THE CERN SYNCHROTRONS

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Abstract
In the year of the fiftieth anniversary of synchrotrons, this lecture reviews the history of the CERN Synchrotrons, starting with the PS, the first proton synchrotron based on the alternating-gradient principle invented in 1952 at Brookhaven National Laboratory. The design work of the PS team, under the enlightened leadership of J. B. Adams, and the construction of the machine will be evoked. Following the PS, eight other synchrotrons/storage rings, among which the first proton–proton collider (ISR) and two temporary test machines, were designed and constructed at CERN. They are briefly discussed, with special emphasis on the other major contribution of J. B. Adams, the SPS, followed by its conversion to the first $p\bar{p}$ collider. In most cases, initial, nominal, and final performance are outlined. Major conceptual and constructional advances are indicated, which led to a large reduction in the cost per GeV. Finally, after an intensive R&D programme on the high-field superconducting magnets, the construction of the Large Hadron Collider (LHC) is evoked. The role played by J. B. Adams in the promotion of advanced accelerator technology is also discussed.

1 INTRODUCTION

The history of alternating-gradient synchrotrons is inextricably interwoven with that of CERN, and the history of CERN for more than 30 years is marked by the outstanding personality and the decisive contributions of John Bertram Adams.

I am now taking over from John Lawson to cover the period from 1953/54 to the present. In this long period, CERN has designed, constructed, and operated a number of fixed-target accelerators and colliders, which constitute the most formidable ensemble of effective tools for Particle Physics in the world. The main characteristics of this ensemble (Fig. 1), which was progressively developed over the years, are:

1. The possibility of a given machine to operate in different modes, for example as a fixed-target machine or as a collider.
2. The capability of a number of machines to accelerate various types of particles to different energies in rapid succession (in one or in a few seconds).
3. The operational link between practically all machines, whereby the smaller machines, often at the end of their use for a front-line research programme, are used as injectors for new larger machines.

These characteristics underline the fact that optimal use is thus obtained from the investment made in the construction, by extending considerably the effective lifetime of the equipment.

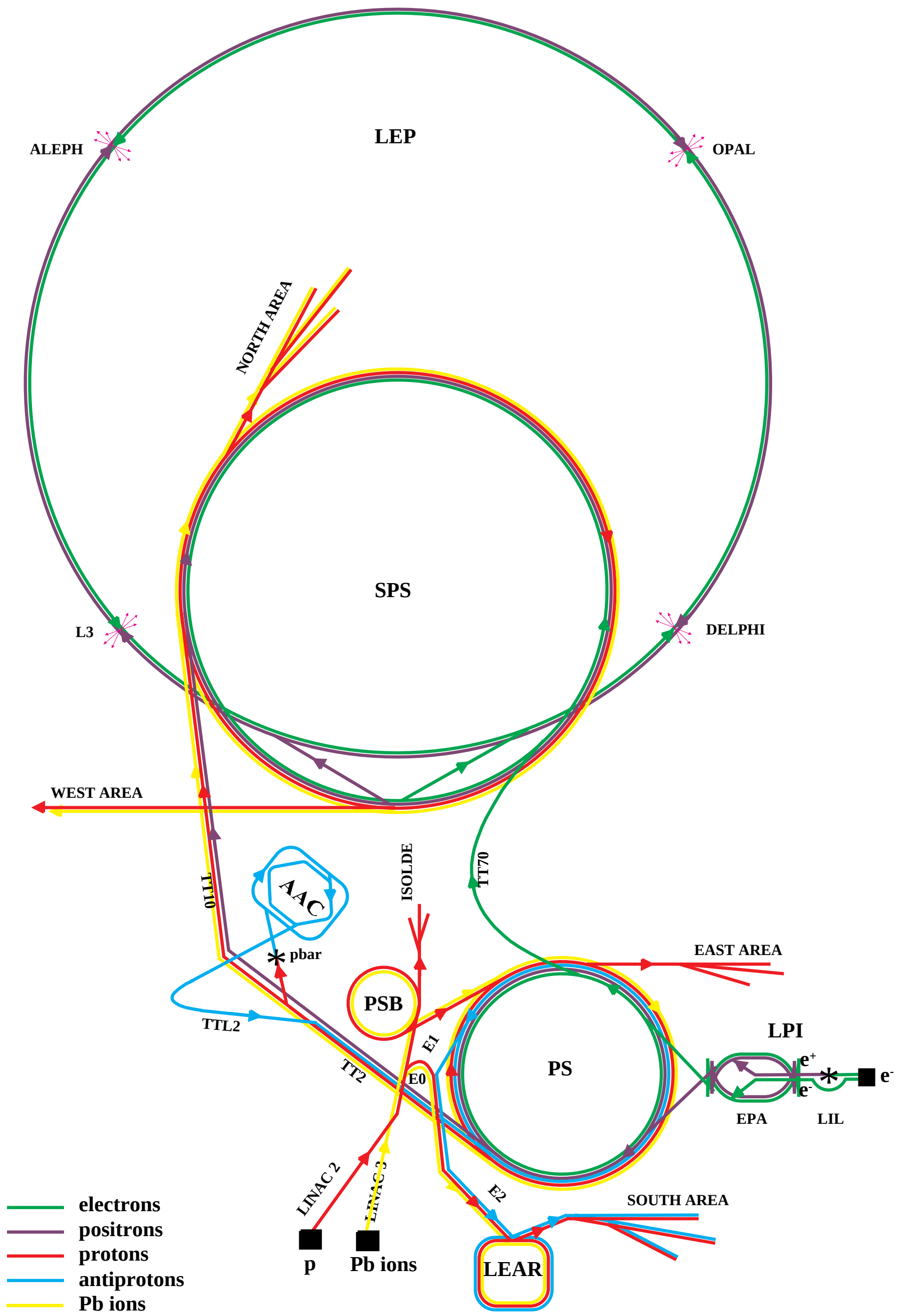


Fig. 1: The 1996 CERN Accelerator Complex.

To date, CERN has built nine synchrotrons/colliders and two temporary test rings (Table 1), of which eight are still running. The best example is undoubtedly the PS (26 GeV), which was originally built as the first alternating-gradient synchrotron (1959) and sustained an important programme of fixed-target physics for almost twenty years. It has provided several types of particles (p, $\bar{p}$, d, α, O, S or Pb, e^- and e^+) to the SPS, LEP and ISOLDE. In the future it will also feed the Large Hadron Collider (LHC).

Table 1
List of all synchrotrons constructed at CERN

Machine	Kinetic energy (GeV)	Year of first operation	Remarks
PS	26	1959	
CESAR	0.002	1962	Test for ISR
ISR	31 + 31	1971	
PS Booster	0.8 ; 1.4	1972	
SPS	450	1976	
ICE	1.36	1978	Test for cooling
AA	2.69	1980	
Sp$\bar{p}$S	315 + 315	1981	
LEAR	1.3	1982	
ACOL	2.69	1987	
EPA	0.6	1987	Accumulator for LEP
LEP	50 + 50	1989	
	90 + 90		
LHC	7000 + 7000	(2005)	

2 THE PS AS THE FIRST ALTERNATING-GRADIENT SYNCHROTRON

The alternating-gradient principle was discovered in 1952 by S. Livingston, E. Courant, H. Snyder, J. Blewett and, independently, by N. Christofilos [1]. It came about during the construction of the Cosmotron (Figs. 2, 3). The desire was to reach the highest possible energy and so Livingston suggested a design change to reach a higher field, but at 1.3 T the saturation made the field index *n* exceed the stability limit ($0 < n < 1$). Livingston suggested placing alternate magnet return yokes outside the orbit so that the high gradients would average out to the low gradient required. Courant analysed the effect and found that the stability was very much improved. In fact the higher the gradients, the better the focusing strength. At that point, Snyder pointed out the analogy with the optical ensemble of focusing and defocusing, globally focusing, lenses and so the principle was born.

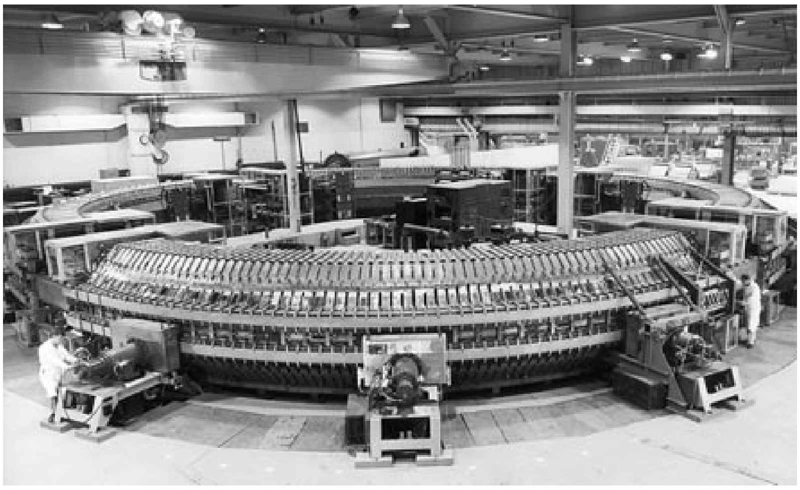


Fig. 2: The BNL Cosmotron.

Fig. 3: The inventors of the AG principle (from left to right E. Courant, S. Livingston, H. Snyder and J. Blewett).

Initially CERN had decided to build a kind of SuperCosmotron (the BNL 3 GeV weak focusing synchrotron) with an energy of 10 GeV. However, the team in charge of the design, led by Odd Dahl, became acquainted with the new principle during a visit to BNL and swiftly adopted the new idea, which allowed the energy to be increased to about 30 GeV for the same total cost [2]. It was a bold decision! Indeed, even a few years later wise and experienced people decided to construct two large synchrotrons, Nimrod in the UK and the ZGS in the USA, based on the weak focusing scheme. It was believed that alternating-gradient machines, if they worked at all, would produce beam currents considerably smaller than the classical weak focusing ones, which had a much larger aperture.

Work in Geneva started in 1953, but I take 1954 as starting year not only because I joined CERN in that year, but much more importantly because the PS Group really started to be assembled around John Adams, freshly appointed as Project Leader. Only a few of these people had some professional career behind them and even fewer had experience in accelerators, mainly John himself, Mervyn Hine and Kjell Johnsen. John and Hildred Blewett from BNL joined the PS team to help with the design. It was the beginning of an excellent collaboration between the two laboratories, which continues to this day. Most of the other members of the team were very young applied physicists or engineers coming straight from University, who in general had heard the word ‘synchrotron’ for the first time in connection with CERN.

One of the great novelties of AG synchrotrons was of course the magnet, and therefore it is no surprise that it received so much attention [3]. The other novelty was the appearance of the transition energy, requiring a sudden jump in the radiofrequency phase during acceleration, where the beam stability is lost.

In all more recent synchrotrons the bending and the focusing functions are separate (the advantages being a higher bending field and therefore a higher energy for a given circumference, and more flexibility of changing the working point), but at that time it was thought natural to incorporate the focusing into the main bending magnets (Fig. 4). This allowed not only a reduction in the number of types of components, but, above all, it meant that very high integrated gradients could be obtained with a feasible local gradient. When I arrived at the Physics Institute beside the Arve in September 1954, I saw in the only laboratory of the PS Division magnet models with very narrow and sharp pole pieces corresponding to an n of 4000, namely with gradients of about 70 T m^{-1}, as in very strong quadrupoles of a FODO structure (Fig. 8). But in a FODO lattice the quadrupoles cover no more than 10–15% of the magnetic length, while with combined-function magnets the gradient is present over the entire length! The magnet weight was estimated to be only 800 t for a 30 GeV machine, which, however, in all probability would not have worked with such a high value of n.

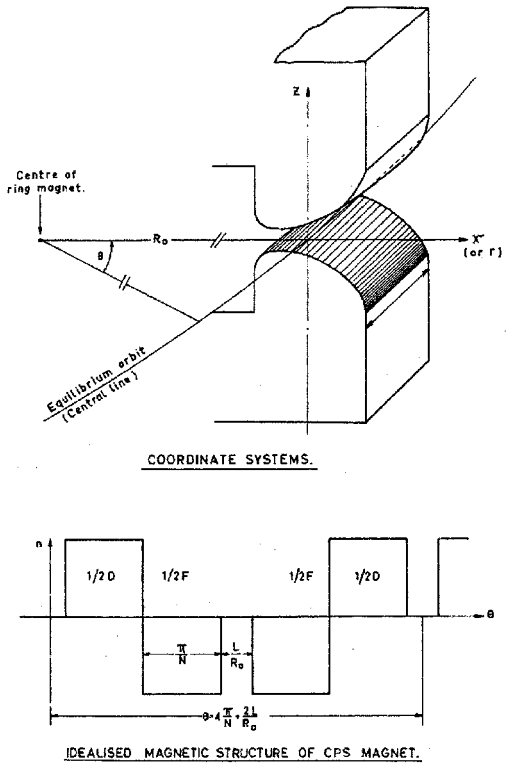


Fig. 4: Idealised magnetic structure of a PS magnet.

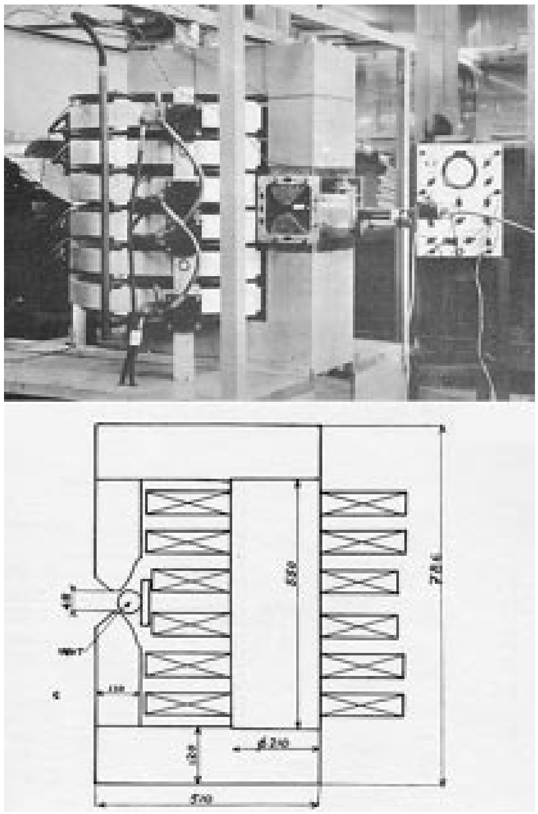
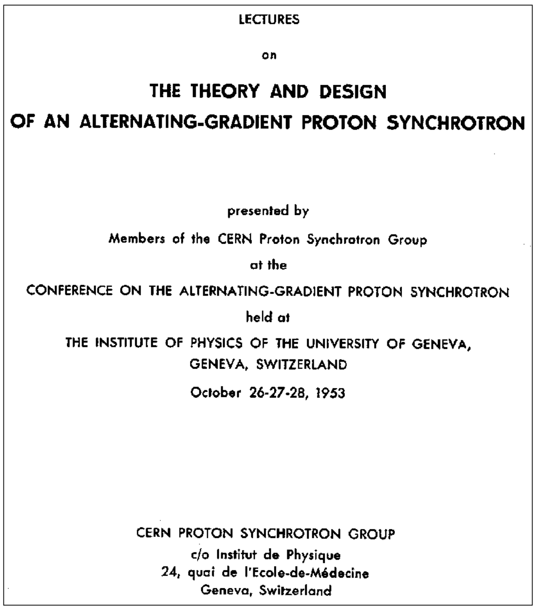


Fig. 5: Magnet model with n = 4000.

