches showed bunch lengthening and corroborated a wall longitudinal impedance of about $Z/n = 16\pm4 \, \Omega$ [4]. These dense bunches were obtained with a damping partition number $J_e = 3.5$. At intensities above nominal value and beam kept on a 3.5 GeV flat-top five times longer than usual, transverse blow-up was observed, ascribed to the presence of ions because the blow-up was highly dependent on the PS mean pressure and bunch spacing.

8.4 PS extraction

The extraction system was the same as that used for past proton–antiproton operation. The positrons were extracted at straight section SS16 and transferred to the SPS via the transfer lines TT2 and TT10, while the electrons were extracted at SS58 and transferred via TT70 and TT60.

The ejection of leptons from the PS was done by means of the full-aperture kicker consisting of twelve independent modules, located in PS straight sections SS71 and SS79. Since at least two modules were to be fired per bunch transfer at 3.5 GeV, not all eight bunches could be ejected without reloading of some of the pulse-forming networks. The favoured approach was to eject a first batch of four bunches firing two kicker modules and to reload when the second batch was re-phased. The kicker reloading time was about 30 ms [1].

9 PS to SPS lepton transfer scheme I: eight SPS bunches into eight LEP buckets

With a view to increasing the bunch intensity, the injection scheme into LEP was determined by the necessity to stay away from bunch instabilities. The most serious instability was the transverse turbulence at 3.5 GeV in the SPS. This transverse turbulence threshold, combined with the restriction of bunch length given by the SPS 200 MHz RF system, fixed the operating point at transfer, characterized by the nominal parameters: $\sigma_z = 0.16 \, m$, $\sigma_y/E = 10^{-3}$, $N_b \sim 10^{10}$ particles per bunch. To upgrade the SPS collider for the Antiproton Collector, a new 100 MHz RF system was installed in 1987. This system, with its six single-cell cavities delivered a total RF peak voltage of 2 MV. Investigations were carried out to study whether the injection of lepton bunches from the PS into a 100 MHz SPS bucket twice as long would have been helpful.

With the longitudinal acceptance limit pushed higher by a factor two, the number of particles per bunch could be doubled and the previously mentioned new beam parameters obtained, i.e., $\sigma_z = 0.32 \, m$, $\sigma_y/E = 10^{-3}$, $N_b \sim 2 \times 10^{10}$ (or more) leptons per bunch, which fulfilled the same stability
requirements as the previous nominal operating point. At equilibrium $\sigma_e/E$ is determined only by $J_e$, whereas the bunch length scales as the inverse square root of the RF voltage. This required at 114 MHz an RF voltage of about 250 kV on the PS extraction flat-top to get $\sigma_s = 0.32$ m. With this setting, the bucket area would have been too small due to the large energy loss per turn ($\sim$200 keV at 3.5 GeV). This was why the two PS RF systems operated in conjunction: the 114 MHz RF cavity for capture, acceleration, and shaping, with a 3.8 MHz RF cavity ('long bunch expansion' mode) to compensate the energy loss per turn during shaping.

After the initial commissioning tests, lepton bunches of design characteristics were delivered to the SPS with better than 90% overall transmission efficiency. At the nominal intensity the beam quality was not affected by collective effects. Higher bunch intensities ($\geq 2 \times 10^{11}$) were achieved, though transverse blow-ups have were observed due to the presence of ions.

In this SPS to LEP transfer scheme, the eight PS bunches would be expected to land in eight equidistant LEP buckets. This condition could be best fulfilled if the SPS bunches were also equidistant. Each bunch could be transferred every 27/8th SPS turns, or 7/8th LEP turn.

At that time the SPS RF system was modified, adding four superconducting RF cavities operating at the 352 MHz frequency of the LEP cavities, both to compress the bunches and match the beam to the LEP RF frequency.

### 9.1 Eight PS bunches into eight SPS buckets

Accelerating eight bunches in the SPS implied that there were at least eight locations around the ring where the bunches could be placed. This required the harmonic numbers to have a common factor equal to eight to accept eight equidistant bunches. This was clearly the case if the selected SPS RF parameters were chosen to be: (i) $h = 2312 = 2^3 \times 17^2$ (100.284 MHz) for the 100 MHz RF system (four cavities) after suitable re-tuning; (ii) $h = 4616 = 2^3 \times 577$ (200.221) for the 200 MHz RF system (twenty-one cavities) after re-tuning; (iii) $h = 8120 = 2^3 \times 5 \times 7 \times 29$ (352.209 MHz) after the introduction of the SPS 352 MHz RF system (four superconducting cavities).

Considering the 11 to 1 ratio of the SPS and PS circumferences, the eight PS bunches could be transferred into the eight SPS buckets without breaking the RF lock between the two machines. Figures 11 and 12 display a scheme compatible with the inflector hardware [9]. It specifies which PS bunch was injected into what SPS bucket, and shows the corresponding timing of the injector pulses. Note that the time interval between pulses was almost identical to the one encountered with the original scheme. The 30 ms interval between fourth and fifth bunch injection was caused by the limitations of the SPS positron inflector, not by the need to re-phase the PS. This merely required that the eight PS bunches be equidistant too, as initially foreseen.

