Eur. Phys. J. C 34, 15–23 (2004)
Digital Object Identifier (DOI) 10.1140/epjc/s2004-01762-0

THE EUROPEAN PHYSICAL JOURNAL C

CERN's contribution to accelerators and beams

G. Brianti

Formerly CERN

5 Chemin des Tulipiers, 1208 Geneva, Switzerland

Received: 15 December 2003 /
Published online: 4 May 2004 –

1 Introduction

Looking back at happy events of the past, the temptation is to see them with the magnifying glasses of the "good old times". In the cases of the discoveries that we celebrate today, I dare say that CERN's contributions to accelerators and beams were objectively important and even essential. Indeed, it was more than competent mastering of well proven techniques of beam acceleration, beam storing and beam handling. Of course, it needed all this, even brought to extremes, but the additional decisive touch was due to real inventions and to techniques used for the first time.

Today, I am proud to represent here the CERN accelerator community of that time. I am one of many, who, particularly in the case of the proton–antiproton project, worked enthusiastically for supplying the beams leading to the discovery of W's and Z's.

I will concentrate on:

- particle focusing, the Magnetic Horn;
- beam intensity enhancement, the PS Booster;
- proton–proton collisions, the ISR;
- proton–antiproton collisions, made possible by the stochastic beam cooling, and the entire proton–antiproton complex;
- LEP and LHC.

Giorgio Brianti

2 Magnetic horn

In 1961 S. van der Meer (Fig. 1) invented a device called the "Magnetic Horn", which helped a great deal to focus the particles emerging from a target, with the result of vastly enhanced flux at the detector, in particular of neutrinos. One can call it a "current sheet lens" since it produces a highly focusing magnetic field in a space of cylindrical symmetry by a kind of coaxial line with a hollow central conductor, made of a thin aluminium sheet (Fig. 2). The current is in the range 100 to 400 kA in order to reach magnetic fields of several Tesla. Therefore, the horn must be pulsed (half-sine wave of about 15 μs) to avoid excessive heating. The geometrical configuration and wall thickness can be easily adapted to the beam energy and to the application. Horns have been in use for

Fig. 1. S. van der Meer describing the Horn to visitors

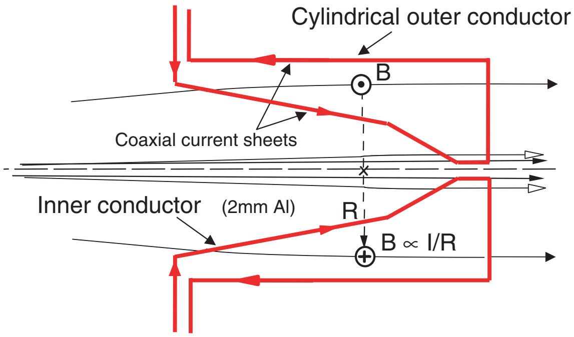

Fig. 2. Cross-section and principle of the Horn. The target produces charged particles: positively charged pions and kaons are emerging at various energies and angles (Courtesy of J.-M. Maugain)

Fig. 4. Photograph of the Horn used for focusing antiprotons

40 years, mainly for neutrino beams and for collecting antiprotons. In the case of neutrino beams, one usually uses two horns to collect efficiently pions and kaons of one given electric charge (Fig. 3). Switching the polarity of the horn system allows to switch between neutrino and antineutrino beams.

The photograph in Fig. 4 shows the Horn used for focussing the antiprotons at the entrance of the Antiproton Accumulator (AA).

3 PS Booster

In the mid sixties, it became clear that the best way to increase the PS intensity to the level required by the experiments and the ISR (10^{13} p/pulse) was to increase substantially the injection energy. Indeed, the main phenomenon limiting the intensity was incoherent or single particle tune shift, which scales like $(\text{beta})^2(\text{gamma})^3$. P. Germain launched the study of different alternatives (linacs and synchrotrons), which was led by H.K. Reich. The final choice favoured a multi-channel synchrotron, named the PS Booster [1].

The number of vertically stacked synchrotrons was set at four, each of them able to obtain a 2.5 intensity increase with respect to the PS without a substantial increase in emittance (particularly important for the ISR). The energy was set at 800 MeV (a momentum of 1463 MeV/c), which ensured more than a ten-fold increase of the incoherent (or individual) particle limit at injection into the PS. The ring radius was chosen to be one quarter of the PS radius (Fig. 5). The cross-sections of the dipoles and of the quadrupoles are shown in Figs. 6 and 7.