The great preoccupation at that time were the tolerances to be respected, in particular for the magnets and their alignment. A difficult compromise had to be struck between very strong focusing, with the benefits of a small aperture, small, light magnets, but the disadvantage of extremely tight tolerances, and weaker focusing with more relaxed tolerances and hence larger magnets. At that time Adams, Hine and Johnsen made substantial contributions to complete the theory of an alternating-gradient synchrotron, paying special attention to the tolerances of the various components [4] (Figs. 6, 7). It was also discovered that the machine aperture did not depend so strongly on n. The n value was then progressively decreased to 288, namely a gradient of about 5 T m^{-1} (or 35 T m^{-1} of a FODO structure), and the magnet weight increased to 3300 t for the final machine, optimized for the slightly lower energy of 26 GeV [5] (Figs. 8, 9).



LECTURES

on

THE THEORY AND DESIGN
OF AN ALTERNATING-GRADIENT PROTON SYNCHROTRON

presented by

Members of the CERN Proton Synchrotron Group

at the

CONFERENCE ON THE ALTERNATING-GRADIENT PROTON SYNCHROTRON

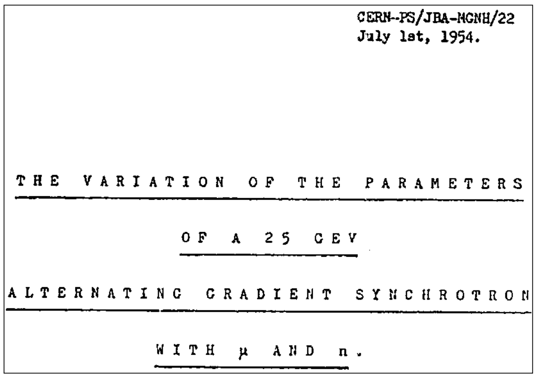
held at

THE INSTITUTE OF PHYSICS OF THE UNIVERSITY OF GENEVA,
GENEVA, SWITZERLAND

October 26-27-28, 1953

CERN PROTON SYNCHROTRON GROUP
c/o Institut de Physique
24, quai de l'Ecole-de-Médecine
Geneva, Switzerland

Fig. 6: Cover of proceedings of 'Lectures on the Theory and Design of an Alternating-Gradient Proton Synchrotron', 26–28 October 1953.



CERN-PS/JBA-MGNH/22
July 1st, 1954.

THE VARIATION OF THE PARAMETERS
OF A 25 GEV
ALTERNATING GRADIENT SYNCHROTRON
WITH μ AND n.

Fig. 7: Cover of 'The Variation of the Parameters of a 25 GeV Alternating-Gradient Synchrotron with μ and n, by J. B. Adams and M.G.N. Hine, 1 July 1954.

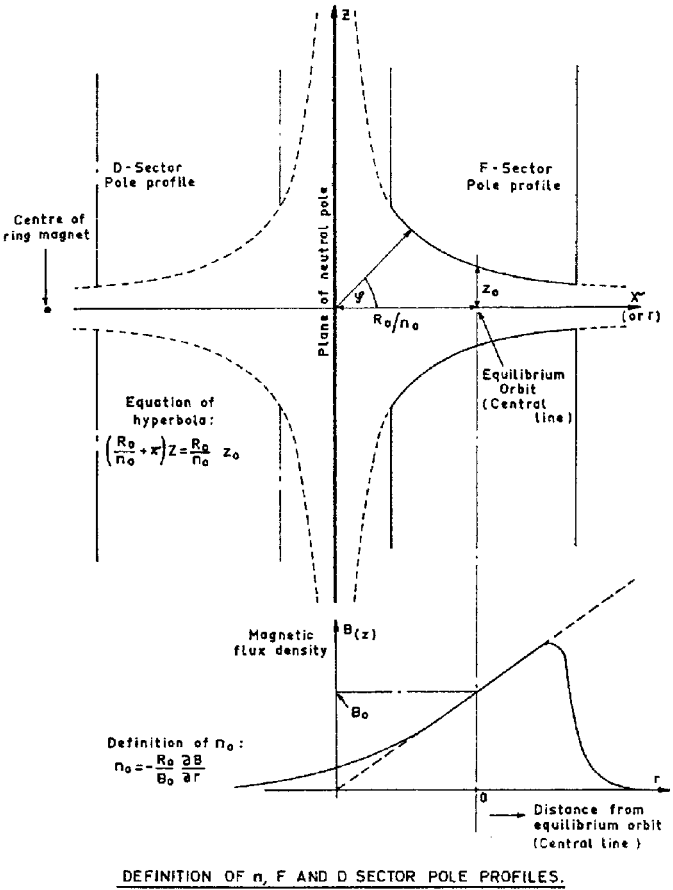


Fig. 8: Definition of hyperbolic pole-pieces.

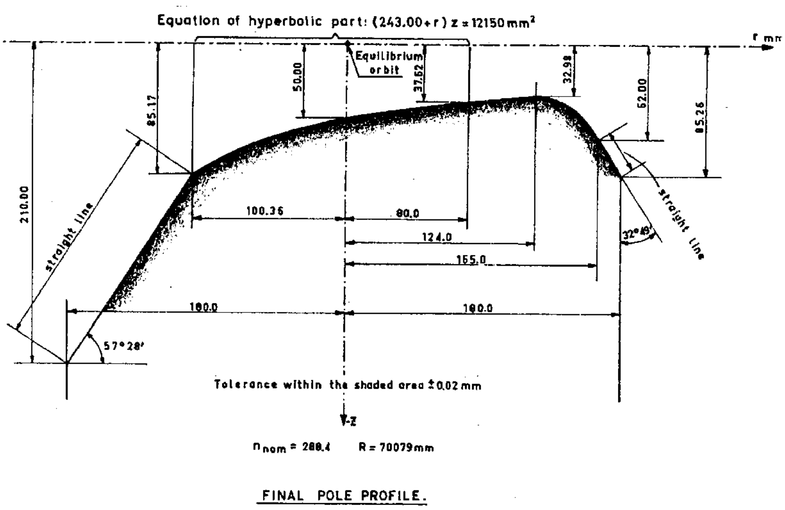


Fig. 9: Final pole profile.

Paying extreme attention to tolerances and in general to very sound engineering of any single component was, I believe, of capital importance not only for the success of the PS but also for all the subsequent machines at CERN. It taught all of us how to tackle technical design and construction on the basis of an attitude which was one of the facets of J. B. Adams's personality, a 'constructive pessimism', just the opposite of 'blind optimism'. Indeed John was a pessimist not in a negative way, but in the sense that he believed that Nature had no reason to make gifts to accelerator designers. Therefore the correct attitude consisted in understanding the finest details of each problem in order to make a design leaving nothing to chance on the way to success. Some people confused this with conservatism and overcautiousness. But how can one consider as conservative one of the most extraordinary engineers of our time, a man who undertook to construct the first proton AG synchrotron in the world, the first underground large accelerator and, finally, the first $p\bar{p}$ collider?

The apparent simplicity of the magnet system masked a fair degree of sophistication, requiring many studies and a lot of experimental work. Complication was due to:

i) determination of the pole profile in the presence of some saturation by means of a model with movable plates (no electronic computers available) (Fig. 10);

ii) a fairly low injection energy, with the consequence of an injection field too close to the remanent field. The large fluctuations to be expected for the remanent field would have prevented the machine from working, if no special precautions had been taken. This meant that a steel store had to be constituted where the laminations were arranged in a number of piles equal to the number of the laminations in a block. A block was assembled by picking a lamination from each pile;

iii) two types of blocks ('open' and 'closed') being required with somewhat different magnetic behaviour, especially at low fields due to the influence of the remanent field;

iv) the need to determine experimentally the acceptable lamination thickness for the envisaged acceleration rate (Fig. 11);

v) the idea that no galvanic loop should embrace a varying flux, which led to the gluing of the pile of laminations of a block with a new miracle material, Araldite. This complicated the construction by adding a few steps to the process, some of which were particularly difficult, like the removal of the excess polymerized glue around the block.

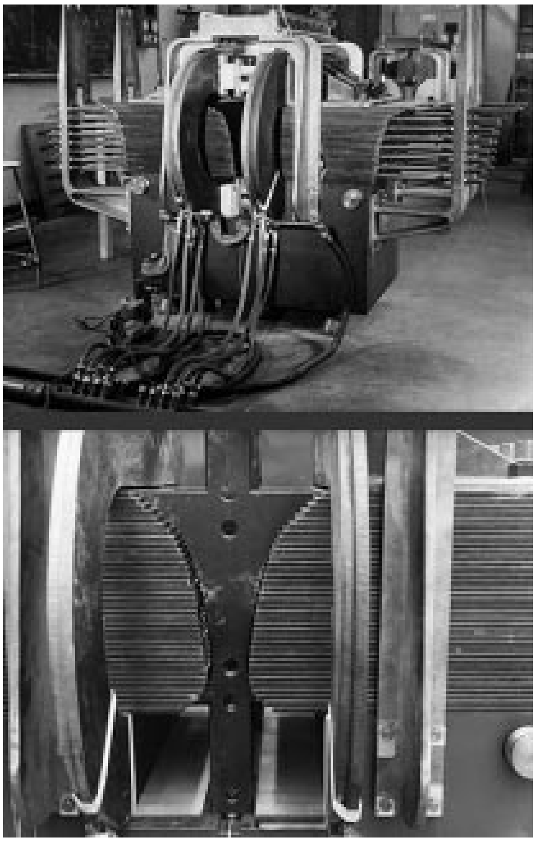


Fig. 10: Model with movable plates to determine final profile.

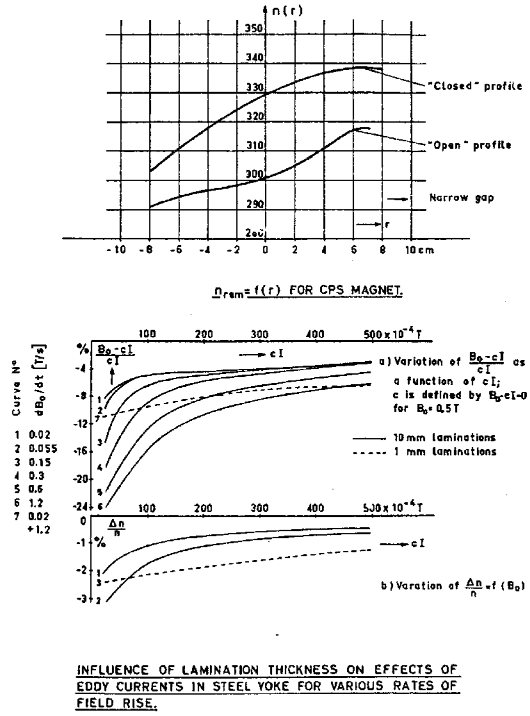


Fig. 11: The ‘n’ values of open and closed blocks at the remanent field show an important difference. The acceptable lamination thickness determined experimentally.

The final form of the magnet block is given in Fig. 12. The construction of the 1000 blocks was entrusted to Ansaldo in Genoa with steel laminations produced in the nearby factory of Italsider (Fig. 13). Ansaldo won the contract because of the higher precision of their punching dies, compared with those made by other European manufacturers.

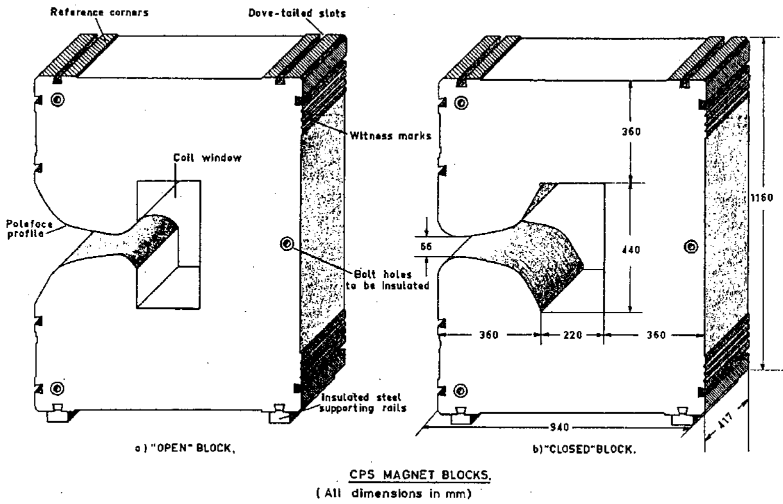


Fig. 12: Final form of the magnet blocks.