![Fig. 11: An arrangement of the eight equidistant bunches in the PS and in the SPS (1 SPS turn = 11 PS turns)](image)
Tests of electrons and later of positrons were done on 1.2 s cycles while the PS was delivering beams of different particles to its other users, in a 14.4 s supercycle (later in a 19.2 s supercycle). It required only two injection cycles, one positron and one electron. Acceleration of leptons was achieved on these two consecutive 1.2 s cycles in the nominal supercycle for LEP filling (see Fig. 13) [10]. During lepton acceleration in the ‘bunch expansion’ mode, the HF ferrite cavities and the resonant 200 MHz cavities, normally used for proton acceleration, were respectively short-circuited and damped.

The slow cycling, combined-function PS accelerator was used as an electron accelerator besides its other uses as proton, antiproton, and ion synchrotron. After initial commissioning tests it was ready to deliver electron bunches of design characteristics with better than 90% overall transmission efficiency to the SPS. Bunch length and energy spread could also be reduced by a factor of four from the nominal values by simply decreasing the wiggler current. Although at high intensity (greater than $2 \times 10^{11}$ electrons) transverse blow-ups were observed due to the presence of ions, the beam quality was not affected by collective effects at nominal intensity.
10 PS to SPS lepton transfer scheme II: eight SPS bunches into four LEP buckets

In the early LEP operating mode (1989 to 1991), eight bunches were sequentially accelerated in the PS and in the SPS, then transferred and stored by means of double-turn injection in LEP (via betatron phase-space stacking) to provide four bunches with increased intensity for each of the two lepton beams after some SPS turns elapsed.

The LEP injection scheme discussed here was based on a different double-batch injection method also yielding four LEP bunches per lepton beam. During each of these cycles, eight bunches were accelerated in the PS, injected in the SPS, then accelerated and injected into four bunches in LEP. Unlike the early double-turn injection scenario, two SPS bunches were injected into the same LEP bucket by means of synchrotron injection phase-space stacking. This new injection scheme into LEP called for modifications in the RF systems of both the PS and the SPS, caused by the need to increase the number of leptons per bunch. Just the SPS will be sketched since the PS modifications were the same as those undertaken for the eight PS bunches into eight SPS buckets scenario. Figure 14 illustrates the case of the injection of two batches [3]. As the bunch was injected off-energy, it carried out synchrotron oscillations at the synchrotron tune \( Q_s \) and slowly damped into the circulating batch. Using this method, up to four batches could be injected, separated in time by \( \frac{1}{4} \) of a LEP synchrotron period. The second injection had to be timed to take place an odd multiple of half the synchrotron tune \( Q_s \) after the first injection.

![Fig. 14: Double-batch injection into the same LEP RF phase-space bucket](image)

To augment the bunch intensity, the LEP injection energy had to be raised up to 22 GeV to stay away from the head–tail instability that limits the beam current at low energies. The solution was to use, in the middle of the accelerating ramp, the SPS 352 MHz RF system to supply sufficient additional voltage to reach the 22 GeV top extraction energy.

All three RF systems were involved for lepton capture and acceleration in the SPS. Lepton bunches from the PS were captured and accelerated during the first part of the cycle by a 100 MHz RF system, then, the bunches were accelerated with a 200 MHz system, and the 352 MHz RF system was used to arrive at the required 22 GeV energy.

10.1 Eight PS bunches into eight SPS buckets: double-batch injection variant

The eight equidistant SPS bunches could not be injected into the four LEP buckets. Keeping the constraint that the harmonic number of the LEP RF be unchanged (\( h = 31320 = 2^3 \times 3^3 \times 5 \times 9 \)), and that of the SPS RF at 352 MHz was untouched too (\( h = 8120 = 2^3 \times 5 \times 7 \times 9 \)), and also that the ratio...
of the LEP and SPS circumferences was 27/7, it was shown that only seven SPS buckets could be used for injection into a given LEP bucket. Hence there were seven families of SPS buckets, each family containing four equidistant buckets, the families being rotated, one with respect to the other, by a multiple of 1/7\textsuperscript{th} of an SPS turn. Any pair of families could be chosen to find eight SPS bunches for transfer into the four LEP buckets. However, such a SPS bunch pattern would never have been matched with the present eight equidistant SPS bunch scheme. So, the most uniform choice for this second family is the one rotated by 6/7\textsuperscript{th} of an SPS turn, resulting in a pattern of eight SPS bunches spaced alternately by 3/28\textsuperscript{th} and 4/28\textsuperscript{th} SPS turns as shown on Fig. 15 [3, 11].

Capture and acceleration of this bunch pattern meant that the three lepton SPS RF systems operated with harmonic numbers that were all divisible by 28 and thus had to be re-tuned accordingly.

