Subnuclear Physics: Past, Present and Future
Pontifical Academy of Sciences, Scripta Varia 119, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/sv119/sv119-hubner.pdf

THE BIRTH AND DEVELOPMENT OF THE FIRST HADRON COLLIDER THE CERN INTERSECTING STORAGE RINGS (ISR)

K. HÜBNER, T.M. TAYLOR

CERN, 1211 Geneva 23, Switzerland

Abstract

The CERN Intersecting Storage Rings (ISR) was the first facility providing colliding hadron beams. It operated mainly with protons with a beam energy of 15 to 31 GeV. The ISR were approved in 1965 and were commissioned in 1971. This paper summarizes the context in which the ISR emerged, the design and approval phase, the construction and the commissioning. Key parameters of its performance and examples of how the ISR advanced accelerator technology and physics are given.

1. Design and approval

The concept of colliding beams was first published in a German patent by Rolf Widerøe in 1952, but had already been registered in 1943 (Widerøe, 1943). Since beam accumulation had not yet been invented, the collision rate was too low to be useful. This changed only in 1956 when radio-frequency (rf) stacking was proposed (Symon and Sessler, 1956) which allowed accumulation of high-intensity beams. Concurrently, two realistic designs were suggested, one based on two 10 GeV Fixed-Field Alternating Gradient Accelerators (FFAG) (Kerst, 1956) and one suggesting two 3 GeV storage rings with synchrotron type magnet structure (O'Neill, 1956); in both cases the beams collided in one common straight section. The idea of intersecting storage rings to increase the number of interaction points appeared later (O'Neill, 1959).

These studies have to seen in the context of a significant activity in the field of lepton colliders at that time with the storage ring Anello Di Accumulazione (ADA) starting the successful lineage of e+e- colliders at the Italian National Laboratory in Frascati (Touschek, 1961) which was continued by VEPP-2 in 1964 (Auslender, 1966), ACO in 1965 (Orsay Group, 1966) and culminated in LEP at CERN in 1989 (Picasso & Plass, 1989).

At CERN, already during the construction of the 28 GeV Proton Synchrotron (PS) an accelerator research group led by A.Schoch had been formed which produced by the end of 1960 a proposal of two tangential 25 GeV proton storage rings (Hereward, 1960).

After the publication of the ISR proposal in 1960, a rather heated debate took place at CERN and in the physics community whether the next step after the PS should be a powerful synchrotron of either higher energy or of higher intensity providing more intense secondary beams, or a set of proton storage rings to investigate very high-energy phenomena.

In 1962, the intersecting ring topology was adopted for the ISR to increase the number of possible physics experiments (Johnsen, 1963). In order to channel the discussion, the European Committee for Future Accelerators (ECFA) was formed in 1963, chaired by E.Amaldi. It recommended both, the ISR fed by the PS and a 300 GeV synchrotron to compete with the US and USSR where large synchrotron were designed, respectively under construction.

Although the rf stacking had been experimentally proven before (Terwilliger, 1957), CERN decided to acquire experience with these key technique for achieving high-intensity beams and, in turn, a high collider luminosity. On top of it, the ultra-high vacuum technology imperative for the ISR had to be tested. Hence, a small test ring, the CERN Electron Storage and Accumulation Ring (CESAR), was built, as shown in Fig. 1.

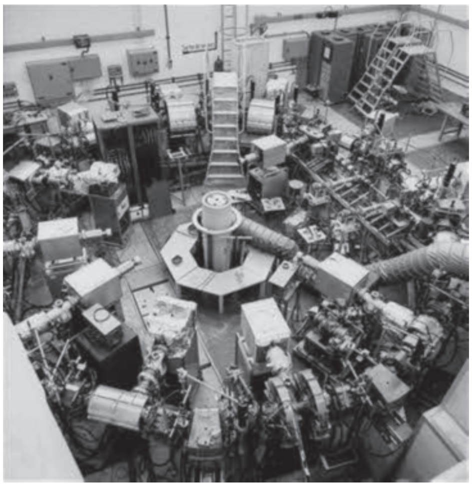

Fig. 1. The CERN Electron Storage and Accumulation Ring (CESAR).

It operated from 1963 to 1967. The beam parameters were carefully chosen so that the accumulation of a 28 GeV proton beam was faithfully simulated by a 2 MeV electron beam in a ring with 24 m circumference exhibiting virtually no radiation damping by synchrotron radiation. CESAR confirmed the rf stacking in 1964 (Hansen, 1965), which provided welcome support for the ISR-project.

The Design Reports for ISR and the 300 GeV synchrotron were published in 1964 (CERN 1964a, 1964b). The CERN directorate under V.Weisskopf decided to favour the ISR which appeared to offer more discovery potential for less cost and a shorter construction time. On top of it, a site was available for the ISR after the French government had offered land in 1962, extending suitably the Meyrin site, while one feared that the choice of the site for the 300 GeV synchrotron could be a source of tension between the CERN Member States (an apprehension which turned out to be justified in the years to come).