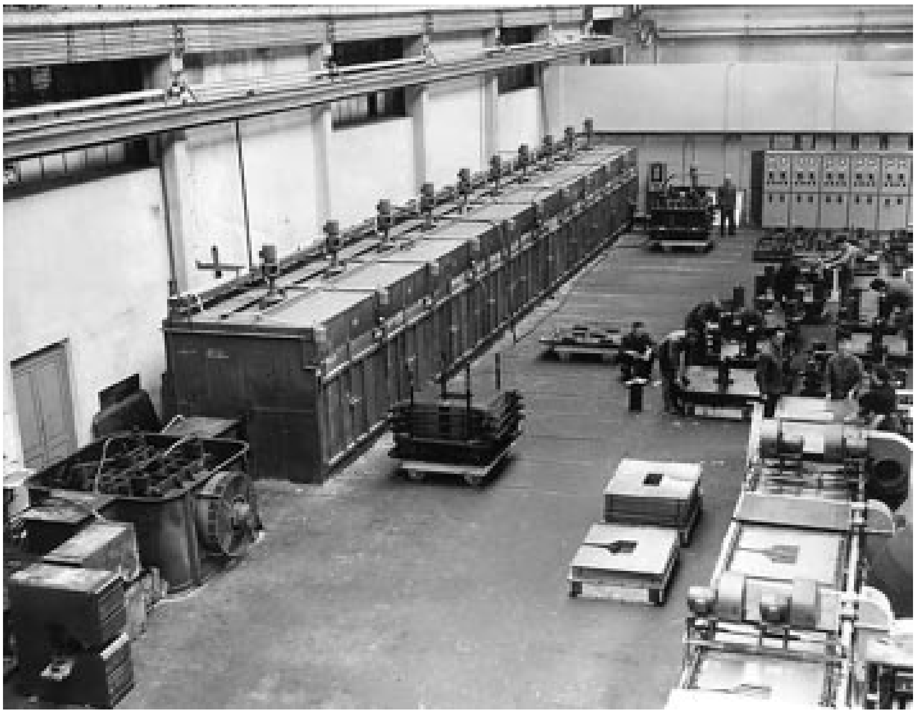


Fig. 13: The Ansaldo workshop.

Completion of the first magnet unit, consisting of ten blocks (five open and five closed), was celebrated by the photograph of the entire Magnet Group sitting on it (Fig. 14). Its very appearance conveys the intention of the builders to obtain a solid long-lasting structure!

Fig. 14: The first magnet unit called Margherita, from the name of the only woman in the Group, Margherita Cavallaro.

Alignment and stability of the installed ring was also of great concern (Figs. 15, 16). This led to the installation of the machine on a circular, reinforced, concrete beam of a circumference of 630 m, elastically mounted, and also to the provision of four radial tunnels to facilitate the alignment.

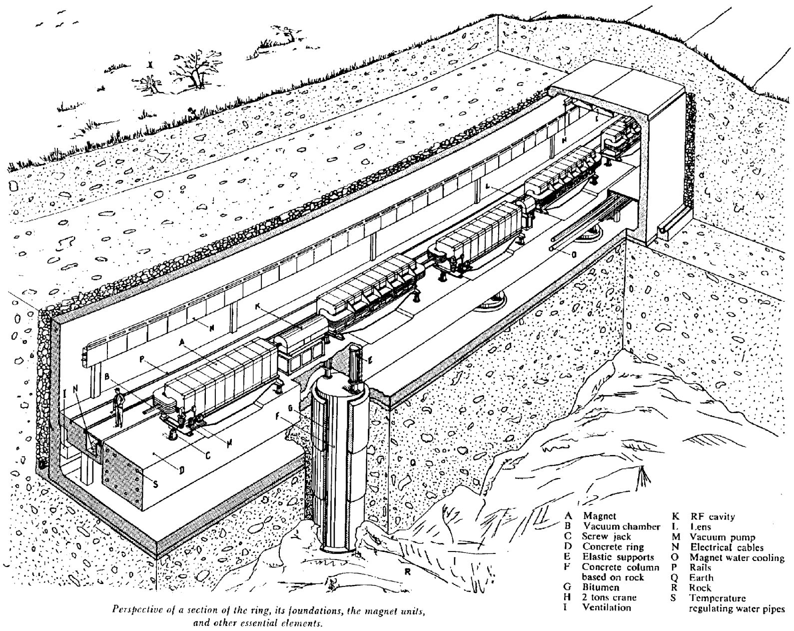


Fig. 15: Perspective view of a section of the ring with the circular concrete beam elastically founded.

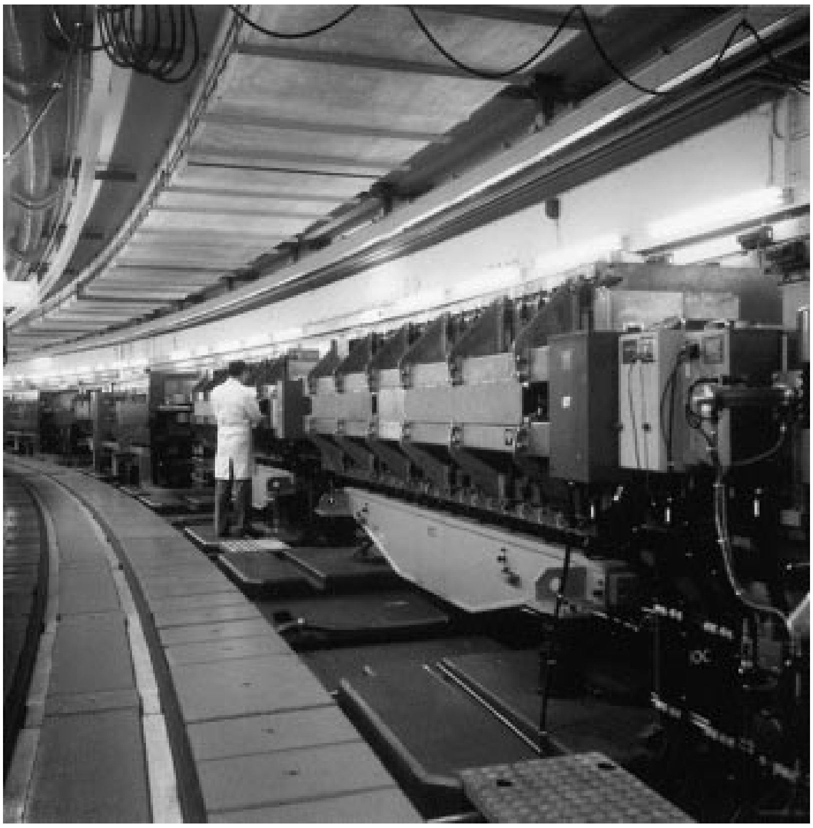


Fig. 16: Interior of the PS ring.

In the short time at my disposal it is not possible to review in detail the technical aspects of the machine. I would rather concentrate on the assessment of the ingredients that made possible the success of this first crucial project. I rank first the exceptional qualities of J. B. Adams as a manager and as an engineer, together with his immediate collaborators Mervyn Hine, Kjell Johnsen, Chris Schmelzer, Colin Ramm, Kase Zilverschoon, Hugh Hereward, Peter Standley, Pierre Germain. This team was able to motivate, educate, and rapidly move into positions of responsibility a second generation of people including Franco Bonaudi, Berend Kuiper, Guido Petrucci, Gunther Plass, Bas de Raad, Renzo Resegotti, Wolfgang Schnell, Simon van der Meer, myself, and others. A second element was certainly the atmosphere and the working conditions created by a group of young people, who did not have to worry too much about administrative procedures and could concentrate on their technical work.

One accidental event, which helped the cohesion of the team considerably, occurred during the very cold winter of 1956. The heating system of the barracks along the Arve failed in a catastrophic way and the entire Magnet Group had to be temporarily housed in a single classroom of the nearby Physics Institute. It was just at the time of the writing of the magnet specifications, which were then produced in a very cooperative way and helped to enhance considerably the team spirit. Finally, we had the support of an excellent workshop, inherited from the Physics Institute, made up of passionate and extremely competent mechanics, who provided us with excellent instruments for our experimental work. Some of these instruments could be considered inventions in their own right.

In autumn 1959 machine commissioning started. The central desk of the Main Control Room was very simple. It consisted essentially of a voltmeter to measure the energy, and of an amperemeter to measure the circulating current, but the local Control Rooms incorporated the essential elements for the guidance, acceleration, and measurement of the beam. Injection of the beam into the machine went rather well, but difficulties occurred for the capture of the beam by the radiofrequency system, which provoked some perplexity and a considerable rush of work. Finally, the solution of an adequate control loop was brilliantly found and in the evening of 24 November 1959 allowed the beam to be accelerated all the way to 24 GeV [6] (Figs. 17–19).

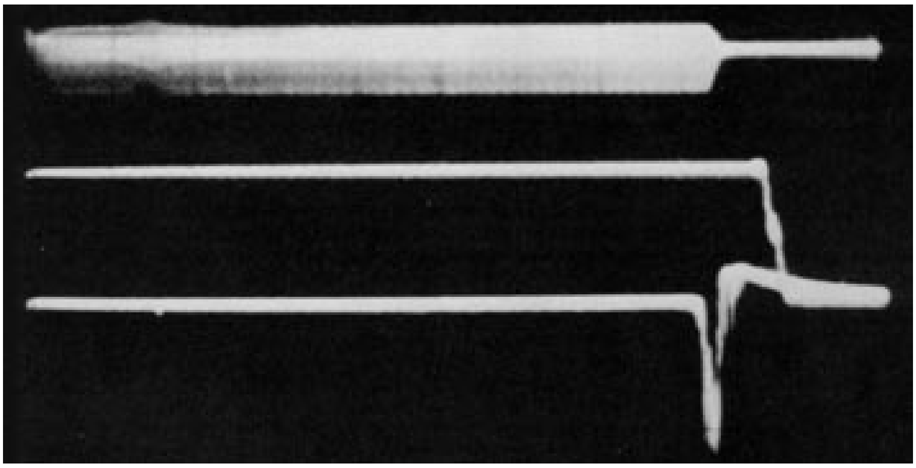


Fig. 17: In the evening of 24 November 1959 the beam is accelerated for the first time to 24 GeV.

Fig. 18: Scenes of the commissioning in November 1959.

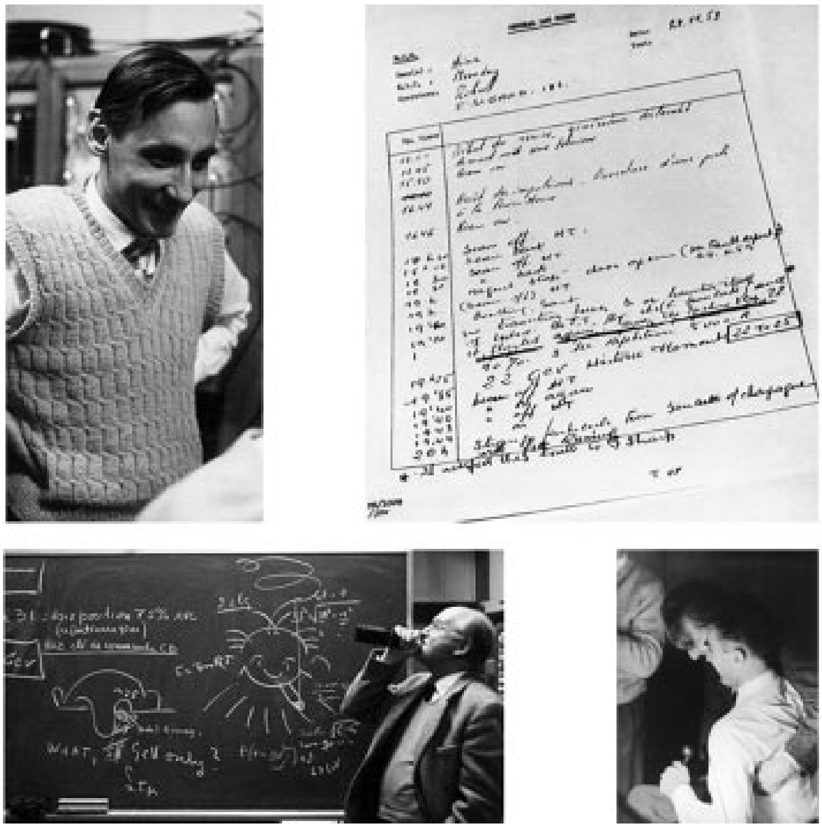


Fig. 19: The event recorded in the log-book. W. Schnell, Ch. Schmelzer, J. B. Adams and G. Bernardini celebrating the success.

3 OPERATION OF THE PS

The PS took over from the Synchrocyclotron and improved the tradition of good service to the users by its reliability of all systems and components, and by providing at all times an excellent operating team, consisting of an Engineer-in-Charge and of very dedicated operators. After an initial delay, mainly due to a busy programme still running on the SC, waves of experimenters started to use the PS and soon became very demanding (Fig. 20).

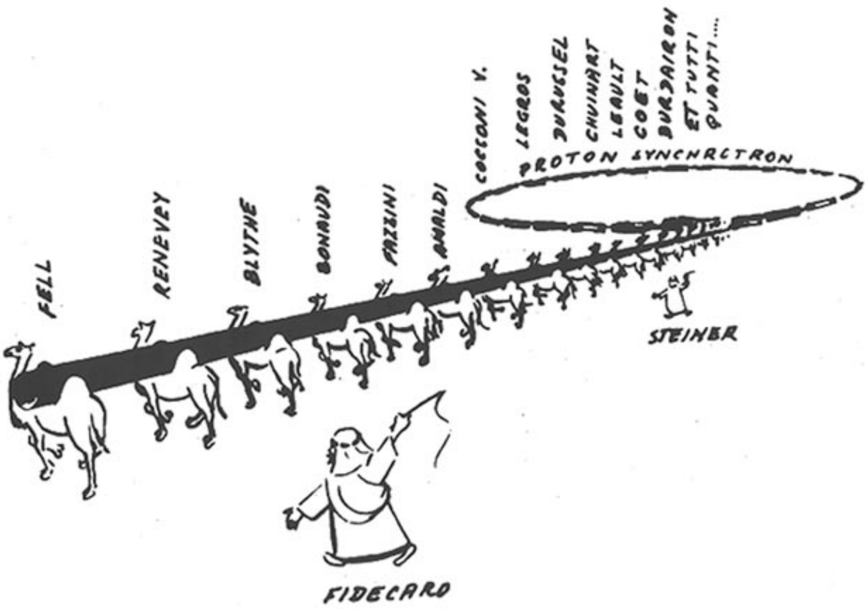


Fig. 20: G. Fidecaro running the show.

Again this was a chance for CERN accelerator staff, who have been constantly stimulated by the pressing demands of the physicists. The initial experimental facilities around the PS included only the South and the North Halls (Fig. 21). They soon became insufficient and then the East Hall, completed by the Hall containing two bubble chambers, was added in the early sixties. Fast and slow beam-extraction systems were added in 1963 to the internal targets, until then the only way to produce secondary particles. Finally, a huge West Hall was added when the ISR were constructed and two large general-purpose experimental set-ups, the bubble chamber BEBC and the superconducting spectrometer OMEGA, were fed by the PS for several years, prior to construction of the SPS.