In summary, the double-batch injection SPS RF parameters: (i) $h = 2296 = 2^3 \times 7 \times 41$ (99.590 MHz) for the 100 MHz RF system, (ii) $h = 4620 = 2^2 \times 3 \times 5 \times 7 \times 11$ (200.395) for the 200 MHz RF system, (iii) $h = 8120 = 2^4 \times 5 \times 7 \times 29$ (352.209 MHz) for the 352 MHz RF system were carefully chosen to enable the transfer of eight equidistant SPS bunches into four equidistant LEP buckets, without the need to re-synchronize in either the PS or SPS.

**Fig. 15:** The arrangement of the eight bunches in the SPS for injection into four LEP buckets. A fair regular choice for the second group of four equidistant buckets is the one yielding a pattern of eight SPS bunches alternately spaced by 3/28\textsuperscript{th} and 4/28\textsuperscript{th} SPS turns

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Controls, timing, and sequencing

1 Introduction
Since the introduction of the first computer, an 8K word IBM 1800 [1], into the PS controls system in 1967, there has been a continuous process of evolution as new technologies and requirements have arrived. The PS today is one accelerator among many at CERN and is an essential component of the LHC injector chain as well as a provider of various particle beams for local experiments and other accelerators. Today the PS control system is highly integrated with those of the other accelerators, and borders between them are becoming indistinct. Much work is still in progress to unify the CERN accelerator control systems and provide a flexible and coherent set of user interfaces to the operations team, while at the same time easing development and maintenance costs [2]. This work is ongoing and will not terminate during the lifetime of the Organization; like in Scotland painting the ‘Forth Bridge’, as one part of the control system is upgraded the next legacy system upgrade becomes urgent, leading to perpetual renovation.

When the PS came on line in November 1959, all control functions were achieved manually via analogue and digital logic modules [3]. The first physics runs were delivering up to $6 \times 10^{10}$ protons per pulse by June 1960; since that time the intensity has increased by almost three orders of magnitude. During the first years leading up to 1967 when the first control computer was introduced, the number of PS experiments multiplied requiring more PS beam destinations to be handled. This trend has continued and the PS complex has been relentlessly growing in complexity ever since. Hence the computer control system has been evolving in a very volatile environment and by 1972, with the introduction of the Intersecting Storage Ring facility and the Proton Synchrotron Booster, the need for sophisticated inter-accelerator and beam-destination sequencing had to be addressed.

2 Program Line Sequencer
The PS accelerator is a strong-focusing synchrotron, and there are fundamental requirements that emerge for such a machine’s control system. The beam is injected into the main PS ring from a source at low energy and circulates around it while held in orbit by the magnetic field. There have been many sources of beam to the PS providing at various times protons, electrons, positrons, light and heavy ions, as well as antiprotons. These different beams may be injected into the PS within seconds of each other so as to provide end-users with the particles they require in rapid succession on a cycle-by-cycle basis. After injection, when the PS ring has the required beam circulating, it can be accelerated by ramping up the magnetic field while at the same time increasing the RF frequency. The balance between the RF and the magnetic field is controlled so that the beam stays in orbit during the acceleration process. Once the beam has reached the required energy, it must be extracted by kicking or pushing it out of orbit with an extraction magnetic element so as to exit down a transfer line towards an experiment or another accelerator. The magnetic field can now be ramped down and the next cycle can begin, thus producing a repeating sequence of cycles that may have different particle types, extraction energies, and final destinations. A cycle can thus be broken up into its processes: injection, acceleration and ramp-up, extraction and flat top, and finally ramp-down.

In the early 1960s an array of switches controlled the PS program by asserting logic levels on equipment to select the beam user while the function generators were pure analogue designs sometimes with feedback. The program lines were cables that travelled between the switch array and the equipment they selected. Each time a different cycle was to be played, the program lines were first selected by the switch array, the bending magnet power supply and RF subsystems were then manually set up and adjusted, so the new cycle could then be played multiple times. With the introduction of the IBM 1800 in 1967, the sequencing of the program lines was automated, a rectangular bit matrix was loaded row by row into a digital output module to control the beam destination (Beam-User) from cycle to cycle. This matrix defined the super-cycle, once the last row had been executed the row index pointer was reset and the cycle sequence could be repeated.
indefinitely. The PS power house provided the main bending magnets with power so it was logical that it also produced the next cycle pulse that was used to clock the Program Line Sequencer (PLS) on to the next cycle row. Later more and more program lines were added to the PLS. One group of these program lines exclusively selected one possible beam destination while other groups of lines selected other cycle parameters. It is interesting to note that 50 years on, we still use the terminology PLS, Group, User, User-Matrix and super-cycle, these early concepts were to have a profound influence on the future designs and how the control systems at CERN would evolve [4].