After more than 30 years of good and reliable service, one can point out that the four channels allow the combination of beam bunches in the way suiting best the served

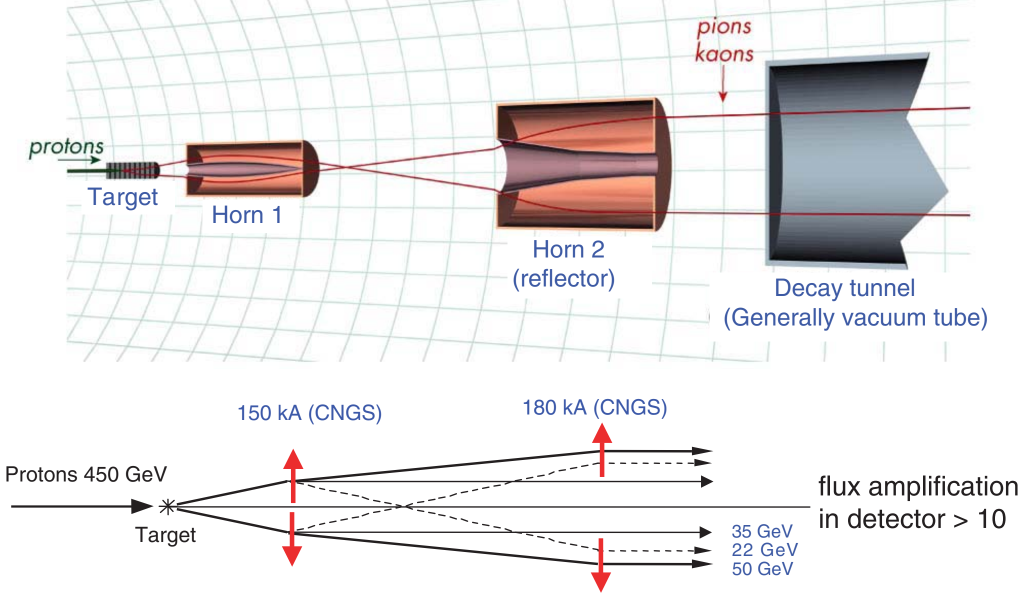

Fig. 3. Set of two horns as used for the CERN Neutrino Beam to Gran Sasso (CNGS). Usually, two horns are needed to produce a parallel wide band beam where a much larger number of particles emerging at various angles and energies are collected (Courtesy of J.-M. Maugain)

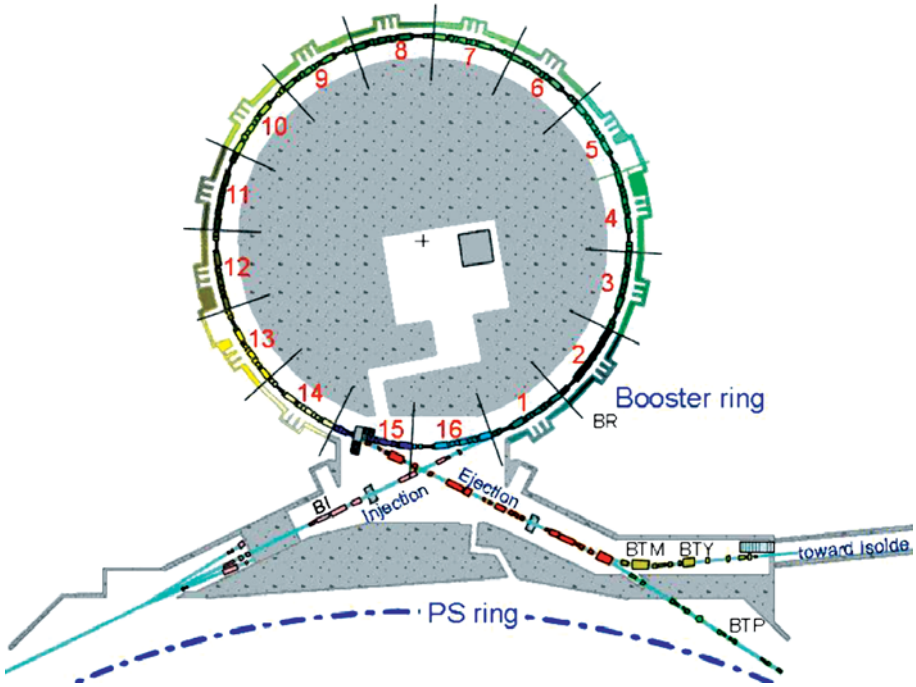

Fig. 5. PS Booster layout (From Sven De Man, 28/03/2000)