The beam intensity increased from 2×10^{10} to 3×10^{11} protons per pulse during 1960 and to 6×10^{11} protons per pulse in 1962. Further progress was slower: 10^{12} protons per pulse were obtained only in 1964. The need for substantially higher intensities and in particular for higher current density per bunch, important for the ISR, prompted the Management to launch an improvement programme with the aim of a ten-fold increase in both the intensity and the phase-space density, which took the form of an injector synchrotron, the PS Booster.

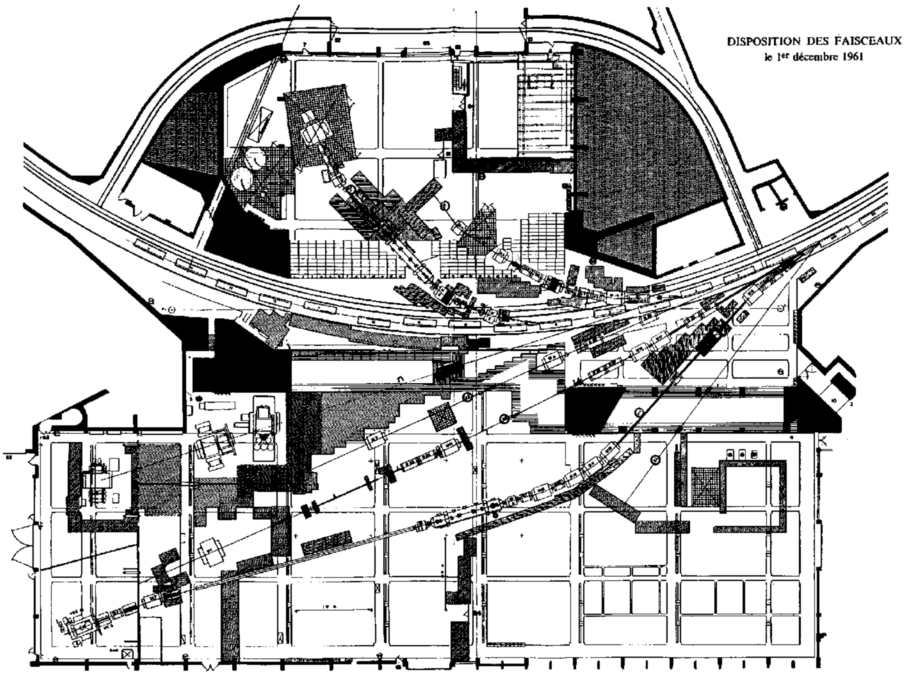


Fig. 21: South and North Experimental Halls.

4 THE PS BOOSTER

The main phenomenon limiting the current was known to be the incoherent (or individual) particle limit, which scales with $\beta^2\gamma^3$ at the injection into a circular machine. A ten-fold increase implied bringing the injection energy into the PS to 800 MeV (momentum 1463 MeV/*c*), which needed the insertion between the linac and the PS of an injector synchrotron. Two routes could be envisaged: a rapid cycling machine piling up ten or more pulses per PS cycle, or a slower multi-channel synchrotron.

The number of vertically stacked accelerators was set at four, each of them able to obtain a 2.5 intensity increase with respect to the PS without a substantial increase of the beam emittance. The increase in phase-space density was particularly important in view of the ISR.

This four-deck machine is the only one of this type [7] (Figs. 22–24). The lattice is based on triplets (1/2F–1D–1/2F) inserted between the bending magnets (Fig. 25), and features a low vertical beta-function in the magnets allowing a small vertical gap (important because of the four superimposed machines). The four beams can be recombined in various ways, depending on their further use, at the injection into the PS (Figs. 26, 27). The initial energy was 800 MeV and the radius was set to 25 m, just one-quarter of that of the PS owing to the envisaged recombination scheme. This excessive radius for such a low energy allowed the building of relatively long magnets of low field (otherwise they would have been simply a pair of end effects). It is for this reason that the machine energy can be raised to 1400 MeV (momentum 2148 MeV/*c*) for the LHC without magnet modifications.

A curiosity of the layout is that the centre of the ring is exactly on the border between France and Switzerland, with the consequence that we had to cover all the service buildings with an artificial hill, since no construction (except for customs) can span national borders. From the technical point of view, one can cite the peculiarity of the four-aperture stacked magnets, the all-metal quick connections on vacuum chambers made of Inconel X, with square undulations of variable amplitude, instead of the bulkier and more expensive ceramic, and thyristor-based power supplies for the main magnet.

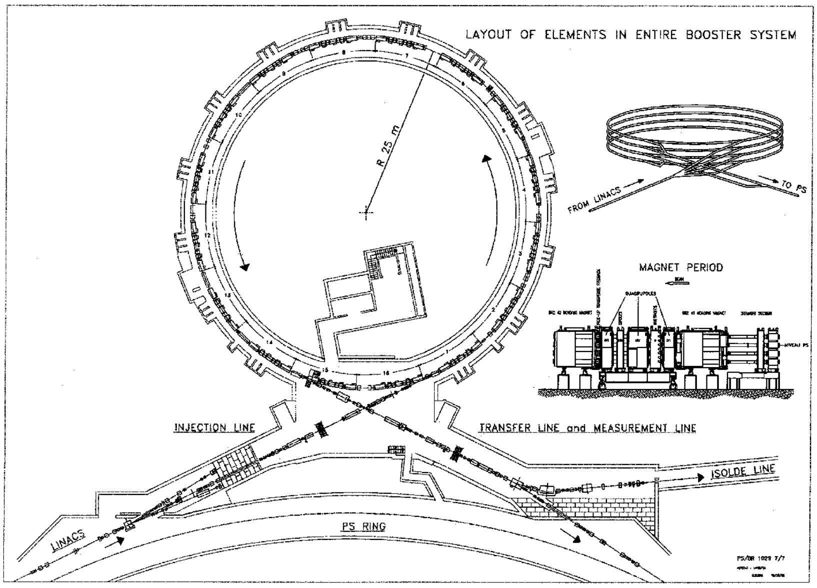


Fig. 22: Layout of the PS Booster.

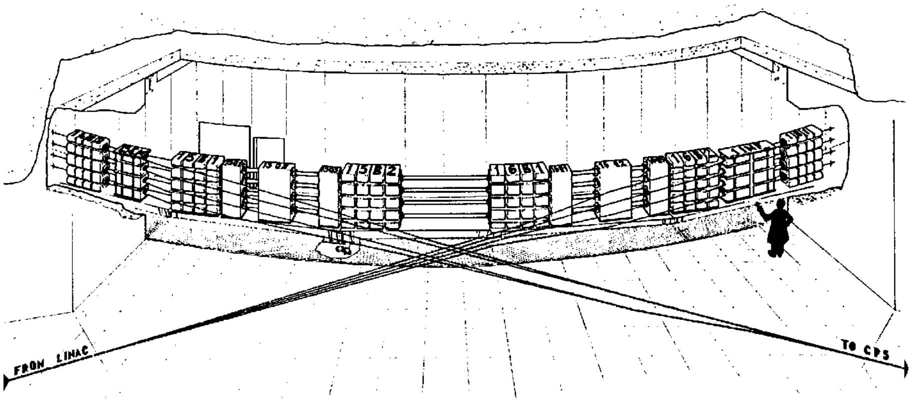


Fig. 23: Perspective view of the PS Booster.

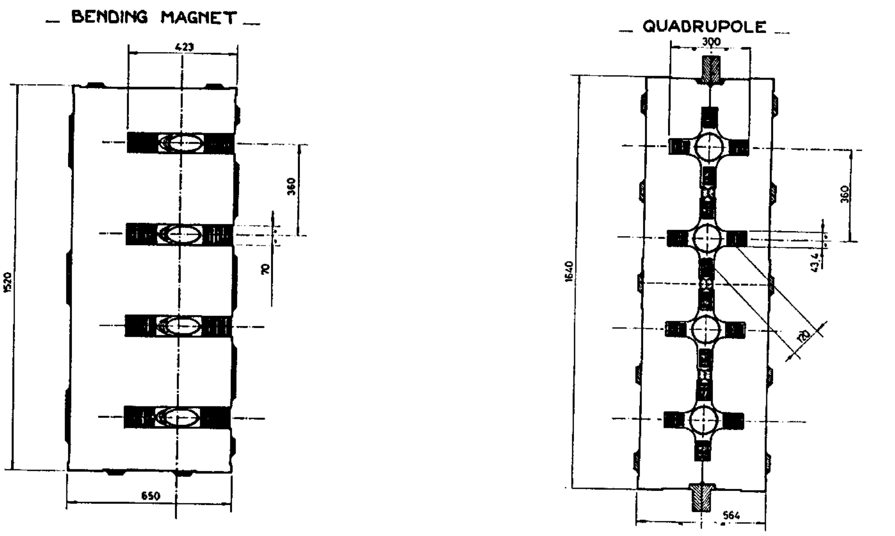


Fig. 24: Cross-sections of the Booster magnets.

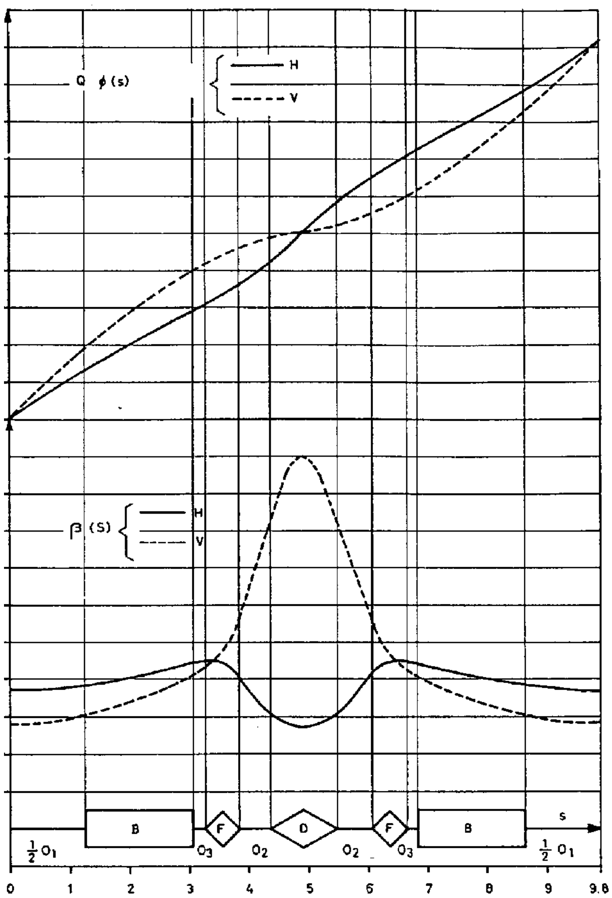


Fig. 25: Lattice functions of the PS Booster.

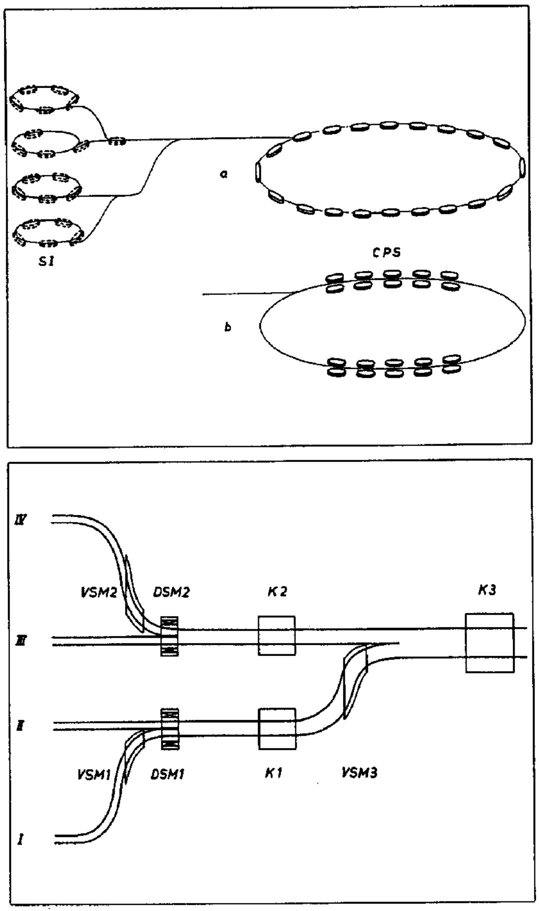


Fig. 26: Original beam recombination schemes: a) for normal PS twenty-bunch operation, b) for high-bunch intensity (two Booster bunches into one PS bucket).

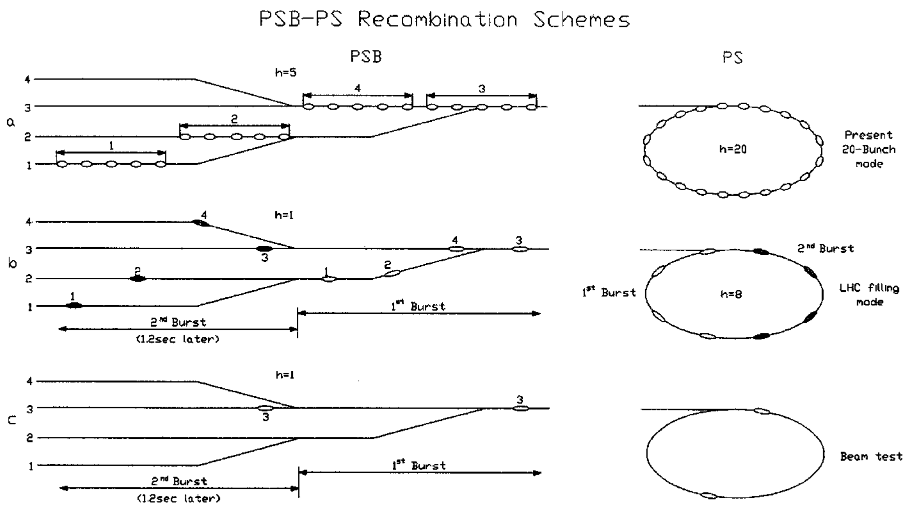
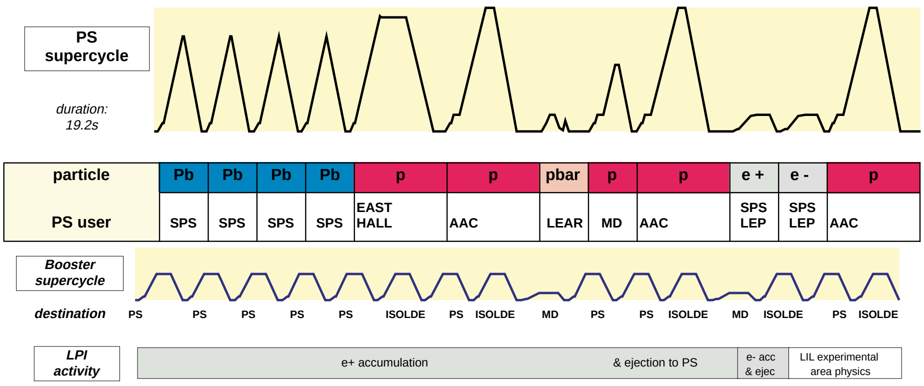


Fig. 27: PS filling mode based on: a) present 20-bunch mode, b) one high-intensity bunch for LHC.