3 And then came the SPS

In 1976 the 450 GeV Super Proton Synchrotron came on line and demanded protons from the PS. Its control system was designed according to the technologies available at the time, many of which were later very interesting for the PS, in particular computer local-area networks, the Nodal interpreted networking language, and the idea of the data module which is probably one of the earliest known uses of the concept of Object-Oriented Programming [3]. Owing to the physical size of the SPS, 6.9 km in circumference, local control facilities for equipment specialists at geographically separate locations were a basic requirement. As there was no such thing as a Local-Area Network (LAN) available at that time, a packet-switching network was designed and specified at CERN and the building of it was contracted out to industry. This system was called the Message Transfer System (MTS) and supported true peer-to-peer networking. It was arranged in a star topology with a 16-bit Norsk Data mini-computer at the central hub. The Message Control Computer dealt with packet routing and supported multiple remote computer nodes; it was thus an early example of a network router. A Nodal interpreter was implemented with the capability of remotely executing code on any computer node from within a program, and arguments were bound to their values by name at run time. These features made it very simple to implement distributed programs, for example, those that acquired/controlled data on equipment connected to the front-end computers and passed the values to/from applications running in the control room. To unify access to equipment on the front-end computers, a device/property equipment access methodology, the Data Module, was designed and a standard API to call it was built into the Nodal interpreter. In a word ‘brilliant’. The use of CAMAC was pioneered at CERN in the ISR machine and the experience was very positive. The serial CAMAC technology was found to be an excellent way to address CAMAC modules controlling end-user equipment by Loop, Crate, Station, Sub-address and Function (LCNAF).

4 The PS controls renovation

By 1980 it was becoming obvious that with all these new customers, and with LEP on the horizon, a serious upgrade of the PS Complex control systems was in order [4–6]. At that time the PS Complex contained two linear accelerators — Linac I and Linac II —, the PS, its Booster the PSB, the Antiproton Accumulator (AA), the Low Energy Antiproton Ring (LEAR), and various experimental areas and transfer lines. The Lepton Injector Linac (LIL) and the Electron Positron Accumulator (EPA) were under construction, while there were plans for the Antiproton Collector (AC) on the books.

In the new PS controls project, Pulse-to-Pulse Modulation (PPM) was to be the fundamental concept built in to every level of the control system, from the auxiliary CAMAC crate controllers based on the Texas TMS 9900 microprocessor, all the way up to the application programs and displays. The idea was that the PS was to be time-sliced into virtual accelerators, each with its own cycles in the super-cycle. An operator could work on his virtual machine without unnecessarily disturbing other operators working on other virtual machines. This meant that the call to a Data-Module had to have an extra cycle parameter added. The new PLS-Line parameter was used to index columns in the Data-Module data table, giving independently addressable virtual accelerators where control and acquisition values were kept. The above mentioned TMS 9900 was able to address a CAMAC PLS receiver module to read the current PLS line and perform IO to/from a local cache of data table columns. This meant that the routine cycle-to-cycle
PPM was achieved completely within the CAMAC crate without the intervention of the host Norsk Data minicomputer. Only when the acquisition values were needed in the control room, or control values changed, was access across serial CAMAC required. The PLS was now running on it own Norsk Data computer and the program lines were serialized into a 10 kHz bit stream and distributed before each cycle around the complex to all the CAMAC crates. This message containing the PLS lines was called the ‘telegram’. It contained 256 bits denoting the PLS line Group values of both the present and the next cycles. Two CAMAC modules had been designed to react to the PLS telegram, a pure PLS receiver to provide the telegram to the TMS 9900 or the host Norsk Data computer, and a General-Purpose Preset Counter (GPPC) that was able to count a programmable delay conditioned by the telegram to produce cycle-dependent timing pulses for end-user equipment.

5 The PS/SL controls consolidation project

By 1990, it became fairly obvious that TCP/IP and Ethernet was by now a suitable candidate to replace our home-made TITN network and that the Norsk Data mini computers on which we were relying were becoming obsolete when compared with offerings from IBM, HP and DEC [7–9]. It was time to change track and follow the market forces so as to guarantee the future availability of the industrial components on which the control system relied. The new PS control system would be based on DEC workstations running Ultrix (DEC Unix) and CAMAC was to be gradually phased out in favor of VME. Communications would use TCP/IP over Ethernet and Sun-RPC, file servers would use NFS. Graphical User Interfaces were built on X-Windows and the OSF Motif widget set. The last Norsk Data mini computer and its Sintran-III operating system was finally removed from the PS control system in 1996.

6 CERN-wide timing

A collaboration project between the SPS/LEP and PS divisions was started in 1992 to define a common timing transmission standard [9, 10]. The large geographic area of the SPS control system had prompted the design of a long-distance message-based timing-transmission distribution. Four 32-bit timing frames were Manchester encoded at 512 kbits per second each millisecond and transmitted over an RS485 twisted-cable pair to remote equipment. The TG3 receivers had an embedded processor, able to decode up to four timing frames per millisecond and drive outputs accordingly to pulse end-user equipment, or to provide interrupts to real-time tasks for synchronization. The SPS timing transmission had good parity-error detection and importantly very good galvanic isolation, as needed for long-distance cables. At that time the smaller PS machines were still using individual LEMO cables and the serial telegram transmission. A new VME module, the TG8, was designed and built that had eight counters implemented on an FPGA and an on-board 68332 Motorola microprocessor. By including a Content Addressed Memory on the board, the frame decoding rate on the TG8 was increased to eight frames per millisecond; these frames now encoded timing events, PLS telegrams, the date and time, and a 1 kHz clock. Thus, each millisecond, one tick of the millisecond clock was sent by the Master Timing Generator (MTG) leaving space for up to seven other frames to be transmitted. The MTG was implemented on a PCI card that could be loaded with event tables and was synchronized to the date and time using a long-wave radio receiver.