After considerable debate, the ISR construction was approved in principle in the framework of a Supplementary Programme, foreseen in the CERN Convention, in June 1965, and financial participation by all Member States except Greece was accepted in December of the same year. Kjell Johnsen was appointed project leader. The prevailing argument had been “to remain competitive for as low a cost possible”. However, it was also decided that the study of the 300 GeV synchrotron would be continued. A detailed account of the emergence of the ISR can be found elsewhere (Pestre, 1990).

2. Construction

The layout of the ISR with the transfer lines from the PS are shown in Fig. 2.

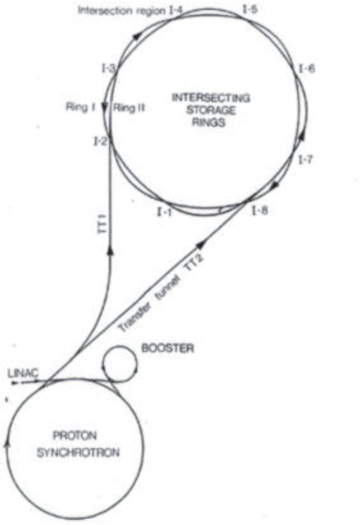

Fig. 2. Layout of ISR and of the transfer lines from the PS (Russo, 1996).

The PS and ISR sites are separated by the Swiss-French border. The maximum energy of the ISR was chosen to be 28 GeV, identical of the PS, and the orbit length was 943 m, exactly 1.5 times the PS circumference.

The main magnets were of the combined-function type, providing both a dipole field for the bending and a quadrupole component for the beam focusing. These C-shaped magnets offered a good access to the vacuum chamber, which turned out later to be decisive for the continuous up-grading of the vacuum system, and allowed for elaborate pole-face windings to fine-tune the magnetic field in the magnet gap. It was also claimed that the combined-function magnets were the cheapest option. The magnetic field was 1.33 T at 28 GeV. Fig. 3 shows a photo of the magnet during measurement.

Fig. 3. Combined-function magnet in the process of being measured.

A simple FODO structure was chosen as the magnet lattice after experience with the FOFDOD lattice of the PS. Here F/D stands for horizontally focusing / defocusing magnets, with a straight section O between them. The layout of an octant of the ISR around an intersection point can be seen in Fig. 4 and Fig. 5 gives a view of intersection point 5 (I5) after completion.

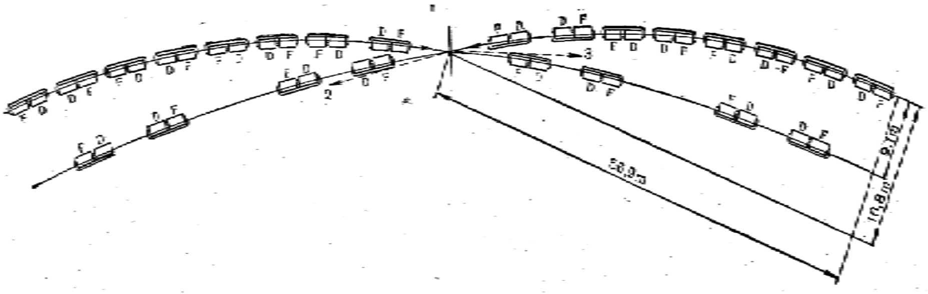

Fig. 4. One Octant of the ISR magnet lattice (Johnsen, 1963).

Fig. 5. ISR Intersection point 5.

The construction was smooth and rapid due to the excellent preparation during the design phase and due to the fact that the leading members of the team had solid experience from the construction of the PS. The earth excavation started in November 1966, only about 10 months after approval. By end of 1967, all magnets were ordered, and production of the required 11'000 t of magnet steel was complete by October 1968. In 1969, the tunnel, constructed by the cut-and-fill method with prefabricated walls, was finished, and two thirds of the magnets were installed.

3. **Commissioning**

Testing of the transfer lines started in April 1970, the last magnet was installed in May, and the earth shielding was complete in July. In October, a 15 GeV/c beam was injected into ring 1 and circulated immediately. Even rf stacking worked for the first time successfully leading a accumulated beam of 1 A. Ring 2 became ready in January 1971 and the first p-p collisions took place on January 27th.

The beam lifetime was as expected from the measured average vacuum pressure and rest-gas composition. This was of great relief for the team as hadron beam collisions was a new territory and some simulations had predicted a high beam decay rate brought about by beam blow-up through non-linear betatron resonances excited by the mutual interaction of the two colliding beams. This blow-up would not be counteracted by synchrotron radiation damping of particle oscillations as in e+e- colliders since the synchrotron radiation was completely negligible, the synchrotron radiation loss per turn being only $6 \cdot 10^{-14}$ GeV for 28 GeV protons in the ISR with its bending radius of 78.6 m in the main magnets.