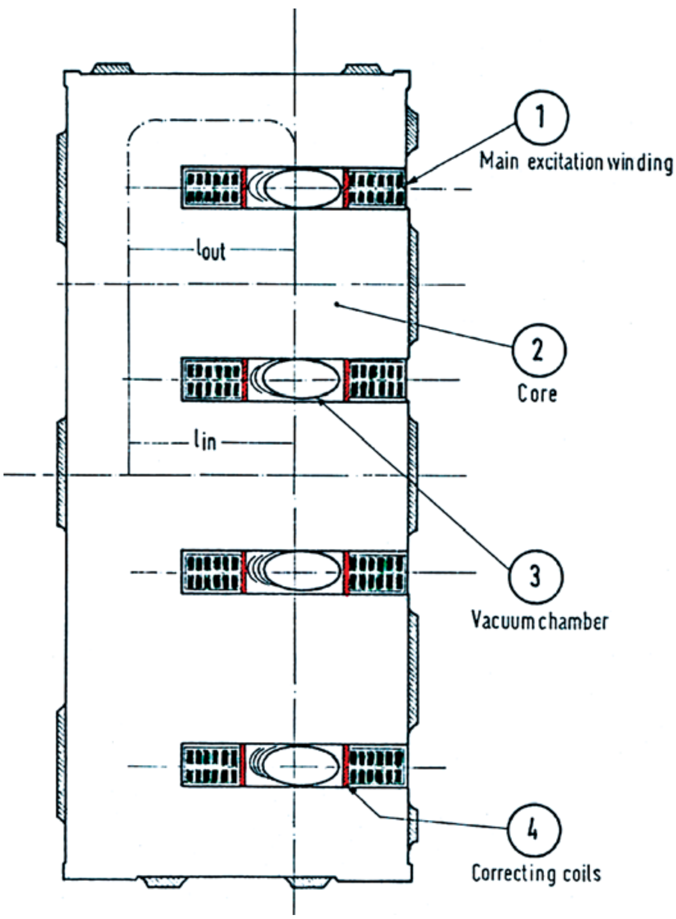

Fig. 6. Cross-section of Booster Dipole

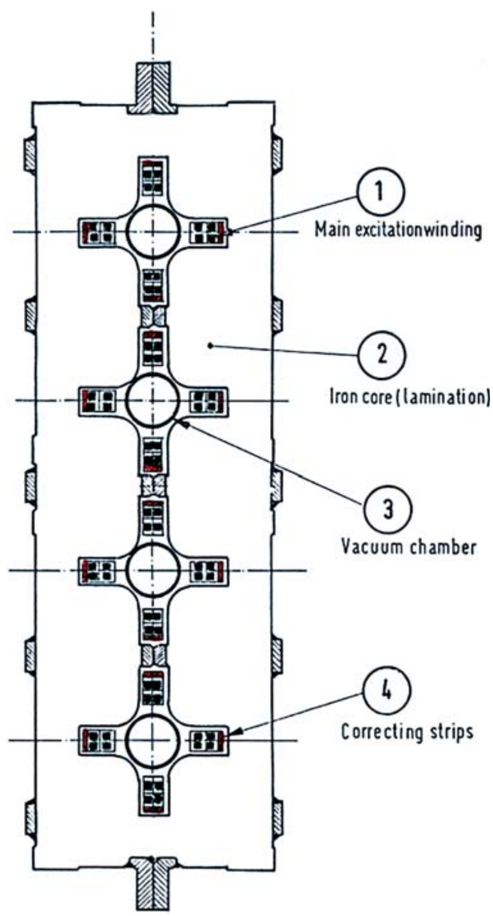

Fig. 7. Cross-section of Booster Quadrupole

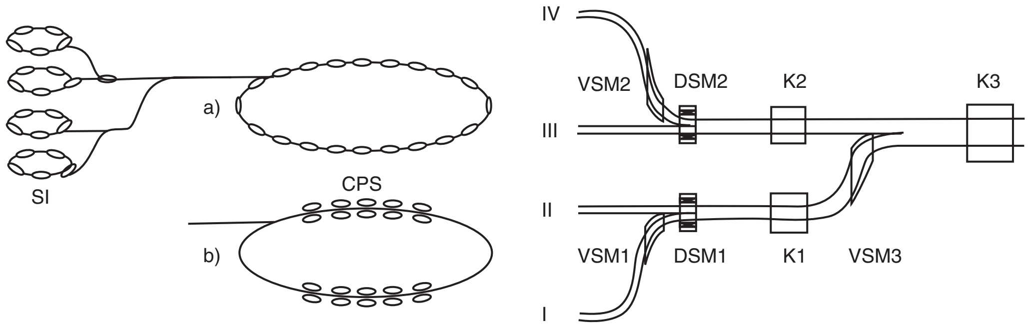

Fig. 8. On the left is shown the arrangements of bunches ejected from Booster: a) twenty sequential bunches; b) two times five vertically stacked bunches; on the right is shown the injection into the PS ring

machine. For example, 20 sequentially ejected bunches (Fig. 8*a*) or 2×10 bunches by vertically stacking bunches from 2 Booster rings (Fig. 8*b*) for the production of antiprotons or even a single bunch per ring as required by the LHC.

Figure 9 shows the evolution of the Booster intensity in one ring due to successive improvements. The Booster provided a substantial and very welcome increase in proton intensity of the PS, in particular, for neutrino physics with Gargamelle in 1973 and for CHORUS and NOMAD in the late 1990's. The performance increase was also essential for the anti-proton programme at the SPS. The energy was increased firstly to 1 GeV and then to 1.4 GeV, as required by the LHC, without any change of the magnets. Figure 10 is a photograph of the Booster taken from the injection/ejection region.