5 THE PS AND BOOSTER TODAY

Today, after 36 years, the PS is still going strong as injector to the higher energy machines for the production of various types of particles (Fig. 28). Its performance in terms of beam intensity (Fig. 29) is quite remarkable. Performance of the Booster over more than twenty years has also been excellent as regards the achieved beam current, phase-space density, and the reliability. In fact the already ambitious goal of 2.5×10^{12} protons per pulse has been exceeded by more than a factor of four in the best ring (Fig. 30), and a very high availability (93–95%) obtained. The PS complex is being adapted and improved as the injector of the next machine, the LHC.



PS COMPLEX - Example of supercycle used in Fall 95

Fig. 28: Example of supercycle used in the PS for various types of particles.

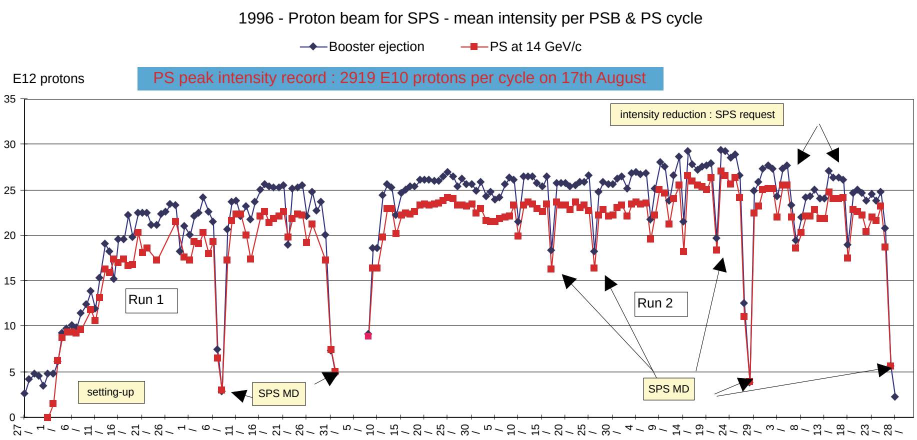


Fig. 29: Mean Booster and PS beam intensity for SPS fixed-target programme.

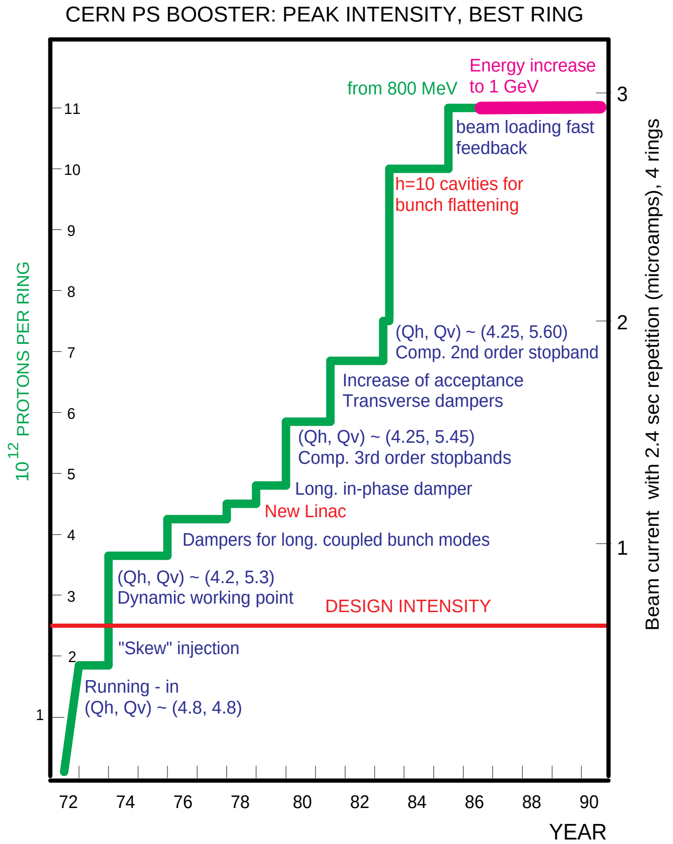


Fig. 30: Evolution of Booster beam intensity in the best ring.

6 INTERSECTING STORAGE RINGS (ISR)

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 later became (1960) the Accelerator Research Division. After some consideration of esoteric concepts, such as a plasma accelerator, the work concentrated on two possible lines: a proton–proton collider, made of two rings of magnets fed by the PS (later to become the ISR) or a 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) [8] to test ultra-high vacuum systems and particle accumulation and storage. To my knowledge, it was the first machine with separated-function magnets (Fig. 31).

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 BEBC. The total sum was close to one billion Swiss francs, but Vicky carefully avoided making the addition of the items, which were approved in succession one by one.

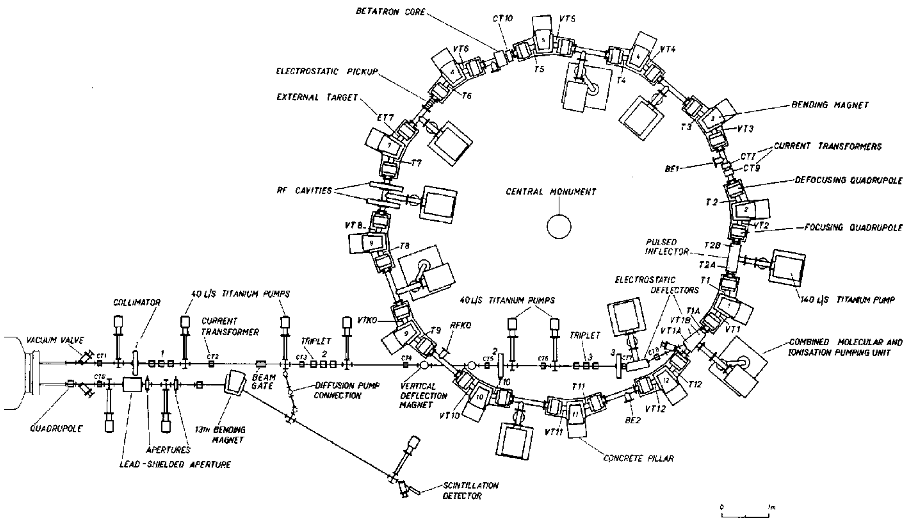


Fig. 31: Layout of CESAR, the electron ring to test beam stacking and accumulation in preparation for the ISR.

The ISR was the first proton–proton collider and reached eventually a centre-of-mass energy of 62 GeV by accelerating the PS beams to 31 GeV [9] (Figs. 32, 33). It was planned for a high luminosity and indeed it stored and made to collide almost incredible beam currents (57 A) and scored a world record luminosity during a physics run of more than 10^{32} cm^{-2} s^{-1}. The method for obtaining very high current was the so-called stacking in momentum space, which was typically one thousand times the space occupied by a single injected pulse from the PS.

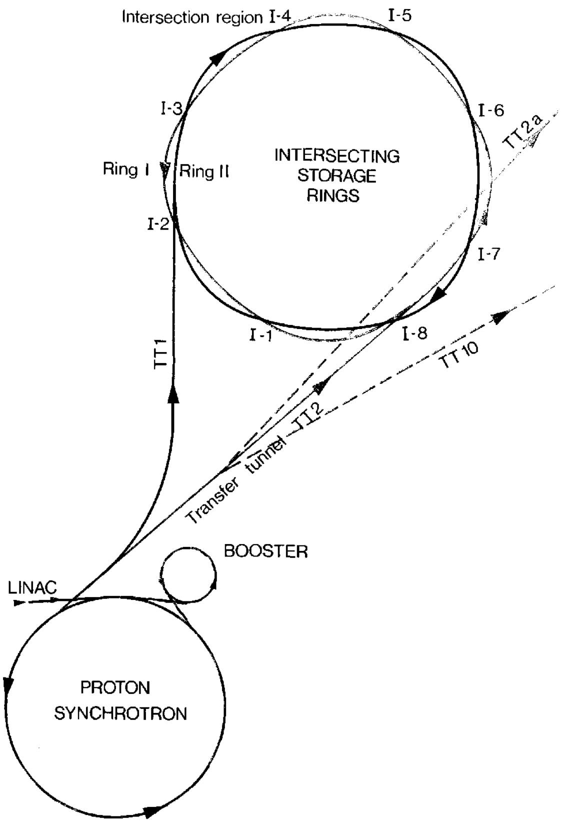


Fig. 32: Layout of the ISR.

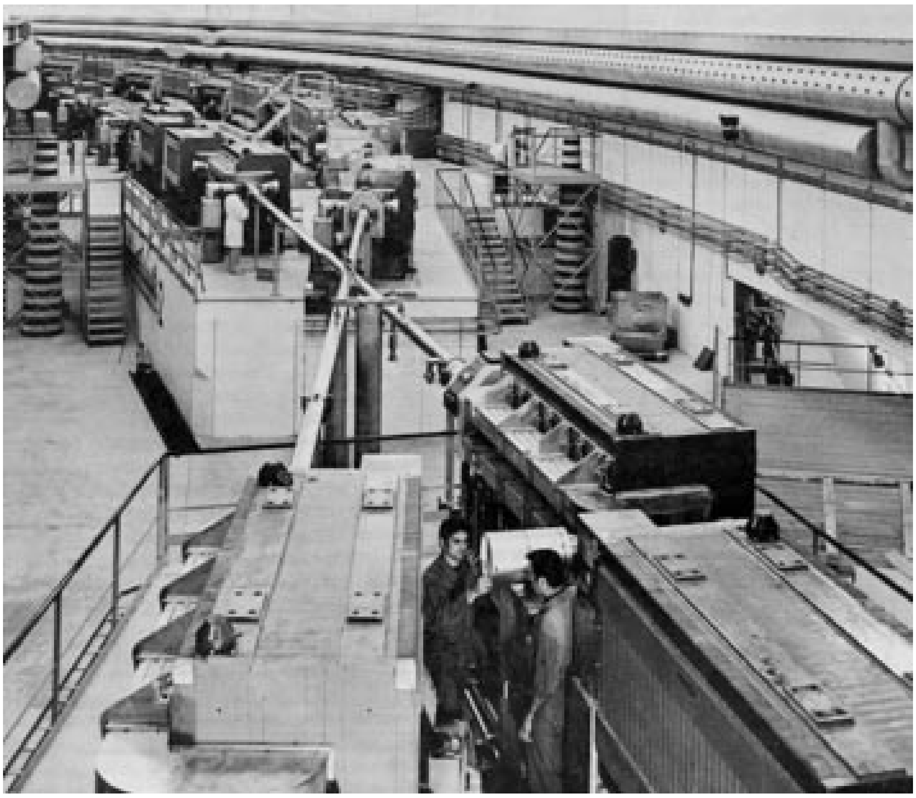


Fig. 33: View of an ISR intersection region.

A considerable enhancement of accelerator technology was due to the ISR, in particular concerning reliability and time stability of all components, and also of accelerator theory and experimentation faced with space-charge effects and non-linear resonances. Coming only shortly after the first operation of the PS, this enhancement constituted a challenge and a chance for accelerator people and prepared them for the following very innovative collider, the $\mathrm{Sp\bar{p}S}$. Also the requirements on vacuum were considerably enhanced (a thousand times lower pressure than the PS). For years the two ISR rings constituted the largest ultra-high vacuum system in the world.

The machine sustained a very active and advanced physics programme during fourteen years, which included also runs as proton–antiproton collider, until it was closed down in 1984 in order to concentrate resources, mainly personnel, on LEP design and construction. It marked the world history of proton synchrotrons not only because it was the first collider, but above all for the very intense beams (corresponding to 10^{15} circulating protons), which enabled accelerator physicists to face, investigate, and master a number of space-charge phenomena and beam instabilities. For the experimenters, it constituted an excellent environment for the design and construction of 4π-detectors and a number of remarkable results were obtained.

ISR performance and technical innovations, which deserve a much more extended treatment, are summarized in Tables 2 and 3, as presented by the Project Leader, K. Johnsen, at the closure ceremony. In addition to current and luminosity, it is important to mention the very low current loss rate and the long duration of physics runs. Concerning accelerator technologies and methods, one can cite of course beam stacking, brought to perfection, the invention of stochastic cooling by S. van der Meer, subsequently applied so successfully to $\bar{p}$ accumulation and storage, the development of the Schottky-scan diagnostic method and of on-line space-charge compensation. Finally, it was the first machine to incorporate industrially-built superconducting quadrupole magnets.

Table 2
ISR performance

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/min
Duration of physics runs	50–60 h
Maximum duration of $\bar{p}$ beam	345 h

Table 3
New techniques found or applied in ISR

Beam stacking
Schottky scan diagnosis
On-line space-charge compensation
Stochastic cooling
Industrially-built superconducting quadrupoles for low-beta insertion

7 300 GeV PROGRAMME / SPS

A fixed-target machine of considerably higher energy than the PS was already envisaged by the newly instituted European Committee for Future Accelerators in 1963, but almost eight years were necessary for its launching. Apart from financial reasons, its approval was certainly hampered by the fact that there was no space for such a large machine built with the traditional cut-and-fill method in or around the CERN site. The twelve Member States were therefore asked to propose new sites (Fig. 34), which were examined and discussed for years from the technical and political points of view with no tangible result.

Fig. 34: The various new sites proposed by Member States.

At that point, J. B. Adams, already appointed Director-General of the new Laboratory, put forward the brilliant idea of installing the accelerator in an underground tunnel tangent to the CERN site and fed by the PS as injector, hence saving money and staff by not duplicating existing services on a new site. In this way it was possible to construct a tunnel even larger than the one of Fermilab (radius

2200 m). It was the second decisive contribution of John Adams for the future of CERN! Indeed, without this the Geneva site would have been closed long ago and probably the history of CERN would have changed considerably. In fact, the way was so well paved by the SPS that the idea of building the following large project, LEP, away from Geneva was not even considered seriously by Council. It is fair to say that the first proposal to build a large machine on or close to the CERN site was put forward years before by C. Ram and C. J. Zilverschoon, but with the traditional cut-and-fill method the energy would have been limited to 150 GeV.