Regular physics runs for the experimental teams started in February with 15 GeV/c beams and collisions at 26.5 GeV/c, the highest momentum the PS was scheduled to produce, were recorded for the first time in May 1971, providing the unprecedented centre-of-mass energy equivalent to a 1500 GeV proton beam hitting a fixed target. In this first year of operation, already 1800 h could be scheduled for physics runs during which a surprising 95% availability of the accelerator was recorded (Johnsen, 1973).

4. **Performance and technology**

After a flying start a continuous effort was made throughout the lifetime of the ISR to improve its performance (Johnsen, 1984, 1986, 1992). The stored d.c. proton current per ring was increased from 10 A reached in the first year to typically ≤ 40 A in physics runs with 57 A as record value. The peak luminosity was steadily increasing over the years as can be seen from Fig. 6.

Fig. 6. Evolution of the ISR peak proton-proton luminosity (Johnsen, 1984.

The maximum luminosity achieved was $1.4 \cdot 10^{32}$ cm^{-2} s^{-1} which was far above the design value of $4 \cdot 10^{30}$ cm^{-2} s^{-1} and which remained for a long time the world record until the trophy went to the e+e- collider at Cornell in 1991.

Of particular importance was the vacuum system as the residual gas pressure in the vacuum chamber determines the luminosity averaged over time, which is the real figure of merit of a collider. The instantaneous ISR luminosity

$$L(t) \sim \int (I_1 \cdot I_2 / h)\, dt \qquad (1)$$

is a function of the product of the beam currents in the two rings and of the effective height of the beams in the interaction point. Since the beams crossed horizontally, the width of the beams did not affect the luminosity. The parameters in (1) are determined by the residual gas pressure and the gas composition because the beam decay is brought about by the nuclear and single Coulomb scattering of the protons on the residual gas atoms and the growth of the effective height with time is due to multiple-Coulomb scattering.

Leading-edge vacuum technology was chosen in the design phase after the successful test in CESAR which had served also for this aspect as ISR test bed. The design value for the average vacuum pressure was 10^{-9} Torr (N_2 equivalent) and 10^{-11} Torr in the interaction points to limit the background for the experiments (Fischer, 1972). As can be seen from Fig. 7 the average pressure significantly decreased over time through a continuous effort maintained with great perseverance but also because of sound initial choices.

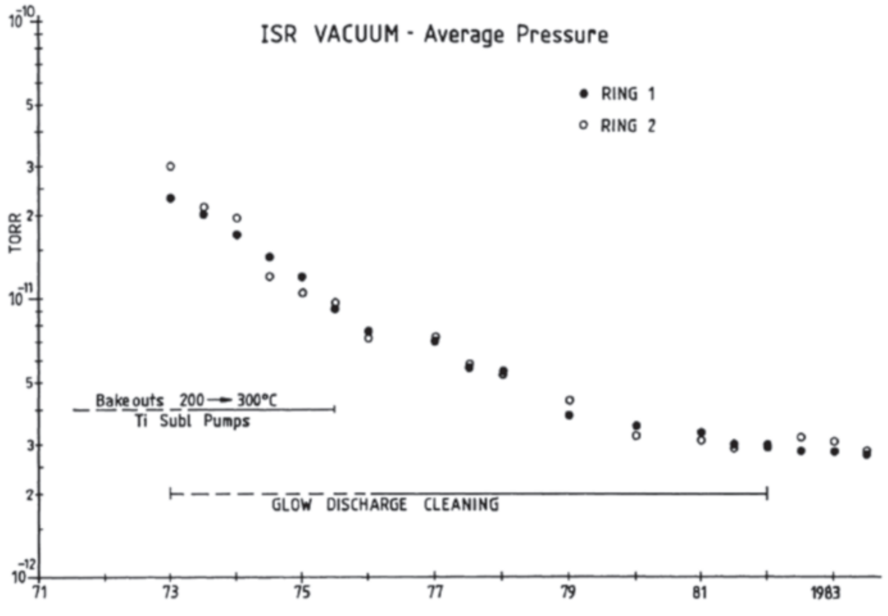

Fig. 7. The average pressure of the ISR vacuum for the years 1971-1983 (Johnsen, 1984).

The key features of the vacuum system, some introduced at the design stage, some later were: stainless steel vacuum chambers of low magnetic permeability; flanges with metal seals; gas-discharge cleaning of the chambers prior to installation; bake-out in situ to 300°C; sputter ion pumps (350 l/s) combined with Ti-sublimation pumps (2000 l/s) at critical places such as the interaction regions; gauges for pressures as low as $2 \cdot 10^{-13}$ Torr; clearing electrodes to remove electrons from the potential well of the proton beam; and damping resistors in cavity-like parts of the vacuum chamber to control induced electro-magnetic fields adverse for beam stability. The result was that the typical beam loss rates eventually were in the range of a few ppm/min, orders of magnitude below the design value of 0.1 %/min.