The idea of an accelerator network became essential for the PS Complex [11], particle beams were manufactured by executing cycles in one accelerator and then transferring the beam to the next down-line machine where another cycle was executed and so on. For example, to provide the SPS with a proton beam, the path through the accelerator network might be Linac-II to PSB to PS to SPS, and to get positrons into LEP the path would be LIL to EPA to PS to SPS to LEP; such a path through the network is called a beam. A beam therefore is defined as a sequence of cycles executed in one accelerator after another until it is extracted from the network, that is, a beam is an end-product of the CERN particle-beam factory. There is also the possibility to replace one beam by another in real time depending on external conditions such as machine interlocks and operator requests or inhibits. To handle all this, operators express their requirements for the network by
building a Beam Coordination Diagram (BCD). They define the BCD using an interactive editor program in which individual accelerator cycles can be defined that can be combined to build beams. These beams and their alternatives are assembled into a BCD to be sent to the central timing for execution. During execution of the BCD the external conditions are read and the central timing takes decisions about which beam to execute next.

In 1998 the SPS had its own independent MTG-based central timing system that was synchronized to the PS Start super-cycle timing and played a fixed super-cycle with predetermined rendez-vous points for beam transfers from the PS. It was realized, however, during the planning of the LHC, that synchronized rapid super-cycle changes for the whole LHC injector chain would be required to fill it, and this implied tight PS–SPS synchronization during the change-over. By 2003 the two central timing systems were merged into a single system, the Central Beam and Cycle Manager CBCM [12], which now managed all machines at CERN. During this process a new MTG and Timing Receiver Card (CTR) were built taking full advantage of the hardware description language VHDL and the very powerful FPGA chips available. The central timing now receives the UTC second [Pulse Per Second (PPS)] from a GPS receiver and this signal conditions an atomic clock to produce a 10 MHz train; all other central timings are produced from this PPS and the 10 MHz clock.

7 Conclusions

Over the last 50 years many lessons have been learned about the importance of adopting open standards rather than relying on proprietary technologies over which we have no control; much of the renovation process is motivated by this fact. This has led to the adoption of Linux as the system of choice for front-end computers, servers, and workstations. Graphical user interfaces are written in Java, while the real-time tasks and server layers are written in C++. Communication from the control room to the servers and front-end computers is across a CORBA middleware.

Today many of the front-end systems are implemented using the VME bus in crates running LynxOs, a real-time Unix-like variant, on Power-PC CPUs acting as the bus master. Work is under way to migrate these proprietary closed systems towards Linux systems with real-time kernel extensions running on multi-core Intel- based platforms. This work involves porting device drivers, libraries, and real-time tasks to the more cost-effective and performant industry standard platforms. At the same time we can now take advantage of off-the-shelf industrial PC machines with PCI bus, which are considerably faster and much cheaper than the VME crates. Since the arrival of the LHC, many important ideas from its control system are planned to be included in the latest PS controls renovation project INCA [2]. We are also planning for the next-generation timing system (White Rabbit) [13], based on open hardware designs, in collaboration with other laboratories, with industry, and with academic institutions. The new standards will be based on synchronous gigabit Ethernet and the IEEE 1885 PTP hardware clock synchronization protocol.

In the early days, equipment specialists worked on their specific problems locally. As the PS Complex grew, approaches became broader, eventually producing methodologies applied within the entire PS Complex; next the view was of all of CERN, then we found that we could share approaches with other laboratories, and now the Open Source movement makes our approach truly global.

It has been said that one person can have an idea, but it takes many to put it into practice [3]. What we have learned from 50 years of PS controls evolution is that no matter how good an idea may be, it has a finite lifetime and must inevitably be replaced by a better one.

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Wire scanner

1 Introduction
It has always been important to measure the profile and the emittance in both planes of the circulating beam in the PS.

The first devices to be installed were fast measurement targets. Small targets are flipped on the side of the beam, their horizontal (or vertical) position is varied and measured until a specified percentage of loss is observed on a beam current transformer. They can give good information on the tails of the beam but not on the heart and they are partially destructive. The precision is reduced at lower energy since the velocity of the mechanism is too low with respect to the beam size variation.

Another development was the Ionization Beam Scanner (IBS). This electron-optical crossed-field device derives its signal from the electrons liberated by the ionization of the residual gas in the beam vacuum chamber. The proton beam is scanned in such a way that the electrons collected at any instant come from a slice of the beam close to the equipotential of the collector. This equipotential is driven through the beam to give, in time, an electrical signal proportional to the projected proton density distribution in a certain plane. It presents the advantage of a faster and repetitive measurement and low interaction with the beam. Unfortunately, several factors perturb the measurement (field imperfections, space charge from the beam etc.) and limit the use of the IBS.