The layout of the machine and of its experimental areas [10] is given in Fig. 35. In addition to the construction of the tunnel, which constituted an excellent training for the future LEP machine, probably the most important technical innovation concerned the control system based on distributed computers, interconnected by an innovative communication network, and the very modern equipment of the Main Control Room (Fig. 36). But, under the impulse of J. B. Adams, other systems also profited from the most advanced technology in their field such as the magnets working at 2 T and the extraction elements, particularly the electrostatic septum (Figs. 37, 38).

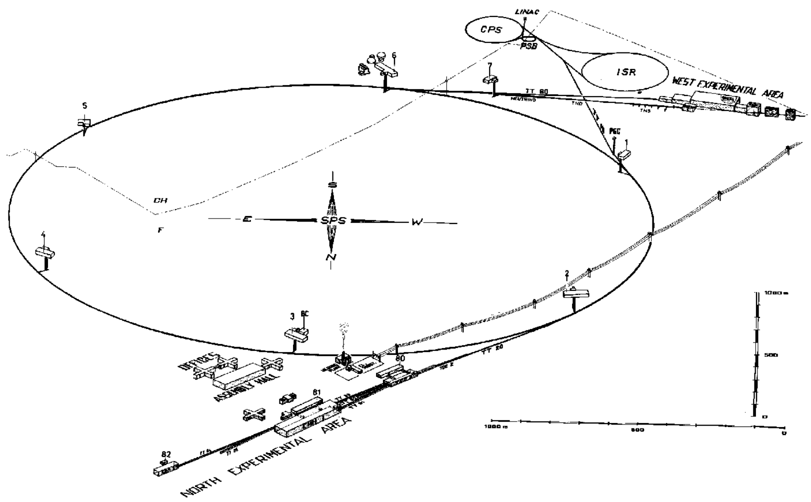


Fig. 35: The layout of the SPS with the West and the North Experimental Areas.

Fig. 36: The Main Control Room.

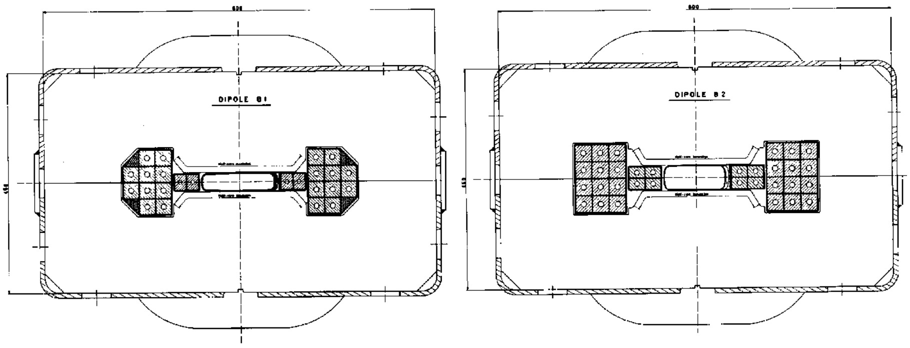


Fig. 37: The two types of bending magnets of the SPS.

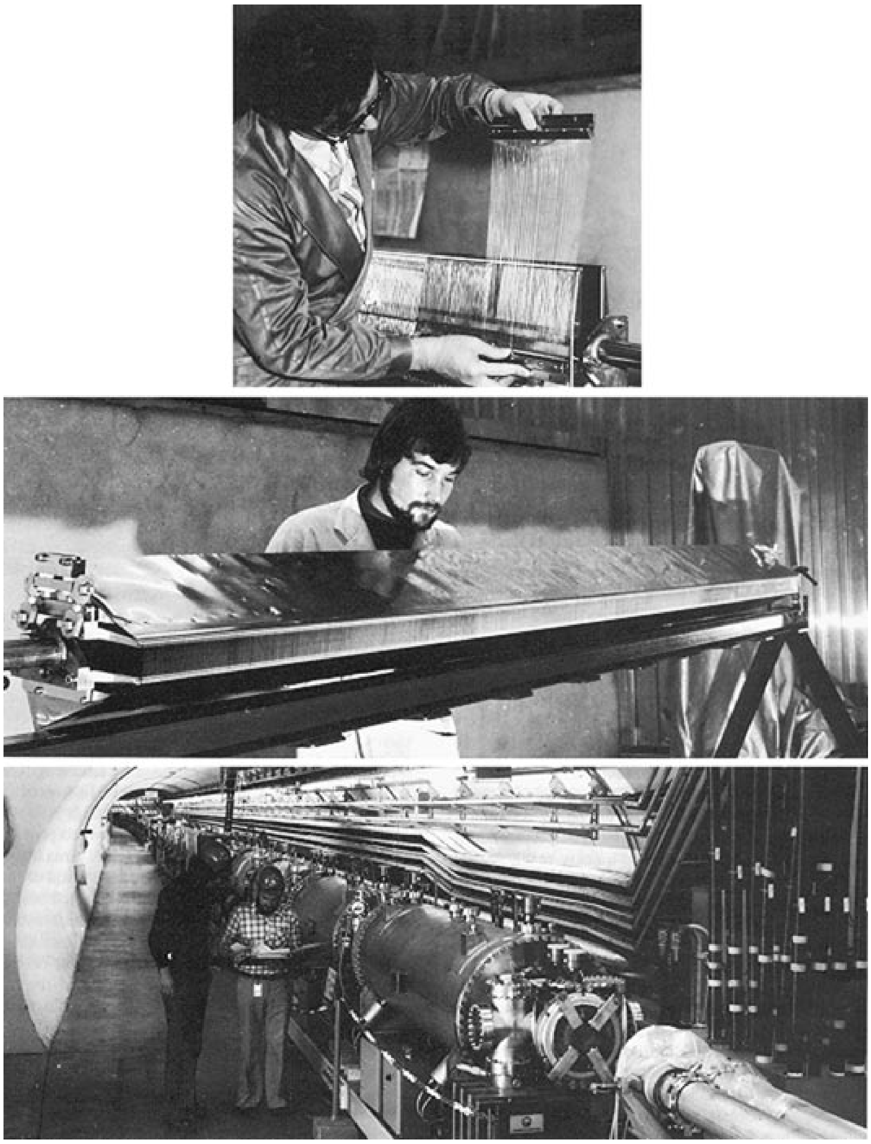


Fig. 38: Extraction elements of the SPS.

John Adams had considerably refined his management skills and, seconded by a senior staff with solid experience both at CERN (PS, ISR, Booster) and elsewhere, he was able to conduct the project respecting the initial definition of construction schedule and budget (Fig. 39). Even a fault induced in the coils of one half of the already assembled magnets by the inappropriate use of a cleaning acid by one manufacturer was unable to change the course of events. The repair was organized so well that the completion date could be maintained. It was therefore to the great satisfaction of all, but actually with no surprise, that the first beam at 300 GeV and then immediately after at 400 GeV was obtained on 17 June 1976 during a Council session! (Figs. 40–42).

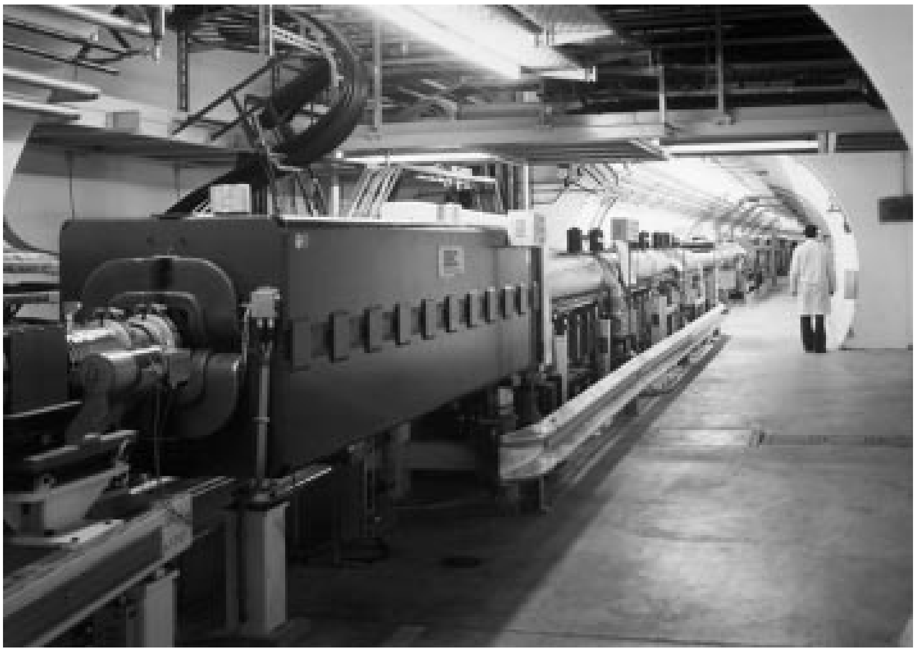


Fig. 39: Interior of the SPS tunnel.

Fig. 40: The commissioning starts.

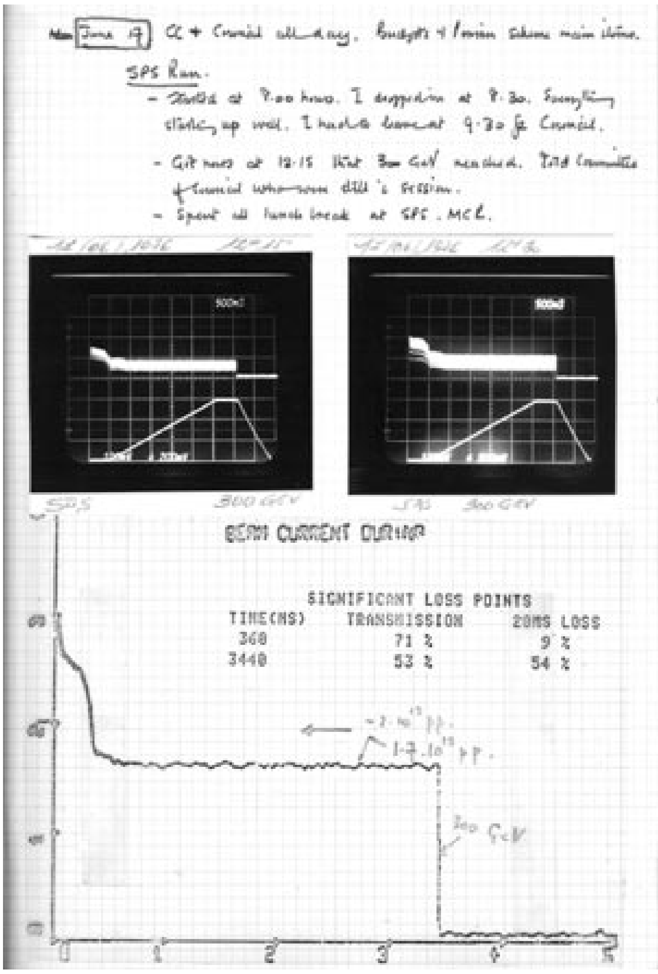


Fig. 41: Eureka! 300 and then 400 GeV reached on 17 June 1976 (from the day-book of J. B. Adams).

Fig. 42: Great satisfaction in the Main Control Room.

The experimental facilities again used the West Hall, equipped with high-energy secondary beams to feed the European bubble chamber BEBC, the spectrometer OMEGA and other electronic detectors, and in the construction of three North Areas, one for general-purpose beams, one for a very sophisticated muon beam, and one for the high-intensity proton beam. For the first time the complete secondary beams, with their beam monitoring and particle measuring systems were designed, constructed, and run by the SPS Machine Division (Experimental Areas Group).

The beam intensity reached the nominal value of 10^{13} protons per pulse only a few months after the first accelerated beam, in October 1976. Since then the energy was increased to 450 GeV and the intensity progressively brought to the present record of 4.5×10^{13} protons per pulse (Fig. 43).

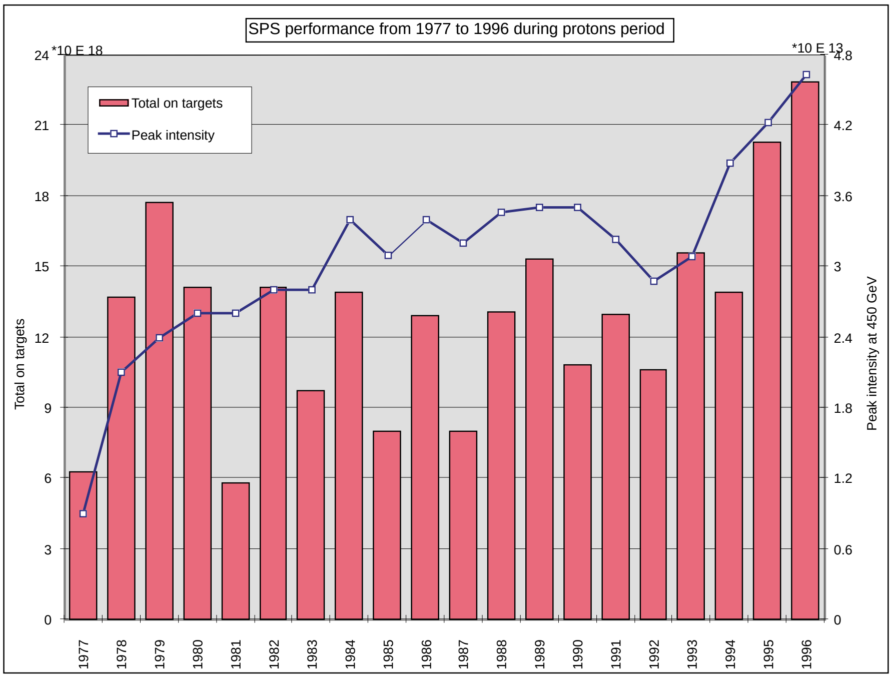


Fig. 43: Peak beam intensity and number of accelerated protons on targets from 1977 to 1996, showing the records obtained in 1996.

8 SPS $p\bar{p}$ COLLIDER

During its commissioning as a fixed-target accelerator (1976), Carlo Rubbia put forward the brilliant idea of converting the SPS to a $p\bar{p}$ collider, making use of the stochastic cooling method invented by S. van der Meer a few years before and tested in the ISR. After some hesitation, the accelerator community lined up behind J. B. Adams for the construction of the Antiproton Accumulator and the transformation of the SPS into a collider. But, prior to the final design of the Antiproton Source, a test synchrotron called ICE (standing for Initial Cooling Experiment) was quickly assembled with existing magnets in order to test both electron and stochastic cooling (Figs. 44, 45). As anticipated, the stochastic cooling method was confirmed and the design and construction of the Antiproton Accumulator was entrusted to R. Billinge and S. van der Meer. Despite the great sophistication of a number of elements, particularly for the stochastic cooling systems, the ring was assembled and tested successfully in less than three years [11] (Fig. 46).