A particular challenge were the long vacuum chambers in the detectors surrounding the interaction points as scattering and loss of secondary particles had to be minimized by using very thin walls. Self-supporting chambers with wall thickness of only 0.3 mm and 0.2 mm made respectively of Ti and stainless steel were outstanding achievements (Brunet, 1979), as illustrated in Fig. 8.

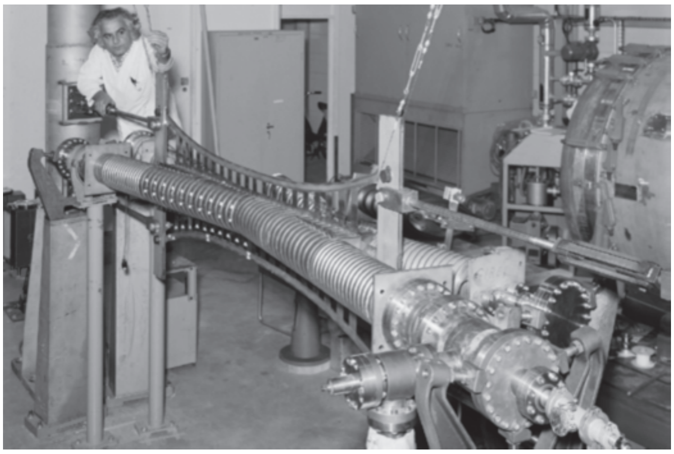

Fig. 8. Thin-walled vacuum chamber for an interaction point with its support girder.

A method had to be developed for maximizing and measuring the luminosity of the beam interaction, resulting in the establishment of the now ubiquitous method of scanning by means of controlled local bumps in the beam orbits, using small dipole correction magnets (van der Meer, 1968). In order to reduce the effective height of the beam in some interaction points and, hence, to boost the luminosity additional quadrupoles for stronger focusing of the beams, “low-beta sections”, were installed. The first one of these (Gourber, 1981) was installed in intersection I7 and later in I1. It was made up from conventional magnets while the second one (Billan, 1983) installed in I8 featured more powerful superconducting quadrupoles developed at CERN – the first time a superconducting magnet system had been used for beam handling in a working accelerator.

Some of the interaction points were equipped with large magnets for the experiments. The Split Field Magnet was the first and largest such spectrometer facility. It became operational towards the end of 1973 and was designed mainly for providing magnetic analysis in the forward region, the place of physics interest at that time. As the magnet system was acting on the ISR beams, its field was designed such as to restore the correct proton orbits. This was done by providing vertical dipole fields of opposite signs upstream and downstream of the crossing point (where it was zero), completed by 2 large and 2 mall compensator magnets (Billan, 1972) as shown in Fig. 9.