In 1978, a proposal was issued to derive the transverse profile of the circulating beam from the interaction between the particles and a thin wire rapidly moving through it [1]. A first version of this device was developed and it came into operation in 1985. The signal from a secondary particles monitor or the secondary emission current of the wire is sampled against the wire position and directly gives the beam profile.

2 The mechanism
Two monitors, a horizontal and a vertical one, were installed in the PS ring (Fig. 1–4) [2]. In the present version, the mechanical device has been kept unchanged, but there are now four units installed in the machine. Each one consists of:

- a motor and the parts fixed directly to its axis,
- a transmission system, in air and in vacuum,
- a stainless-steel vacuum face,
- a U-shaped wire support and its bearings,
- a wire stretched between the two prongs of the support.

The motor is a commercially available, standard printed-circuit permanent-magnet D.C. device in a low inertia execution with aluminium current conductors (Fig. 5). The movement is transmitted to the parts inside vacuum by two push–pull rods connected to the mobile end-flanges of two metallic bellows with a stroke of 7 mm. Directly on its axis, it carries a tachymetric dynamo as a velocity captor and a potentiometer as a position indicator.

Four rolling tapes, wound around the cylindrical tube, convert a 180° rotation of the motor into a 130° rotation of the U-shaped support. This corresponds to the angle between the ‘down’ position, when the wire is entirely outside the beam aperture, and the ‘up’ position, when it is on the far side of the beam.
The arms of the U are built up of standard stainless-steel tubes of 2 mm outside diameter, and 0.25 mm wall thickness (Fig. 2). At the ends, short flexible parts hold the beryllium wire stretched between the two sprung arm-ends with a force of about 20 grams to prevent excessive sag due to acceleration. Each end of the thin wire is crimped in a small aluminium insert, insulated from the arm to allow secondary emission charge measurements.

3 First-generation system (1984)

All the controls were performed by a LeCroy first-generation stand-alone PC with an 8-bit processor running under the CP/M operating system and its associated CAMAC crate [2]. It took care of the digital control of the fast wire displacement. The position and velocity captors were connected through a multiplexer to an analogue-to-digital converter in the CAMAC crate of the PC. Home-written assembler subroutines received this information and allowed the forwards and backwards motion of the mechanisms as they provided the input signals to the power amplifiers feeding the motors through digital-to-analogue converters.

About 16 ms after the motor current was switched on, the wire holder had a rotational speed of about 135 rad/s and the wire crossed the beam area at the speed of 20 m/s. This required a linear acceleration of close to 1400 ms$^{-2}$. The velocity was kept almost constant during the beam traversal and then decelerated to reach the rest position.

When the beam was intercepted by the wire, a LeCroy 1 MHz waveform analyser sampled simultaneously the corrected-position potentiometer voltage and the scintillator signal. The clock used
was derived from the RF acceleration system to be synchronous with the particle revolution. This avoided beating phenomena with the bunch structure. Then the data were read and sorted out. The data processing consisted of a linear least-square fit of the potentiometer voltage, a calculation of the positions from the potentiometer voltages, and a calculation of the root-mean-square value of the distribution using a 5% bias to avoid excessive effect of the tails. Finally, the value of the emittance was presented for a two standard deviations projected profile (Fig. 6).

The first profiles were obtained with two 14-dynode scintillators and their photomultipliers. But they turned out to be distinctly non-linear and sensitive to the value of the high voltage chosen for the photomultipliers.

The whole control sequence for a measurement could be performed locally at the microcomputer or from the main PS consoles through a RS232 connection between the local CAMAC crate and the front-end computers of the main PS control system.

Fig. 5: The motor and the transmission system

Fig. 6: Results display on the LeCroy microcomputer

A 50 µm diameter beryllium wire was used at that time. Its interaction with the protons caused Coulomb scattering and emittance blow-up. Calculation shows that this is, expressed in normalized blow-up and µm [3]:

- 0.029 in the measurement plane and 0.053 in the other one at 26 GeV/c,
- 0.23 in the measurement plane and 0.42 in the other one at 3.5 GeV/c,

to be compared to usual normalized emittances of the order of 30 µm.

Energy loss in the beam heats the wire. For a $10^{13}$ ppp beam of 26 GeV/c and a normalized emittance of 30 µm, one finds a temperature rise of 650°C. The wire could stand intensities above $10^{13}$ ppp since the effort on the wire is low and the melting temperature of beryllium is 1287°C.

The device proved to be very helpful during the proton–antiprotons runs of the 1980s to help improve the luminosity in the SPS in collider mode. However, the reliability was poor and the precision questionable. The 50 µm diameter beryllium wires usually broke after a few hundred measurements, presumably by fatigue, the photomultipliers did not provide a good linearity or proper dynamic range, and the first-generation PC used for the controls had become obsolete.