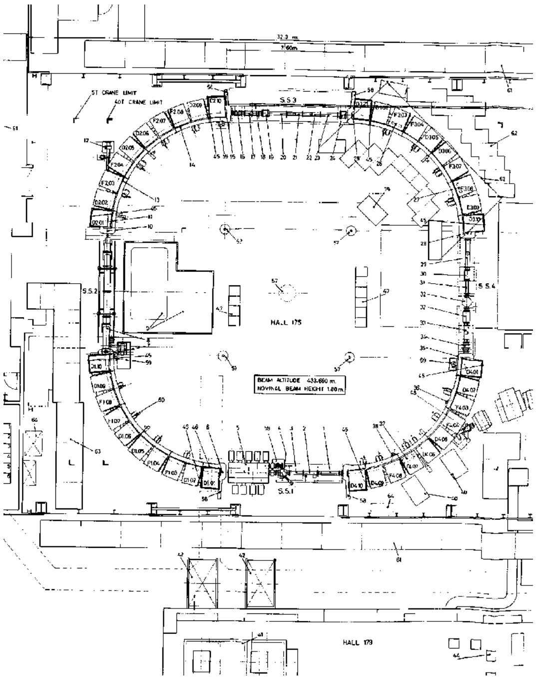


Fig. 44: The ring of ICE (Initial Cooling Experiment).

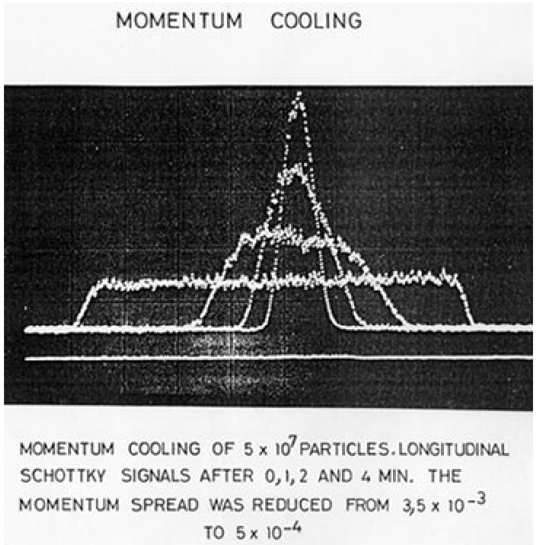


Fig. 45: First demonstration of momentum cooling in ICE.

Fig. 46: The Antiproton Accumulator.

The SPS itself had to be modified in view of the collider operation. On this occasion, the excellent conception and engineering of the SPS ring proved its value by allowing a considerable improvement of the vacuum system and the addition of low-beta sections thanks to straight-sections of sufficient length. The reliability of all systems and components also proved to be at the appropriate level for long running periods. Also the construction of two large underground experimental areas provided excellent training for the subsequent LEP areas.

A particular feature of the SPS was to alternate in the same year periods of fixed-target and collider operation, which required the $p\bar{p}$ experimental set-ups to be moved in and out of the ring enclosure in a relatively short time. This was important in order to maintain the continuity of work of the experimental teams engaged in the two programmes.

The luminosity at the beginning (few 10^{29} cm^{-2} s^{-1}) was sufficient to allow relatively quickly the discovery of the W and Z particles, while the requirement of a higher luminosity and the experience gained with the Antiproton Accumulator led to an improvement of the antiproton source by separating the functions of collection and accumulation of particles. This implied the addition of a second ring, called the Antiproton Collector (AC), around the original AA (Fig. 47). Consequently, the luminosity was raised by a further factor of about ten to reach a peak of 6×10^{30} cm^{-2} s^{-1} in 1990 (Fig. 48).

Fig. 47: Antiproton Collector and Antiproton Accumulator.

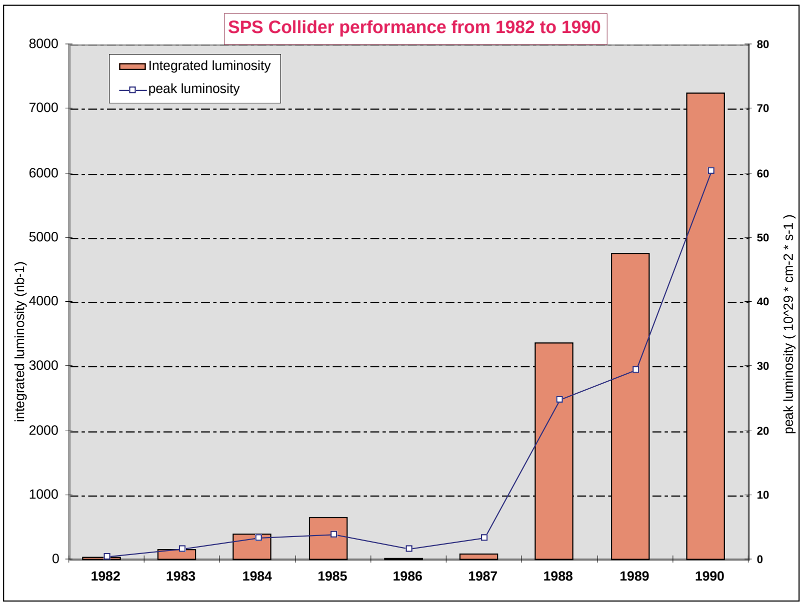


Fig. 48: SPS Collider performance from 1982 to 1990.

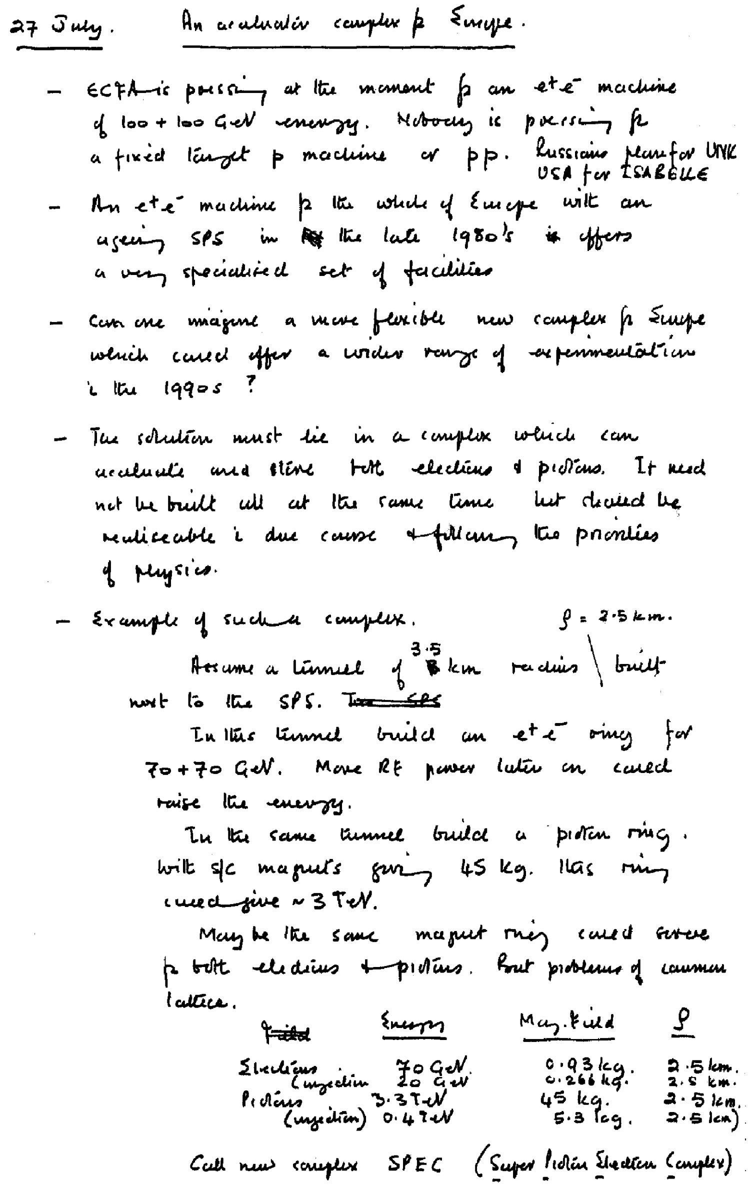
9 LOW-ENERGY ANTIPROTON RING (LEAR)

The existence of the antiproton source prompted the conception and the construction of a new synchrotron, LEAR [12] (Fig. 49), able to store and decelerate antiprotons and then to provide an extracted beam of pure antiprotons of variable energy, down to 2 MeV (almost at rest). The ring incorporates both electron and stochastic cooling, and a slow beam-extraction capable of producing extremely long spills, which can reach a duration of 15 h (54 000 s). This is obtained by slowly superimposing a noise on the stacked beam, driving successive parts of it to the extraction resonance. The flux of the pure external beam ($2 \times 10^6\ \bar{p}$/s) sustains a rich experimental programme. In 1995 the world's first antihydrogen atoms were produced on an internal target (JETSET experiment).

Fig. 49: Low-Energy Antiproton Ring.

10 LARGE HADRON COLLIDER (LHC)

The idea of installing in the envisaged LEP tunnel a second collider using hadrons can be found in J. B. Adams's day-book of 1976/77 (Fig. 50), recording the intensive discussions about the future large project of CERN. Indeed, his feeling was that the community of CERN users would request hadron collisions again after the then preferred e^+e^- 100 + 100 GeV machine.



27 July. An accelerator complex for Europe.

– ECFA is pressing at the moment for an e^+e^- machine of 100 + 100 GeV energy. Nobody is pressing for a fixed target p machine or pp. Russians plan for UNK, USA for ISABELLE

– An e^+e^- machine for the whole of Europe with an ageing SPS in the late 1980's offers a very specialised set of facilities

– Can one imagine a more flexible new complex for Europe which could offer a wider range of experimentation in the 1990s?

– The solution must lie in a complex which can accelerate and store both electrons & protons. It need not be built all at the same time but should be realiseable in due course following the priorities of physics.

– Example of such a complex. ρ = 2.5 km.

Assume a tunnel of 3.5 km radius built next to the SPS. ~~Two SPS~~

In this tunnel build an e^+e^- ring for 70 + 70 GeV. More RF power later on could raise the energy.

In the same tunnel build a proton ring with s/c magnets giving 45 kg. This ring could give ~ 3 TeV.

Maybe the same magnet ring could serve for both electrons & protons. But problems of common lattice.

~~Field~~	Energy	Mag. Field	ρ
Electrons	70 GeV	0.93 kg.	2.5 km.
(injection	20 GeV	0.266 kg.	2.5 km.
Protons	3.3 TeV	45 kg.	2.5 km.
(injection)	0.4 TeV	5.3 kg.	2.5 km)

Call new complex SPEC (Super Proton Electron Complex).

Fig. 50: A page from J. B. Adams's day-book concerning a second ring in the LEP tunnel.

A feasibility study of the LHC started in autumn 1983, soon after the approval of LEP [13]. It became obvious immediately that, in order to exploit fully the dimensions of the tunnel, it would be necessary to aim at a magnetic field as high as possible by cooling the magnets down to 1.8 K with superfluid helium. It was also soon realised that only proton–proton collisions would have a chance to meet the very high requirements on luminosity put forward by the potential users. This implied two separate magnetic channels for the counter-rotating beams. Further, given the space limitations in the tunnel cross-section if the LEP machine were kept in place, it became necessary to adopt the so-called 'two-in-one' solution, whereby two beam channels are installed in a single iron structure and cryostat. This 'two-in-one' solution is also more economical than the one with single-aperture magnets in separate cryostats. As can be seen from Fig. 51, the initial configuration of 1983 was already very similar to the present one (Fig. 52). Owing to the full commitment to LEP, the R&D work started only in 1988 and acquired momentum only in the last few years culminating in the realisation of full-sized dipoles and quadrupoles assembled in a 50 m section, called string test, which meet the very demanding specifications of an operational field of 8.4 T (Fig. 53).

The project was approved by CERN Council in December 1994 [14]. The design is based on a centre-of-mass energy of 14 TeV (14 000 GeV) and a luminosity of 10^{34} cm^{-2} s^{-1}.

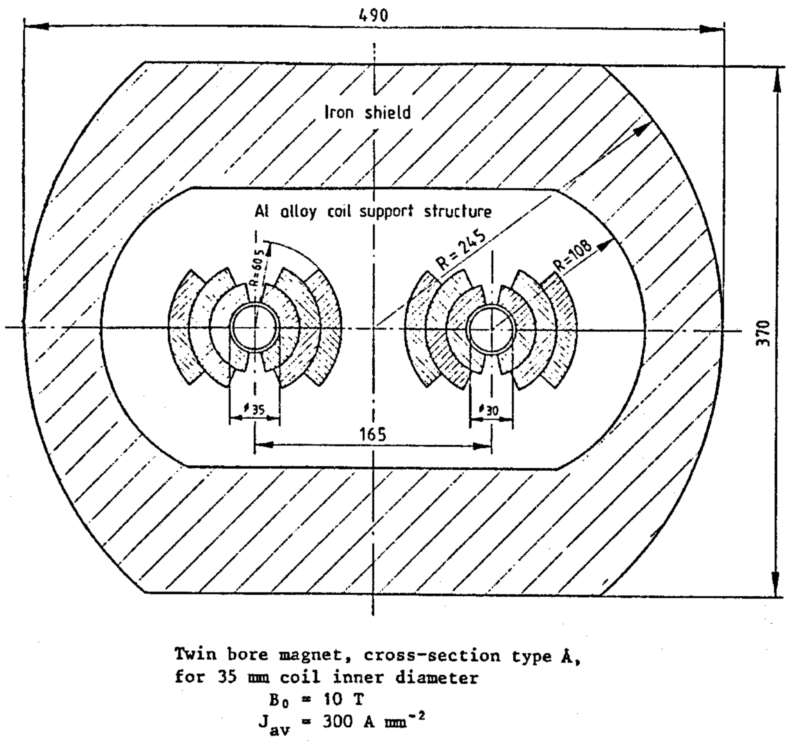


Fig. 51: First configuration of the LHC magnet (1983).