4 ISR, first proton–proton collider

In June 1957, in the middle of the construction of the PS, J.B. Adams set up a small Group in the PS Division to study new ideas for accelerators, which became later (1960) the Accelerator Research Division. The work concentrated on two possible lines: a proton–proton collider fed by the PS (later the ISR) and a proton synchrotron of about ten times the PS energy (later the SPS).

An electron analogue of a storage ring of only 2 MeV was built (CESAR, standing for CERN Electron and Accumulation Ring), to test ultra-high vacuum and particle accumulation and storage.

In December 1965, V. Weisskopf in his last Council Session as Director-General obtained approval for the ISR, the PS Improvement Programme with the Booster and the Bubble Chamber BEBC. The total investment was close to one billion CHF, but Vicky avoided making the addition of the items, which were approved in succession one by one.

The ISR [2] was the first proton–proton collider and reached eventually a centre-of-mass energy of 63 GeV[1]. It was planned for high luminosity and indeed it succeeded in colliding almost incredible beam currents (> 50 A) and scored a world record luminosity of more than 10^{32} cm^{-2} s^{-1}. The very high currents were obtained by stacking in momentum space, typically one thousand times the space occupied by a single pulse from the PS. Figure 11 is a photograph of a typical interaction region.

A considerable enhancement of accelerator technology was due to the ISR, in particular concerning reliability and stability of all components, ultra-high vacuum (1000 times lower pressure than in the PS), very intense beams inducing space-charge effects and non-linear resonances. The know-how and expertise gained with the ISR were essential prerequisites for the success of the antiproton programme. The ISR performance is summarized in Table 1, as was once presented by the Project Leader, K. Johnsen.

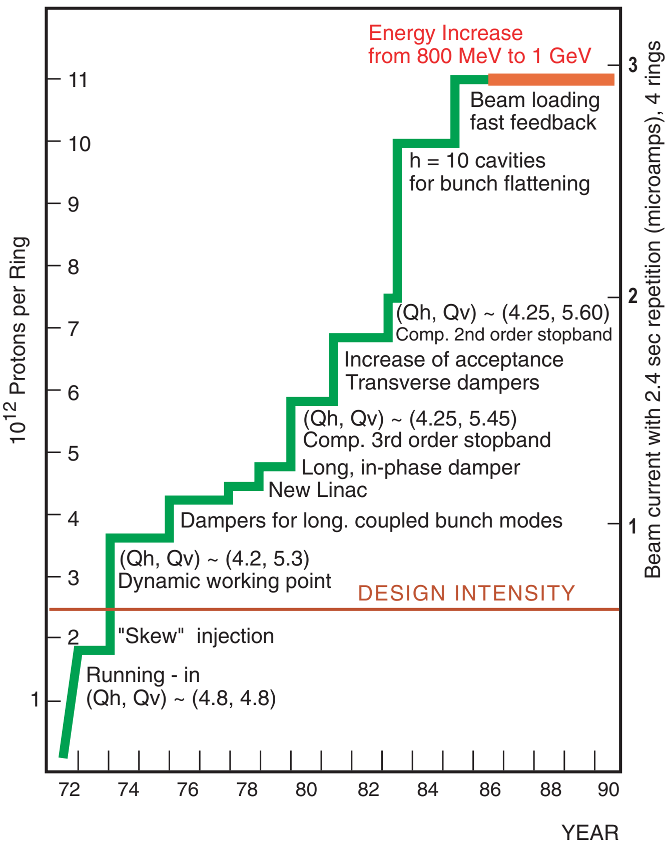

Fig. 9. Evolution of Booster intensity over time

[1] 2 times 31.4 GeV = 62.8 GeV ∼ 63 GeV

Fig. 10. PS Booster seen from the injection/ejection region

Table 1. Summary of the ISR performance (taken from the presentation by K. Johnsen at the ISR closure ceremony in 1984)

Current in normal operation	30–40 A
Maximum current	57 A
Maximum luminosity	1.4×10^{32} cm^{-2}s^{-1}
Typical current loss rate	1 ppm/m
Duration of physics runs	50–60 h
Maximum duration of antiproton beam	345 h

In summary, several technical innovations were either discovered or applied with the ISR. They include:

– beam stacking;
– on-line space charge compensation;
– stochastic cooling;
– industrially built superconducting quadrupoles for low beta insertion.

5 SPS collider

The original report on Stochastic Cooling by S. van der Meer [3] was published in 1972 and the first successful tests were conducted in the ISR in 1974 by W. Schnell, L. Thorndahl and collaborators [4]. In the same period, ideas were put forward for the accumulation of antiprotons in storage rings by D. Möhl, P. Strolin and L. Thorndahl [5], and independently by P. McIntyre.

The decisive event occurred in 1976. Carlo Rubbia, at CERN, put forward the brilliant idea to convert the SPS to an antiproton–proton collider [6], which would make use of a single magnet ring (as for e^+e^- colliders). A similar proposal was made at Fermilab again by C. Rubbia, D. Cline, P. McIntyre and F. Mills [7].