New requirements appeared with the decision to build the LHC and especially the need to measure the emittance of high-intensity circulating beams. An improvement project became necessary and was therefore launched in 1991.
4 The 1994 upgraded system

The main feature of the first-generation wire scanner was its high velocity, obtained with a high-torque motor and low inertia mechanism. This proved very successful and reliable, so the mechanism was kept unchanged. The only modification was that the potentiometer position captor which had been the source of problems was traded for a resolver delivering two signals proportional to the sine and cosine of the shaft angle. These signals are sampled synchronously with the photomultiplier (PM) signals. The geometry of the transmission gives the corresponding wire position in the vacuum chamber. The resolution of the wire position is then better than ± 0.14 mm [4, 5].

Reliability was improved by the use of a wire consisting of a twisted strand of about 20 carbon fibres, each 7 µm thick. It proved to be reliable, and fatigue and temperature resistant.

Two scintillators are installed near the vacuum chamber, one upstream and one downstream of each wire scanner, for profiles with both particle polarities. Light-guides allow mounting of the PM away from the vacuum chamber so as to avoid direct radiation signals and radiation damage. They are simple straight empty pipes with reflecting walls. Carousels of optical filters moved by a stepping motor allow adjustment of the sensitivity over the large dynamic range.

Hamamatsu 2238 photomultipliers have been selected, with 12 mesh dynodes and tri-alkalide photocathodes, linear up to high output currents (600 mA). They work in proportional mode with a good linearity over a wide range. The cathode sensitivity is 60 µA/lm, and the current gain can reach $4 \times 10^5$.

The linearity has been checked over a large dynamic range for various types of beams, with varying intensity and with the help of the optical filters. The worst results never differed from the linear fit by more than 2%, the beam intensity measurement transformer imprecision being also included in this measurement.

The controls were totally renewed.

The emittance blow-up is less than with the beryllium wire since the carbon strand is thinner. Calculations based on the carbon radiation length give these values expressed in normalized blow-up and µm:

- 0.013 in the measurement plane and 0.023 in the other one at 26 GeV/c,
- 0.094 in the measurement plane and 0.173 in the other one at 3.5 GeV/c.

As for the heating of the wire, it has been calculated for $I_p = 2 \times 10^{13}$ ppp and a normalized vertical emittance of 30 µm:

- for a wire velocity of $v = 20$ m/s, $\Delta T = 530^\circ$C,
- for a wire velocity of $v = 10$ m/s, $\Delta T = 1060^\circ$C.

The tensile strength of the carbon wire remains good up to 1300°C so that measurements can easily be done at the high intensities of the PS.

The precision obtained for emittance measurements with the wire scanner is limited by several factors. The acquisition resolution of the wire position is probably the main cause of the overall errors. Another, less severe, limit to the accuracy is the non-linearity of the scintillator and PM assembly. There is also some imprecision on the local $\beta$ and dispersion functions at the monitor location. A last limit is the fact that the result is an average over the measurement time (usually less than 1 ms). Taking into account all these considerations, the precision is estimated to be of the order of 5% in emittance for small beams.

In spite of these limitations, the PS wire scanners provide a straightforward, precise, one-shot, and almost non-destructive way of measuring profiles and emittances in both planes, over a wide range of particles, energies, and intensities. They have been and still are very useful during the preparation of the PS as injector to the LHC. Since at present most physics research is done on
colliders, luminosity is a key parameter which critically depends on the beam emittances. Wire beam scanners are therefore used extensively and have become an essential beam-quality monitoring instrument of the CERN PS.

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The development of longitudinal phase-space tomography in the PS

1 Background

Tomography was born in 1917 when the Austrian mathematician J. Radon published a proof [1] that, for example, any two-dimensional object can be reconstructed from the infinite set of all its one-dimensional projections. This result has been repeatedly rediscovered by mathematicians, radio astronomers, electron microscopists and medical radiologists.

It was rediscovered by the author in 1993 during a CERN colloquium on medical imaging, which prompted the imaginative leap between the X-ray projections of a patient in a rotating body scanner and the turn-by-turn profiles of a bunch rotating in longitudinal phase space. Although a similar leap had already been made elsewhere in the accelerator domain [2–4], the application of existing tomographic reconstruction techniques necessarily assumed rigid, circular motion of the two-dimensional phase-space distribution since its one-dimensional projections cannot be measured simultaneously. This assumption is not generally valid in the longitudinal plane.

Around this time, in view of the LHC, there was keen interest at the PS in how to generate a bunch with a depopulated core in longitudinal phase space such that its profile would be flattened (Fig. 1) making it less susceptible to Laslett detuning [5]. The extent of the depopulation could be estimated by means of an Abel transform [6], but this has the shortcoming of assuming that the particle distribution is matched.

These are the somewhat disparate historical ingredients which eventually led to a tomographic algorithm [7] that could fully take into account the non-linearities of synchrotron motion and reconstruct the two-dimensional particle density of a bunch in longitudinal phase space — even if that distribution were mismatched.

2 Hybrid algorithm

The underlying principle of tomography is to combine the information in a sufficiently large number of profiles to be able to reconstruct unambiguously the fuller picture with the extra dimension
reinstated. The ingenuity of the algorithms employed derives from a need for reconstructions that are both stable and unique despite the necessarily finite set of data profiles.