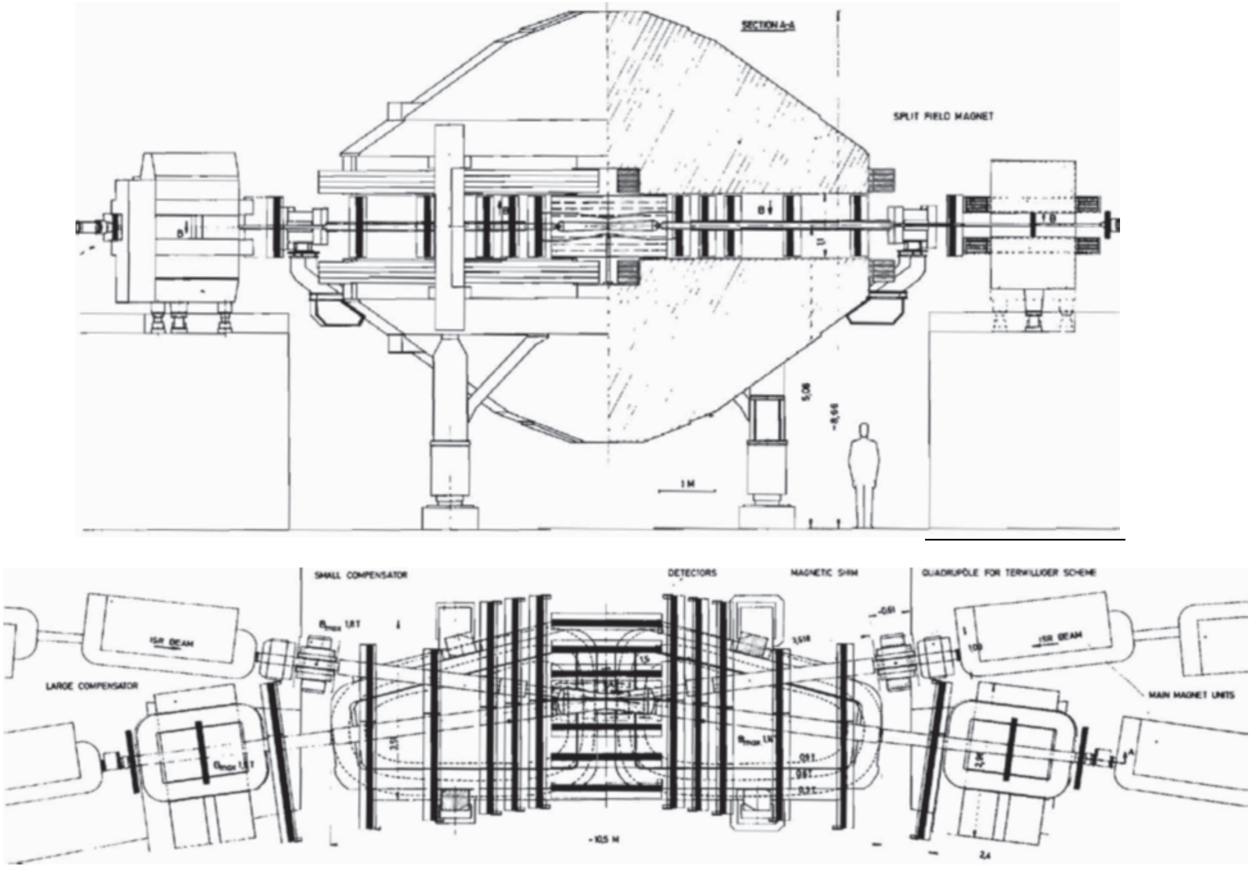

Fig. 9. Layout of the Split Field Magnet (SFM) facility. The multi-wire chambers are also shown.

The useful field volume was 28 m^3, the maximum field 1.14 T, the gap height 1.1 m, length 10.5 m, and mass about 1000 t. The SFM detector saw the first massive application of multi-wire proportional chambers which filled the main and the large compensator magnets, and the facility was used for experiments by more than 20 collaborations.

In late 1976, a thin (1 radiation length), 3 m long, 1.5 T superconducting solenoid – one of the first of its kind – was installed at I1 (Morpurgo, 1977). With a bore of diameter 1.4 m it provided excellent capability for the study of events with large transverse momentum and several upgrades brought higher sensitivity. Good collision rates were ensured by the warm low-beta quadrupole system.

The discovery of the J/ψ in November 1974 was an important wake-up call for the community. The initial priority was to rediscover the J/ψ at the ISR, which was done soon after, but there was also a clear physics justification for a new magnetic facility with an emphasis on high-p_T phenomena, so in early 1976 the ISRC appointed a Working Party, chaired by A. Zichichi, to study the possibility. The outcome was to endorse the need, and to propose two large superconducting devices, a solenoid and a toroid. The proposal was rejected by the ISRC, but as a result of the study and a better understanding of the experimental requirements a more modest magnet based on a novel topology was proposed in early 1977. This was rapidly accepted and the Open Axial Field Magnet (OAFM) was installed and working at I8 by spring 1979 (Guignard, 1979). The 300 t magnet provided an axial field between two conical steel poles clad with copper excitation coils. It is shown in Fig. 10.

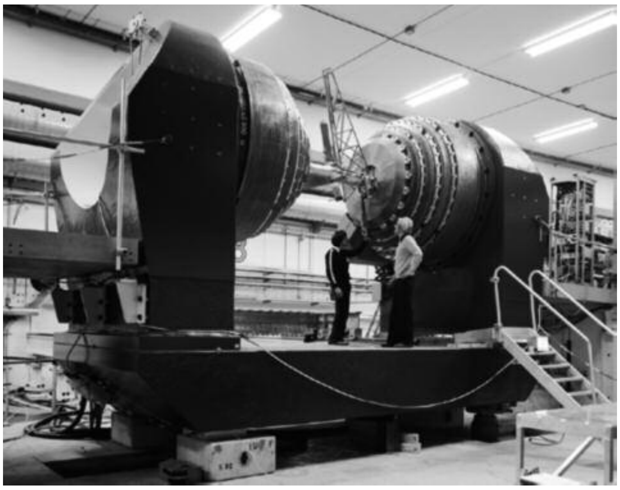

Fig.10. The Open Axial Field Magnet (OAFM) during the measurement campaign.

The result was open access to a barrel-shaped field that was favourably oriented for particles emerging from the interaction at large angles within the volume between the sides of the poles. The field at the centre was 0.5 T and the poles were hollowed out to provide space for the closest superconducting low-beta insertion magnets. Integrating innovative detectors and benefitting from increased luminosity provided by the low-beta insertion, the so-called Axial Field Spectrometer was well equipped to do excellent physics (Willis 1983, Fabjan 2011).