The difficulty consisted in obtaining an antiproton beam of comparable intensity to the proton beam. The only way was to produce antiprotons using the 26 GeV protons of the PS (production rate of one antiproton for one million protons) and then store the antiprotons in an Accumulator Ring prior to their injection into the SPS. The main obstacle to this operation is the large dispersion in angles and momenta of the antiprotons emerging from the target, while the Accumulator Ring has limited acceptances in the three dimensions. The only solution is to condense the beam either by electron or stochastic cooling. Since the latter was applied, let me concentrate on a simplified description of this method.

Macroscopically, the ensemble of the beam particles are contained in an area in phase-space, which, according to Liouville's Theorem, cannot be changed. In reality, the beam is not a continuum, but is made of individual particles with empty phase-space areas between them. The method consists in detecting the deviation of the barycentre of a small group of particles from the required value in a given location of the ring and then sending a correcting signal via a low-loss cable to an appropriate location on the other side of the ring in such a way that, when the particle packet passes through it, it is corrected and pushed toward the centre of the distribution. But what about Liouville's Theorem? If we now look at the beam on a microscopic scale, a way of explaining the Stochastic Cooling is that the empty phase-space areas between the particles are pushed to the outside of the beam and the particles crowded at the centre of the distribution. The operation is repeated many many times, so that, at the end, the phase-space density is increased enormously. The method requires special detectors associated to wide-band electronics (order 10 GHz).

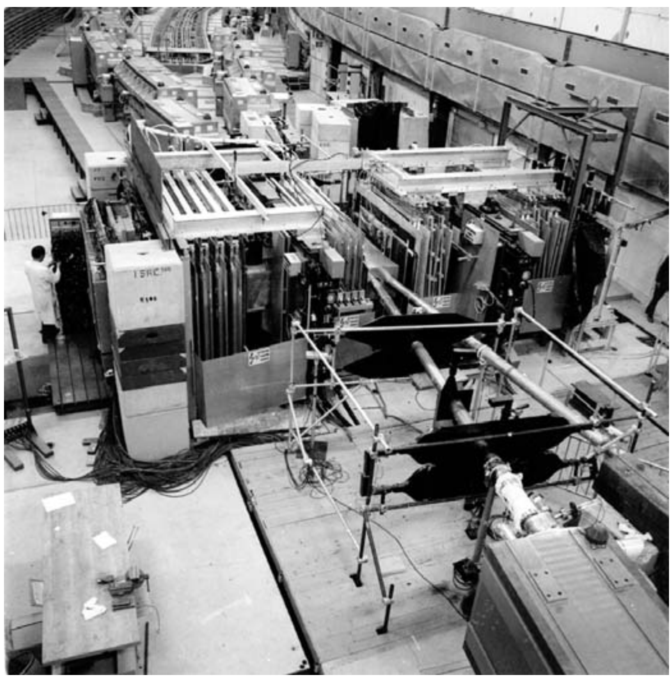

Fig. 11. Photograph of one ISR interaction region

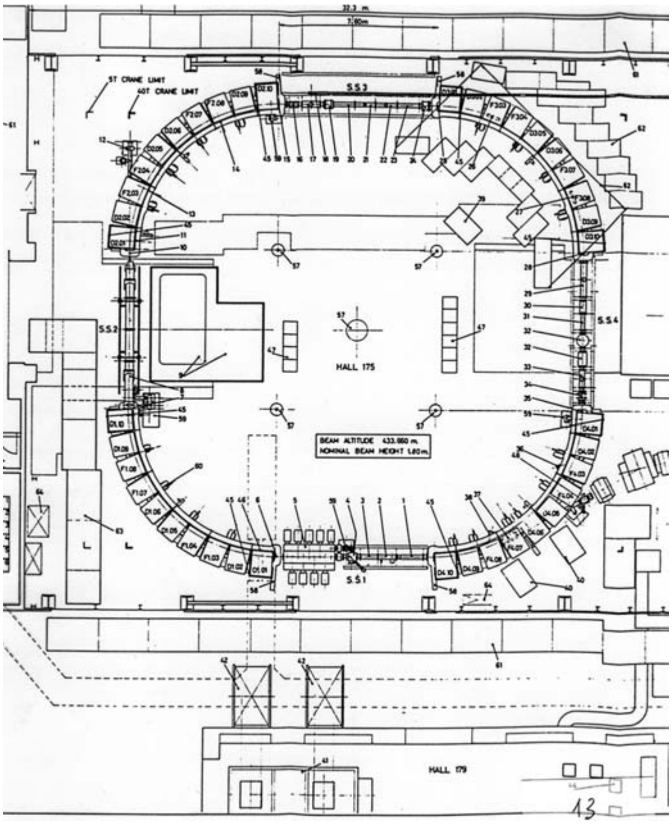

Fig. 12. Layout of ICE (Initial Cooling Experiment)

The SPS needed also to be modified with the insertion of low-beta sections around the collision points, a considerable decrease of the vacuum pressure and, of course, the construction of huge (for the time) underground experimental areas for mobile experiments (UA1 on a platform, UA2 on air cushions). Indeed, it was necessary to withdraw the collider experiments from the ring to allow periods of fixed-target operation at least once a year.