The key to reconstruction is back projection. This is the process by which the contents of the bins of a one-dimensional profile are redistributed over the two-dimensional array of pixels which comprise the reconstructed image. The back projection of all bins of all projections yields a first approximation to the two-dimensional distribution that produced those projections. The so-called Algebraic Reconstruction Technique [8] (ART) is an iterative algorithm which exploits the fact that the coefficients for back projection can also be used to project the contents of cells into bins. Hence a new set of profiles can be obtained from the approximate distribution. Back projection of the difference between the original set of profiles and this latest one yields an improved reconstructed image.

The problem with conventional ART is that its strategies for estimating the redistribution coefficients are based on straight-line back projection, which is not the geometry of longitudinal phase space. An alternative approach is to consider how the contents of one pixel get projected into the bins of a particular profile. By launching a small number of test particles, which initially are uniformly distributed within the pixel, the calculation of coefficients becomes a simple matter of counting how many particles end up in each bin of a profile at the particular instant when that profile was measured. Provided that the trajectories of the test particles can be followed as a function of time, a set of maps can be built giving the redistribution of pixels into bins for all projections.

Furthermore, one can extract from those maps the information of the reverse transformation, namely the redistribution of bins into pixels, i.e., back projection. Thus, a hybrid algorithm which combines particle tracking with ART allows large-amplitude synchrotron motion to be taken into account since the trajectories of the test particles need not be assumed circular. Indeed, the tracking can be made arbitrarily complex while, afterwards, the tomography proceeds in exactly the same way.

In 1996, these ideas were brought together for the first time in a piece of Mathematica code comprising some 150 lines. And, following a judicious investment in 96 MByte of extra memory for a 133 MHz Pentium Pro PC, the first reconstructions using the one-dimensional projections obtained from a longitudinal pick-up were made (Fig. 2). Tests with simulated data proved the method to be both accurate — r.m.s. emittances could be reproduced at the level of a few per cent — and very robust. Since the iterations converge to the consensus of the information in the profiles, trigger jitter and noise have little consequence. In addition, since the test particles are only tracked for a relatively brief period to build the maps, moderate errors in the accelerator parameters used in the tracking model have only a minor effect. The result is a particle distribution which is consistent with all the measured profiles and the laws of synchrotron motion.

The proof of principle established, the algorithm was rewritten in FORTRAN 90 in 1997 and subsequently entered the public domain [9–11]. Considerable effort was made to optimize the code so that it could be compiled to exploit parallel architectures efficiently and high-performance FORTRAN directives were even added to the tracking routines. The new code immediately gained a factor of several hundred in execution time, particularly once enough experience had been gained to show that the number of test particles launched to build the maps could be reduced without compromising the reconstruction. Naturally, one of the first topics it was used to examine was the process by which empty phase space could be transported into the centre of a bunch to flatten it (Fig. 3).

In 2000, collective effects were introduced as an option in the tracking to allow direct space charge and the distributed impedance of the vacuum chamber to be taken into account as they affect the synchrotron motion [12,13].
Fig. 2: One of the earliest tomograms produced from real data. This inauspicious image was obtained after 10 iterations with 36 measured profiles spanning some 600 turns of the PS machine during the bunch rotation at 24 GeV/c prior to slow extraction. It took something of the order of a day to compute.

Fig. 3: (a) Left, tomographically measured phase-space distribution at 1 GeV in the Booster after brief phase modulation of the RF bucket at just below the synchrotron frequency. (b) Right, the corresponding mountain range of bunch profiles would be difficult to interpret without tomography due to the complete absence of matching.

3 Online tomography

Two digital oscilloscopes with segmentable memory could be purchased in 1999 to pursue online reconstructions at the PS and Booster. A divide-by-N burst generator was cloned from the PS orbit measurement system to provide multiple low-jitter triggers and the so-called ‘bunch-shape measurement’ application program was modified to acquire a mountain range of profiles instead of just a single trace. The application software borrowed heavily from the developments already made in offline tomography, with Mathematica being invoked to post-process intermediate files produced by the FORTRAN and display a tomogram on a console of the accelerator control system. But eventually, in 2001, tomography became an online tool [14].

Essentially the same FORTRAN code is still used to process both offline and online data. Consequently, with a little manual intervention, features not normally considered by the application program can be accessed. For example, reconstructions of bunches controlled by RF with two simultaneous harmonic numbers are not routinely made in the PS, but Fig. 4 shows such a case. The
application permits the measured data to be processed with a single mouse click and today, thanks partly to the continued evolution in processor speed since that original daydream at a CERN colloquium, usually within a matter of seconds.

Fig. 4: Measured data as viewed in the online application (left) during asymmetric bunch-pair merging at 1.4 GeV in the PS. By controlling the relative phase and voltage ratio of a dual-harmonic rf system, it is possible to merge unequal emittances. Here, one ‘bunch’ is a chimera; an empty bucket is conserved during its transportation into the core of a much larger bunch. Tomography (right) reveals a well-preserved empty bucket entering the bunch as the acceptance of the populated bucket shrinks and particles bleed out around the inner separatrix.

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