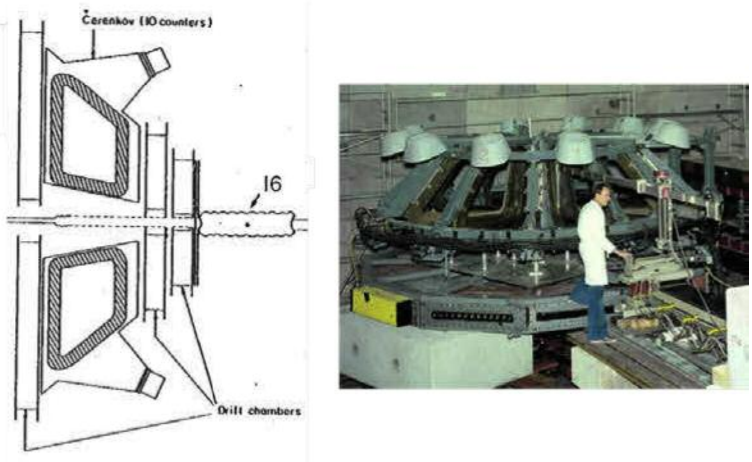

Fig. 11. The Lampshade Magnet (LSM). Left: layout at I6; right: being measured.

Other spectrometers at the ISR included the magnetized iron toroid installed at I2, used for experiments based on muon tracking, the toroidal “lampshade” magnet, shown in Fig. 11 (Giboni, 1979), and various septum magnets which shielded the beam from the analyzing field, such as the double septum magnet (Schlein, 1995) shown in Fig. 12.

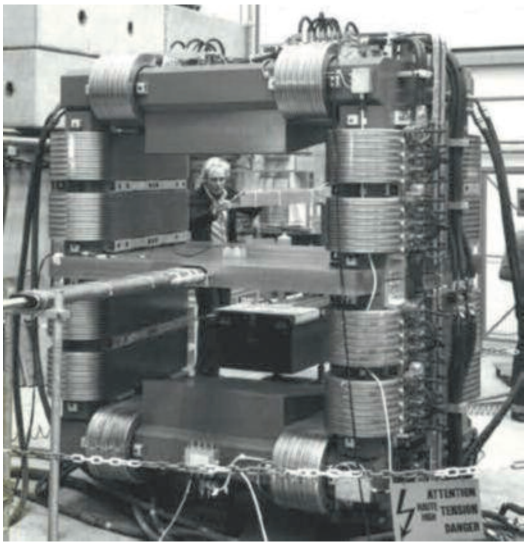

Fig. 12. The double septum magnet during the measurement campaign.

The experience with these spectrometers was instrumental in their choice for subsequent collider experiments (Taylor, 1981), and it is interesting to note that larger versions of the magnet topologies proposed by the ISR Working Party were adopted at the LHC.

A further example of a highlight in the advance of accelerator-related physics and technology was the discovery of the Schottky noise providing a non-invasive tool to monitor the position of stored beam as a function of momentum and of betatron tune in real time (Borer, 1974). The discovery was greatly facilitated by the extraordinary lifetime of the beam and it opened the door for the experimental proof of stochastic cooling of particle beams shown in Fig. 13 (Bramham, 1975). This beam cooling had been invented and suggested for the ISR to counteract beam blow-up by S.van der Meer, 1972.

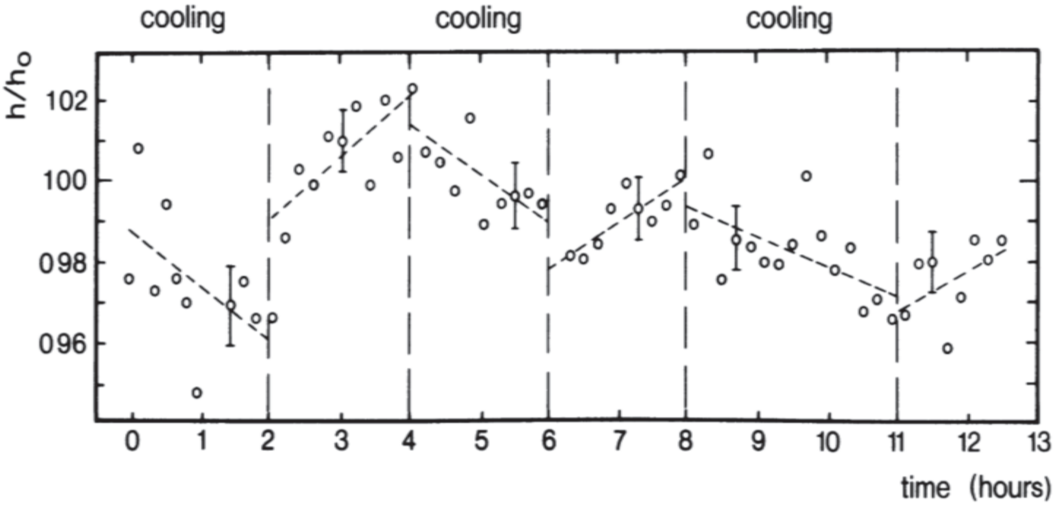

Fig. 13. Evolution of relative effective beam height as a function of time with and without stochastic cooling (Bramham, 1975)