The Research Director-General L. van Hove supported the project from the beginning, while the accelerator community was initially skeptical, but was soon filled by the enthusiasm of undertaking a very challenging enterprise. Prior to the final design of the Antiproton Source, a test synchrotron called ICE (Initial Cooling Experiment) [8] was quickly assembled by G. Petrucci with the refurbished magnets of the *g*-2 experiment in order to test both electron and stochastic cooling (see Fig. 12). The stochastic cooling method obtained a brilliant confirmation, as it is shown in Fig. 13, and turned out to be much superior to electron cooling for the application to the CERN antiproton programme. A Committee chaired by F. Bonaudi finalized the accelerator project [9].

The scheme consisted of using the PS at maximum beam intensity concentrated over one quarter of the circumference, in order to match the circumference of the Antiproton Accumulator (AA) [10]. This was obtained by extracting the beam from the Booster in ten bunches, instead of the usual twenty, by recombining vertically the bunches of pairs of Booster rings, and by further reducing the ten bunches to five in the PS by an ingenious type of RF programming. The beam was then extracted from the PS at 26 GeV and directed to the target at the entrance of the AA. The antiprotons were collected at 3.5 GeV by the magnetic horn shown in Fig. 4.

The design and construction of the AA (Antiproton Accumulator) was entrusted to R. Billinge and S. van der Meer. Despite the great sophistication and the number of elements, the ring was constructed and tested successfully in less than three years (Fig. 14). The process of stacking and cooling of the antiprotons in the AA is shown in Fig. 15 (from H. Koziol). The formation of a full antiproton stack took two to three days or one hundred thousand PS pulses. A question much debated at the time was what to do with the antiproton stack: direct injection into SPS at 3.5 GeV or post-acceleration in PS to 26 GeV in order to inject into the SPS above the transition energy. Since there was no agreement in Bonaudi's Committee about this point, J.B. Adams, Executive Director-General at that time and convinced supporter of the project after the initial hesitation, took it upon himself to study

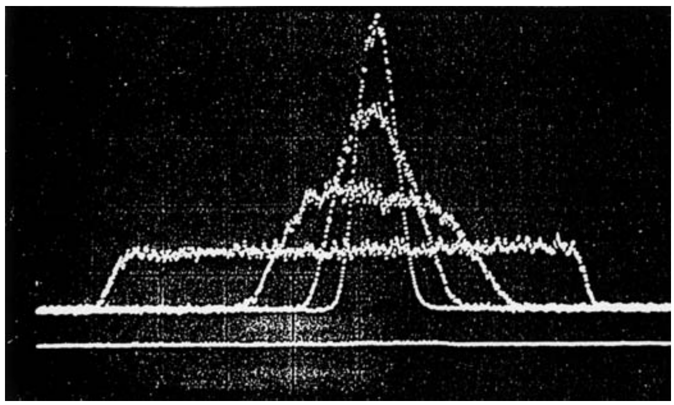

Fig. 13. Momentum cooling in ICE of 5×10^7 particles. Longitudinal Schottky signals after 0, 1, 2 and 4 minutes. The momentum spread was reduced from 3.5×10^{-3} to $5.\times10^{-4}$

Fig. 14. Photograph of the Antiproton Accumulator AA

Table 2. Overall performance of the SPS Collider from 1981 to 1990 (CC = AA + AC)

Year	1981	1982	1983	1984	1985	1988	1989	1990
	AA	AA	AA	AA	AA	CC	CC	CC
Energy (GeV)	273	273	273	315	315	315	315	315
Integrated luminosity per year (nb^{-1})	0.2	28	153	395	655	3372	4759	7241
Initial luminosity (10^{29} cm^{-2} s^{-1})	0.0	0.5	1.7	5.3	3.9	25	30	61
Hours realized	140	748	889	1065	1358	1316	2020	1803