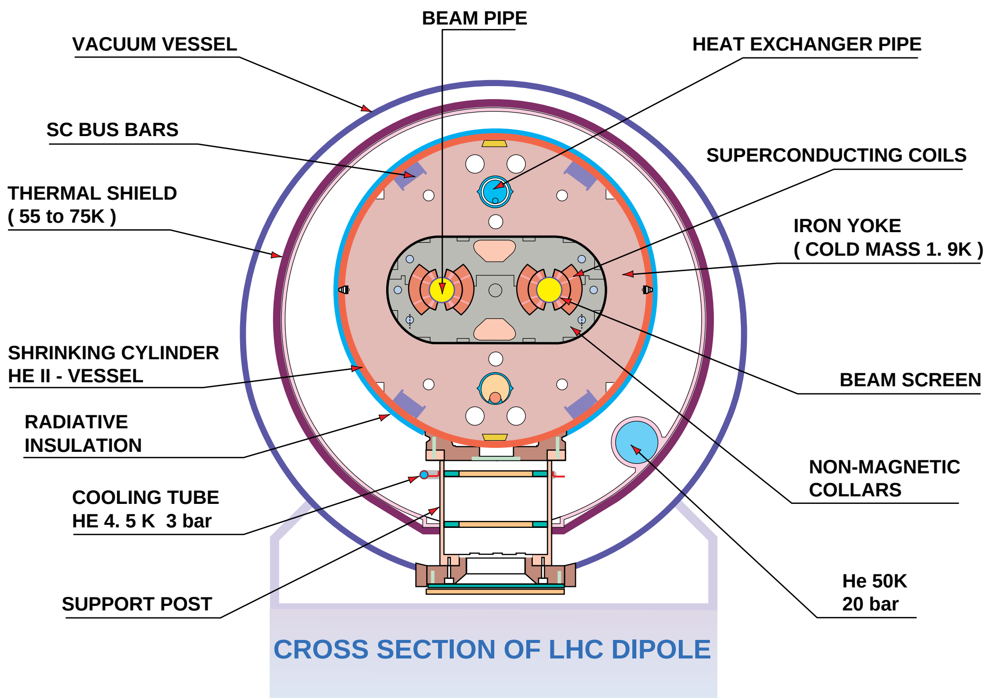


Fig. 52: Present configuration of the LHC magnet (1996).

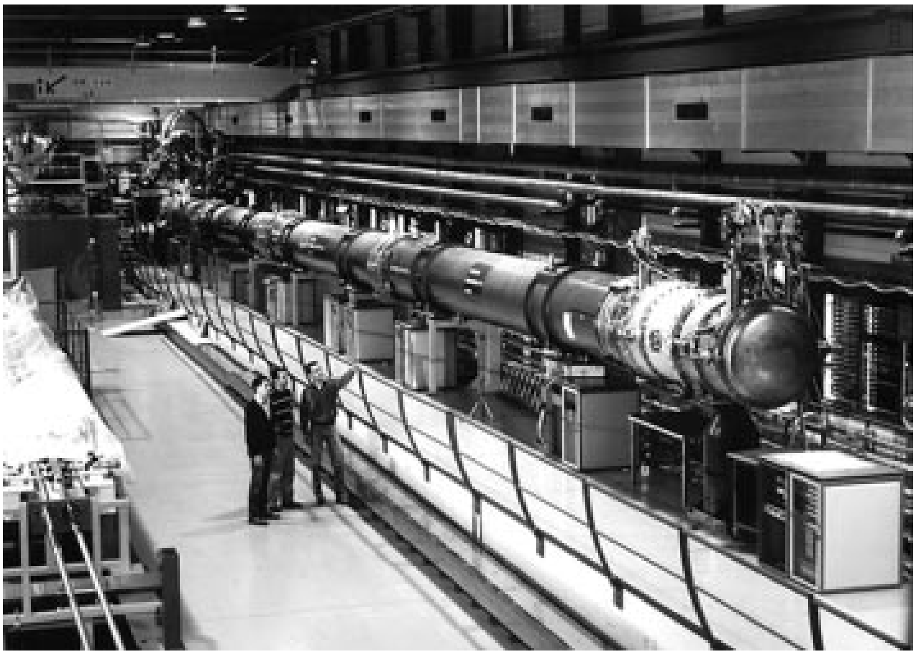


Fig. 53: LHC string test.

11 APPLICATIONS OF SUPERCONDUCTIVITY

It is impossible to close the subject without saying a few words on the role of J. B. Adams in the promotion of advanced technology, particularly superconductivity. The development of both superconducting magnets and RF cavities has a long history at CERN. The first superconducting magnet constructed here was the quadrupole CASTOR with cold iron and twisted conductors. To my knowledge, it was the first magnet to reach the critical current and was used in a secondary beam initially in the West Hall for BEBC and afterwards in the H8 beam in the SPS North Experimental Area until 1984.

During the construction of the SPS the proposal to adopt superconducting magnets was put forward by three Laboratories, CEA Saclay, KfK Karlsruhe and Rutherford Abingdon, the so-called GESSS collaboration. At that time, J. B. Adams judged premature the construction of the new CERN workhorse with this technology, but he encouraged the continuation of the development by promoting the construction of two bending magnets by CEA Saclay in collaboration with CERN, called CESAR [15] (Fig. 54). They showed an operational field of 4.5 T in a coil aperture of 150 mm and were also installed in the H8 beam (Fig. 55) from 1978 to 1984. Another development at CERN was the design and construction of the 5 m long P0 dipole [16] by the SPS Magnet Group, which was an improved version of the Tevatron magnet (field 4.5 T, coil aperture 150 mm). It was important particularly for the development of conductors of high current density (2500 A mm^{-2}), from which the construction of HERA (Fig. 56) later benefited.

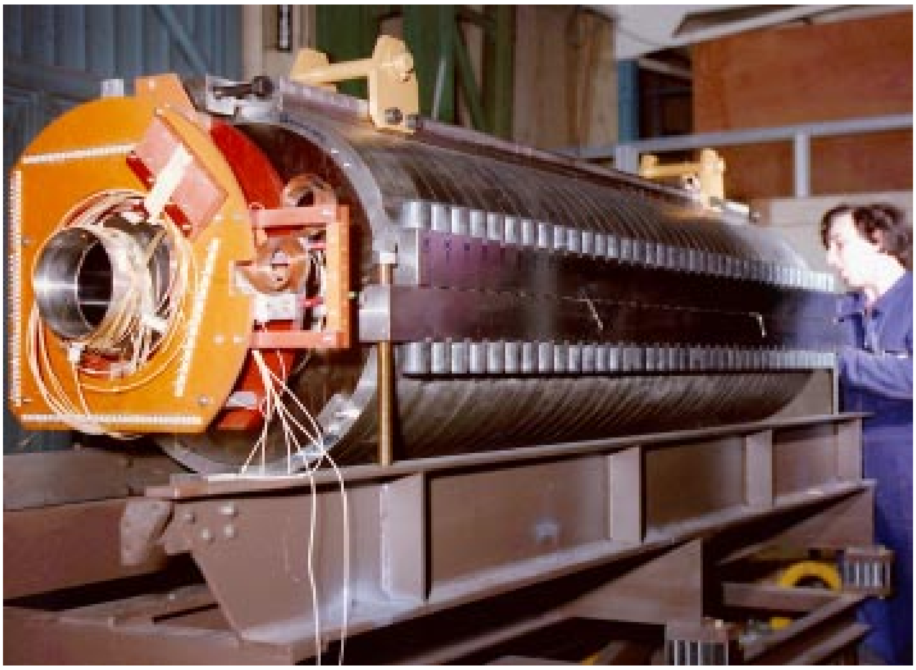


Fig. 54: CESAR superconducting magnet.

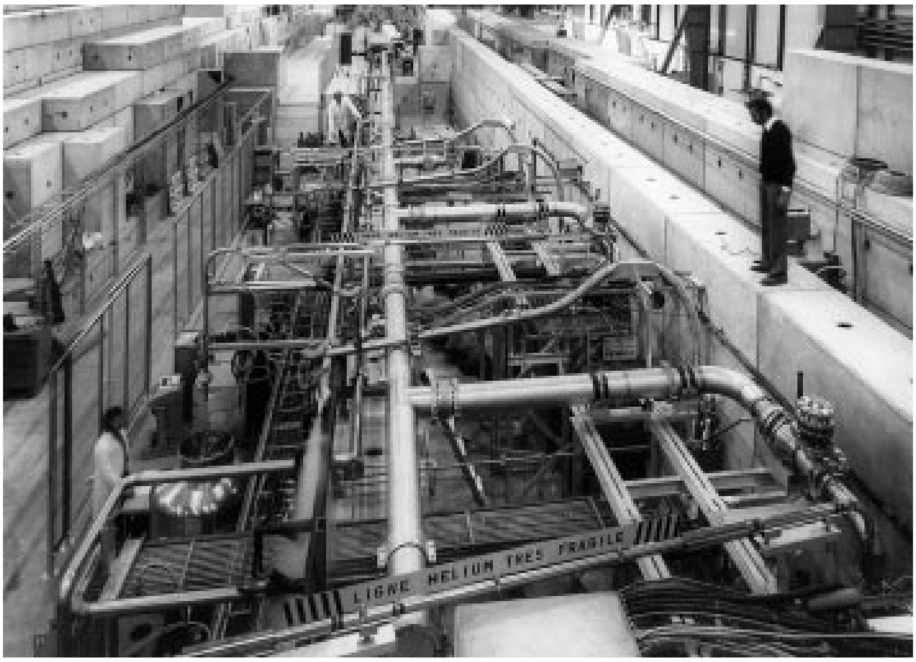


Fig. 55: The H8 beam in the SPS North Experimental Area.

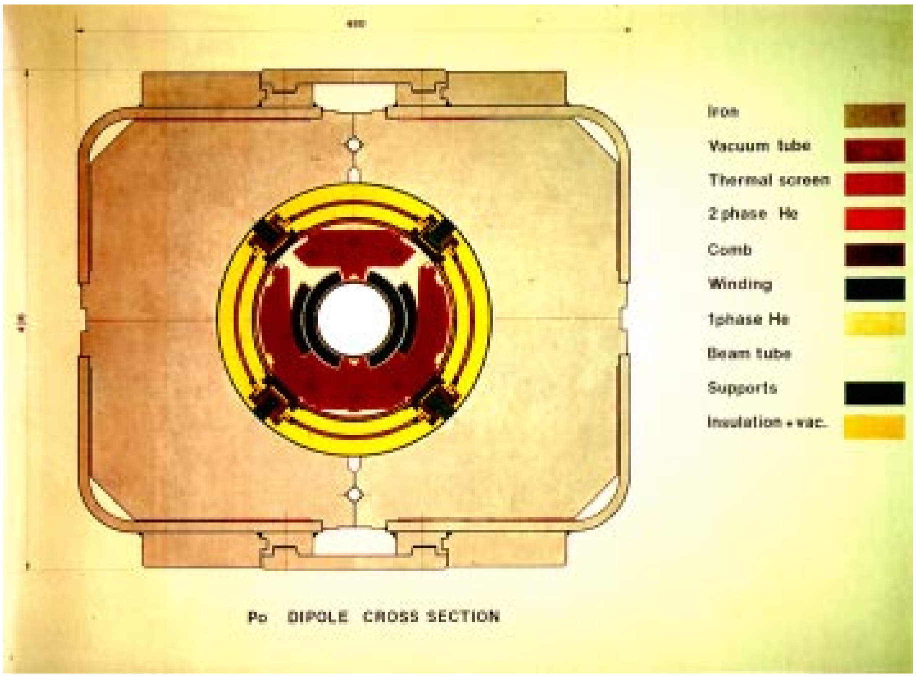


Fig. 56: Cross section of the P0 superconducting magnet.

Concerning the radiofrequency cavities, after a first small-scale development in the late sixties and early seventies, substantive work started in 1979 in view of LEP construction. Initially the work concerned the basic instrumentation, such as the temperature mapping of the cavity, and the 500 MHz cells tested in PETRA at DESY. In 1985 the first prototype copper cavity sputtered with niobium was successfully tested, while in 1986 the scenario for increasing the LEP energy was elaborated. In 1991 a first four-cell niobium-copper cavity was tested in the SPS and in 1993 industrial production started in three companies (Fig. 57). At the end of 1996 the total circumferential voltage provided by superconducting cavities reached 1740 MV and the beam energy 88 GeV [17].

Fig. 57: LEP superconducting radiofrequency cavity.

12 CONCLUSIONS

Construction and operation of alternating-gradient synchrotrons to support excellent research programmes has made CERN, more than forty years after its foundation, *'the'* World Laboratory for Particle Physics. With the construction of the LHC it will even strengthen its position with the official participation of non-European countries.

In these times of financial constraints, it is important to stress how well CERN has fulfilled its role, how effective it has been in promoting technological advances, and in using to the utmost the resources provided by the European Member States and other countries. Table 4 gives a comparison of the three CERN hadron colliders in terms of size and unit cost in MCHF/GeV. It is seen that this unit cost decreases by a factor of about fifty from the ISR to the LHC, largely due to improvements in design and technology. It has to be stressed that in all three cases the colliders are costed as 'green-field' installations, except for the basic injector, the PS, common to all. In fact the Sp$\bar{p}$S is costed as if it was initially constructed as a collider, namely including the tunnel, the infrastructure, the machine itself, the two Underground Areas and the Antiproton Accumulator, but of course without the West and North Experimental Areas. Concerning the LHC, its cost is augmented by the cost of the LEP tunnel and the technical infrastructure. All the costs are in 1996 prices.

Table 4
Characteristics and unit cost of CERN hadron colliders (relative to ISR)

	Energy (GeV)	**R_{av} (m)**	**Energy/R_{av} (GeV/m)**	**Unit cost (MCHF/GeV)**
ISR	62 *(1)*	150 *(1)*	0.41 *(1)*	12.6 *(1)*
Sp$\bar{p}$S	630 *(10.2)*	1100 *(7.3)*	0.57 *(1.4)*	2.67 *(0.21)*
LHC	14 000 *(226)*	4243 *(28.3)*	3.30 *(8.05)*	0.25 *(0.02)*

The contributions of Sir John Adams at the beginning of CERN and in other decisive moments of its history are of overwhelming importance. An essential element of his work was certainly the education of many of us, who had the chance to be led by him, not only on technical matters concerning accelerators and associated technology and engineering, but possibly above all on project management and human relations in large teams. It is his heritage to CERN, which has been and will be carried over, I am sure, by the present and the new staff towards a future as brilliant as the past evoked in this lecture.

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