5. **Conclusion**

The ISR, the first hadron collider, operating from 1971 to 1983 was a fine and unique instrument not only providing p-p collisions but also d-d, p-d, alpha-alpha, alpha-p and p-pbar collisions. It significantly advanced accelerator technology and physics. Its solid design was the broad basis for its own gradual improvement so that the design performance could be surpassed by a substantial factor, but it was also the cradle of many enabling technologies useful for the hadron colliders to come as the p-pbar collider in the SPS at CERN, the Tevatron at FNAL, RHIC at BNL, and LHC at CERN. More detailed summaries of the accelerator design and evolution can be found elsewhere (Russo, 1996), (Bryant, 2011), (Hübner 2011, 2012). The results of the experiments performed at the ISR by a vast physics community had also a considerable impact on our understanding of hadrons (Jacob 1984, Fabjan 2004, Amaldi 2011, Darriulat 2011a, 2011b). Weisskopf (1984) rightly commented at the closure ceremony of the ISR, "First considered a window into the future, but it turned out to be more".

6. **References**

Amaldi, U. (2011). Physics at small angles. *Talk given at Colloquium "40th Anniversary of the First Proton-Proton Collisions in the ISR.* January, to be published as CERN report.

Auslender V.L. (1966). Initial experiments on Electron-Positron Storage Ring VEPP-2. In E.Crémieu-Alcan et al. (Eds), *Proc. Internat. Symposium on Electron and Positron Storage Rings, Saclay,* V-4-1.

Billan, J., Perin R. and Sergo V. (1972). The split field magnet of the CERN intersecting storage rings. In Y.Winterbottom (Ed.), *Proc. 4th Int. Conf. on Magnet Technology, Upton, N.Y.,* 433.

Billan J.& al. (1983). Operational experience with the superconducting high-luminosity insertion in the CERN Intersecting Storage Rings (ISR). In R.S.Taylor (Ed.), *1983 Particle Accelerator Conf., Santa Fe,* 2036.

J.Borer & al. (1974). Non-Destructive Diagnostics of Coasting Beams with Schottky Noise. *Proc.High-Energy Accel.Conf., Stanford,* 53.

Bramham P.& al.(1975). Stochastic cooling of a stored proton beam. *NIM 125,* 201.

Brunet J.C. et al. (1979).The Design and Construction of Transparent Vacuum Chambers for Interaction Areas of Colliding Beam Machines. In Hendrickson (Ed.), *Proc. Particle Accelerator Conference, San Francisco,* 4063.

Bryant P. J. (2011). The Impact of the ISR on Accelerator Physics and Technology*, Talk given at Colloquium "40th Anniversary of the First Proton-Proton Collisions in the ISR".* January, to be published as CERN report.

The CERN Study Group on New Accelerators (1964). Report on the Design Study of Intersecting Storage Rings (ISR) for the CERN Proton Synchrotron, *Report to Council CERN/542 and Internal Report CERN AR/Int.SG/64-9.*

The CERN Study Group on New Accelerators (1964). Report on the Design Study of a 300 GeV Proton Synchrotron, *Report to Council CERN/563 and Internal Report AR/Int.SG/64-15.*

Darriulat, P (2011). Physics at High Transverse Momentum, *Talk given at Colloquium "40th Anniversary of the First Proton-Proton Collisions in the ISR".* January, to be published as CERN report.

Darriulat. P (2011). The Results Obtained with the First pp Collider ISR. *These proceedings.*

Fabjan C.W. and McCubbin N. (2004). Physics at the CERN Intersecting Storage Rings (ISR) 1978-1983. *Physics Reports 403-404,*165.

Fabjan, C. (2011). Evolution and revolution: detectors at the ISR. *CERN Courier,* January.

Fischer E. (1972). Experience Gained in the Operation of the ISR Vacuum System. *Internal Report CERN-ISR-VA/72-39 (1972).*

Giboni, K. & al.(1979). Diffractive production of the charmed baryon Λ^+ at the CERN ISR. *Phys. Let., 85B(4),* 437.

Gourber J.P.,.Keil E. & Pichler S.(1981) The First High-Luminosity Insertion in the ISR, In R.C.Placious (Ed.), *Proc.1981 Particle Accelerator Conference, Washington D.C.,* 1419.

Guignard, G. and Taylor T.M. (1979). Run 1015, 22.3.79, 26 GeV/c, rings 1 and 2, Run 1017, 26.3.79, 26 GeV/c, rings 1 and 2, First running-in tests of the OAFM system. *ISR Performance Report, ISR-BOM-GG-TMT-ml.*

Hansen S., Jones E., Koziol H. & Pentz M.J. (1965). Some Results of Stacking Experiments with the CERN Electron Storage and Accumulation Ring (CESAR), *CERN Report 65-8 (1965).*

Hereward H.G., Johnsen K., Schoch A. & Zilverschoon C.J. (1960). Present Ideas on 25-GeV Proton Storage Rings. *Internal Report CERN PS/Int.AR/60-35.*

Hübner, K. (2011). Design and Cosntruction of the ISR. *Talk given at Colloquium "40th Anniversary of the First Proton-Proton Collisions in the ISR".* January, to be published as CERN report.