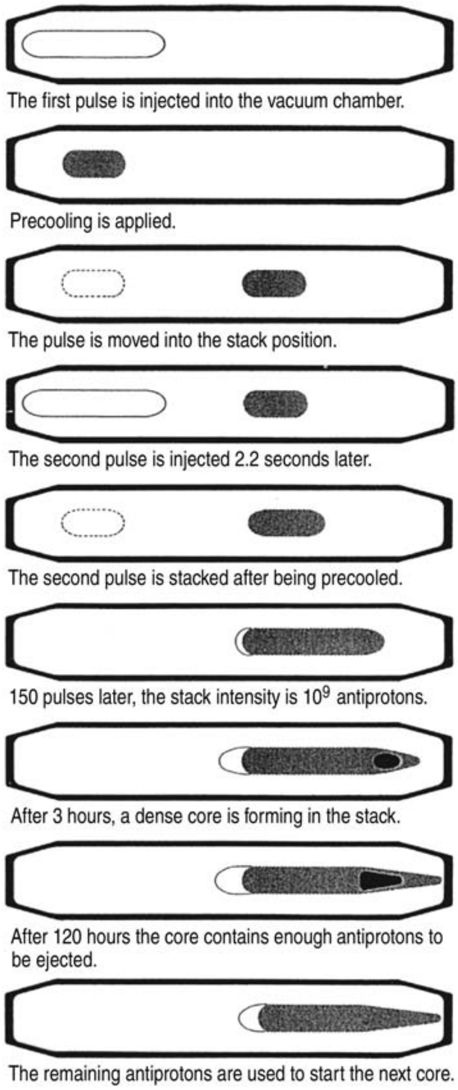

Fig. 15. Stacking and cooling of antiprotons in AA

thoroughly the question and decided in favour of post-acceleration. It was a wise decision, which undoubtedly facilitated the reliable operation of the collider.

The project was approved in 1978 and the first proton–antiproton collisions occurred on 10th July 1981. The first real period of physics exploitation occurred in 1982, with initial luminosities in the low 10^{29} $cm^{-2}s^{-1}$ and integrated luminosity of 28 nb^{-1} (sufficient for the discovery of W's).

The year 1983 saw the collected integrated luminosity increased to 153 nb^{-1} and the discovery of the Z's.

A few years later, a substantial improvement of the Antiproton Source was obtained by separating the function of collection and accumulation/cooling of antiprotons. This implied the addition of a second ring (Antiproton Collector, AC) around the original AA (Fig. 16). Consequently, the luminosity went well above 10^{30} $cm^{-2}s^{-1}$, the record being 6×10^{30} $cm^{-2}s^{-1}$. Table 2 and Fig. 17 illustrate the performance of the SPS Collider over the years 1981 to 1990.

Looking back over the years to the early eighties, one non-technical but very important fall-out of the proton–antiproton undertaking was the daily working together of the experimental teams and of the accelerator people. We all remember with nostalgia the animated discussions at the five o'clock meeting in the SPS Control Room to decide the course of action for the following day. But it worked well in the end!