Hübner, K. (2012). The CERN Intersecting Storage Rings (ISR). *accepted for publication in Eur.Phys.J.H.*

Jacob M. (1984). Review of Accelerator and Particle Physics at the CERN ISR. *Report CERN 84-13, Part II.*

Johnsen K. et al. (1963). Some Problems connected with the Use of Intersecting Proton Storage Rings. In A.A.Kolomenskij (Ed.), *Proc.4th Internat. Conf. on High-Energy Accel., Dubna,* 312.

Johnsen K. (1973).The CERN Intersecting Storage Rings, *NIM 108,* 205.

Johnsen K.(1973). CERN Intersecting Storage Rings (ISR), *Proc.Nat.Acad.Sci.USA, 70,* 619.

Johnsen K.(1984). Review of Accelerator and Particle Physics at the CERN ISR. *Report CERN 84-13, part I.*

Johnsen K.(1986). The ISR and Accelerator Physics. *Particle Accelerators 18,* 205.

Johnsen K. (1992).The CERN Intersecting Storage Rings: the Leap into the Hadron Collider Era. In L.Hoddeson et al. (Eds.), *Third International Symposium on the History of Particle Physics at SLAC Stanford* (p. 285). Cambridge University Press.

Kerst D.W (1956). Properties of an Intersecting-Beam Accelerating System. In E.Regenstreif (Ed.), *Proc.Symposium on High-Energy Accelerators and Pion Physics, Geneva, CERN, Report CERN 56-26,* 36.

Morpurgo, M. (1977). Design and construction of a superconducting aluminium stabilized solenoid. *Cryogenics, 17(2),* 89.

O'Neill G.K. (1956). Storage-Ring Synchrotron. In E.Regenstreif (Ed.), *Proc.Symposium on High-Energy Accelerators and Pion Physics, Geneva, CERN, Report CERN 56-26,* 64.

O'Neill G.K. &.Woods E.J. (1959). Intersecting-Beam Systems with Storage Rings. *Phys.Rev., 115*, 659.

The Orsay Storage Ring Group (1966). Status Report on ACO. In E.Crémieu-Alcan et al. (Eds), *Proc. Internat.Symposium on Electron and Positron Storage Rings, Saclay* II-3-1 and II-4-1.

Pestre D. (1990). The second generation of accelerators for CERN 1956 – 1965, the decision making process. In A.Hermann et al (Eds.), *History of CERN* (Volume II 679). North Holland.

Picasso E. & Plass G. (1989). The machine design LEP. *Europhys.News, 20,* 80.

Russo A. (1996). The Intersecting Storage Rings: The Construction and Operation of CERN's Second Large Machine and a Survey of its Experimental Programme, In J.Knige (Ed.), *History of CERN* (Vol.III,97). Elsevier.

Schlein, P. (1995). Evolution of forward multi-particle spectrometers at storage rings. *NIM-A, 365,* 152.

Symon K.R. & Sessler A.M. (1956). Methods of radio frequency acceleration in fixed-field accelerators with applications to high-current and intersecting beam accelerators. In E.Regenstreif (Ed.), *Proc.Symposium on High-Energy Accelerators and Pion Physics, Geneva, CERN, Report CERN 56-26,* 44.

Taylor, T. (1981). The choice of spectrometer magnets for LEP. *Physica Scripta, 23,* 459.

Terwilliger K.M., Jones L.W. & Pruett C.H. (1957). Beam stacking experiments in an electron model FFAG accelerator. *Review of Scientific Instruments, 28*, 987.

Touschek B. (1961). The Frascati storage rings. In J.S.Bell et al. (Eds.), Proc. *Internat. Conf. on Theoretical Aspects of Very High-Energy Phenomena, Geneva, CERN, Report CERN 61-22.*

van der Meer S. (1968). Calibration of the effective beam height in the ISR. *Internal Report CERN ISR-PO/68-31.*

van der Meer S. (1972). Stochastic damping of betatron oscillations in the ISR. *Internal Report CERN-ISR-PO-72-31.*

Wideröe R. (1953). Anordnung zu Herbeiführung von Kernreaktionen. *Bundesrepublik Deutschland, Deutsches Patentamt Patenschrift Nr.876279.*

Willis, W. (1983). Experience of the axial field spectrometer at the CERN ISR. In S.C.Stewart & P.Némethy (Eds.), *Proc. DPF Workshop on Collider Detectors, LBNL, report LBL-15973,* 5.

PAS Symposium Subnuclear Physics, 30 Oct.-2 Nov.2011, "Birth of the 1st Hadron Collider" KH&TMT