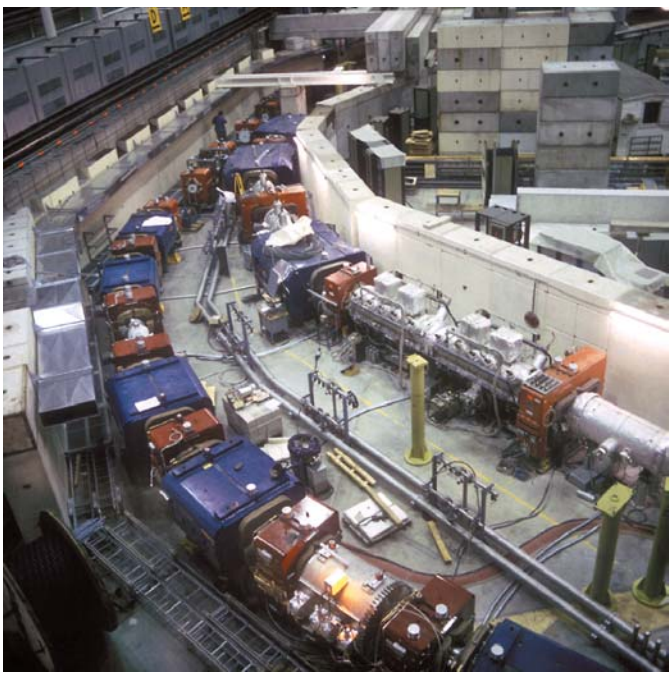

Fig. 16. Antiproton Collector (AC) around the AA

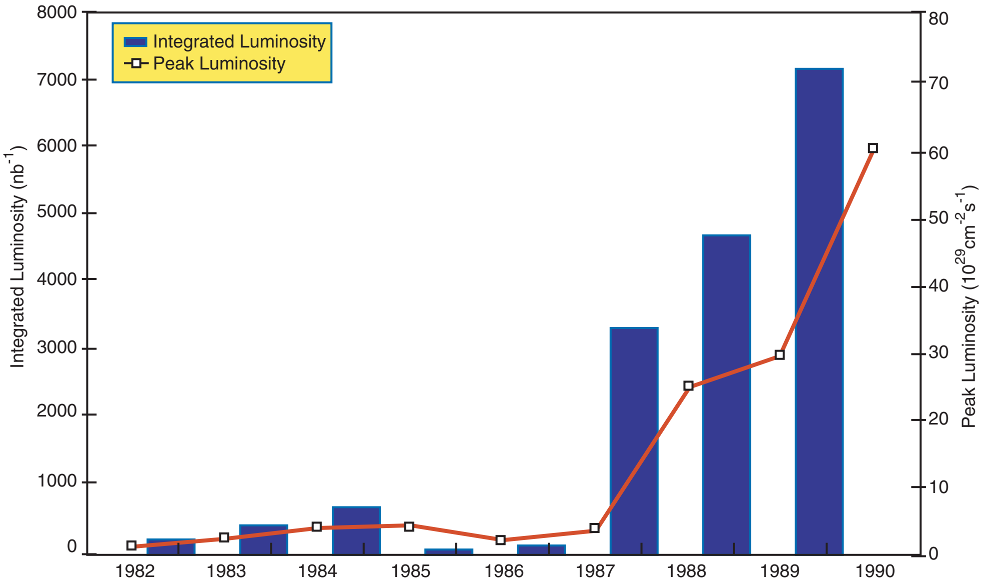

Fig. 17. Overall performance of SPS Collider from 1982 to 1990

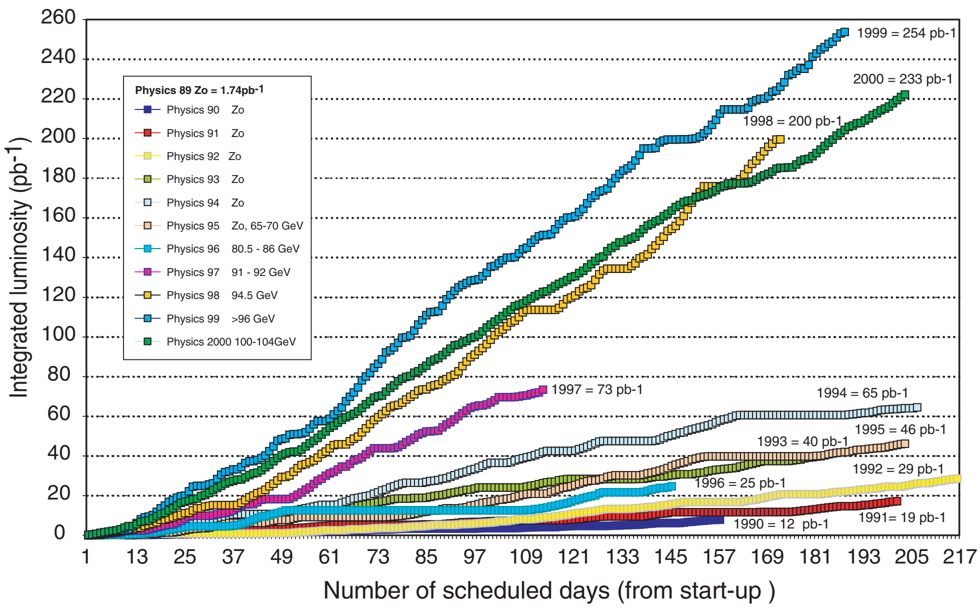

Fig. 18. Performance of the LEP Collider from 1989 to 2000

6 LEP and LHC

After having built the PS, the ISR and the SPS, CERN took on the new challenge to construct an electron–positron collider with the purpose of studying in detail the properties of the W and Z bosons. The SPS Collider stopped operation in 1991 as LEP took over the full exploration of the Standard Model during more than a decade, by producing in particular millions of W's and Z's. Figure 18 summarizes the remarkable performance of the LEP Collider.

CERN has a tradition of developing an evolving accelerator infrastructure. Previous accelerators are used as injectors for the new accelerator. In the case of LEP, it is the tunnel which is being re-used to install a new machine. Today, the LEP tunnel starts being equipped with the elements of the next Collider, the LHC, which will continue the tradition of hadron colliders at CERN at much higher energy and luminosity. It will be the subject of a presentation in this symposium by L. Evans.

References

1. Study Group for CPS Improvements, The Second Stage CPS Improvement Study, 800 MeV Booster Synchrotron, CERN-MPS/Int. DL/B 67-19 (1967)

2. Technical Notebook No. **5**, Intersecting Storage Rings, CERN/PIO 74-2 (1974)
3. S. van der Meer, Stochastic damping of betatron oscillations, internal report CERN/ISR PO/**72-31** (1972)
4. P. Bramham, G. Carron, H.G. Hereward, K. Hübner, W. Schnell, and L. Thorndahl, "Stochastic Cooling of a Stored Proton Beam", NIM **125** (1976) p. 201
5. P. Strolin, L. Thorndahl and D. Moehl, Stochastic Cooling of antiprotons for ISR physics, internal report CERN/EP **76-05** (1976)
6. C. Rubbia, P. McIntyre and D. Cline, Producing massive neutral intermediate vector bosons with existing accelerators, Proc. Int. Neutrino Conf., Aachen, 1976 (Vieweg Verlag, Braunschweig, 1977), p. 683
7. D. Cline, P. McIntyre, F. Mills and C. Rubbia, Collecting antiprotons in the Fermilab booster and very high-energy proton–antiproton interactions, Fermi Lab internal report TM **689** (1976)
8. ICE Team, Initial Cooling Experiment progress reports Number. **1** and **2**, CERN-EP (1978)
9. F. Bonaudi et al., Antiprotons in the SPS, internal report CERN DG **2** (1978)
10. Design study of a proton–antiproton colliding beam facility, internal report CERN/PS/AA **78-3** (1978)