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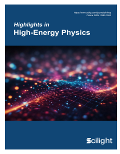

Perspective

A Personal History of CERN Particle Colliders (1972–2022)

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Abstract: In the following, I recall my personal memories of the conception, design, construction and operation of particle accelerators and particle colliders over the 50 years from 1972 to 2022. This is not a technical report, but more a review to give an insight to the historical beginnings and endings of some of the world's most technically complex and expensive scientific instruments.

Keywords: ISR; SP$\bar{P}$S; LEP; LHC

1. Some Fundamentals

1.1. Colliders vs Stationary Target

Advances in accelerator technology have driven higher beam energies, often spurring new tech and cross-disciplinary innovations. A key development was the use of colliders**,** where two beams collide head-on, enabling much higher collision energies than single beams impinging on stationary targets.

However, collider technology is more complex. The two counter-circulating beams bring to collision packets of particles. This implies that high-intensity, tightly focused beams are needed to produce sizable interaction rates. To preserve the lifetime of circulating beams, ultra-high vacuum ($<10^{-9}$ Pa) is also essential to reduce beam-gas interactions.

1.2. Two Ring vs. Single Ring Colliders

If the collider has two separate rings, then the beams can be electromagnetically steered into collisions at a predefined number of locations thereby avoiding the problem, in a single-ring collider with beam lifetime due to the large number of collisions points (normally twice the value of the number of bunches). The disadvantages of a two-ring collider are technical complexity and cost which may be increased by up to a factor of two. However, with two separate rings the collision rate can be significantly increased.

1.3. The Non-Linear Beam-Beam Effect

In storage ring colliders, beams collide to produce high-energy interactions. Each charged beam generates electromagnetic fields that affect the opposing beam. Close to the beam center, this effect is approximately linear, acting like a focusing (or defocusing) magnet—this is known as the beam-beam tune shift. However, at greater distances, the effect becomes highly non-linear, degrading collider performance. There is a critical upper limit to the tune shift, beyond which performance declines, making the beam-beam limit a fundamental constraint in collider design.

1.4. High Energy Superconducting Hadron Colliders

A hadron collider's maximum energy depends on the ring's size and the strength of its magnetic bending fields. While ring size is limited by cost and geography, magnetic field strength is constrained by technology. Superconducting magnets, which enable higher fields and lower power use, have been key to increasing beam energy—though they come with added complexity and cost.

2. ISR the First pp and $p\bar{p}$ Collider

The CERN Intersecting Storage Rings (ISR) was the first proton–proton (and $p\bar{p}$) collider ever constructed and operated. The ISR collided first beams in 1971 and operation for physics was from 1971 to 1983. Table 1 gives the basic parameters of the ISR.

Table 1. Basic parameters of the ISR.

Colliding particles	pp, dd, pd, αα, αp, ppbar
Particle momentum	3.5 to 31.4 GeV/c
Circumference (m)	942.5m (300 π)
Number of main magnets	132/ring
Magnetic dipole field	1.33T (max)
Length of main magnets	4.88/2.44 m
Betatron oscillations/turn	8.9 (h), 8.88 (v)
β* (h/v)	21 m /12 m
β* (h/v)	2.5 m / 0.28 m in sc low-beta section
RF system per ring	7 cavities, 9.5 MHz, 16 kV RF peak voltage

The ISR consisted of two independent storage rings intersecting at eight points with a crossing angle of 14.8 degrees (see Figure 1, the control room, and Figure 2, interaction points 1 and 8). The circumference of the rings was 943 metres (1.5 times that of the CERN Proton Synchrotron (PS) which supplied particles to the ISR). The larger circumference was needed to allow space for the long straight sections in the interaction regions and the injection sections. The first proton–proton collisions took place in 1971 with beam momenta up to 26.5 GeV/c, which is the maximum momentum available from the PS injector.

Figure 1. ISR Control Room.

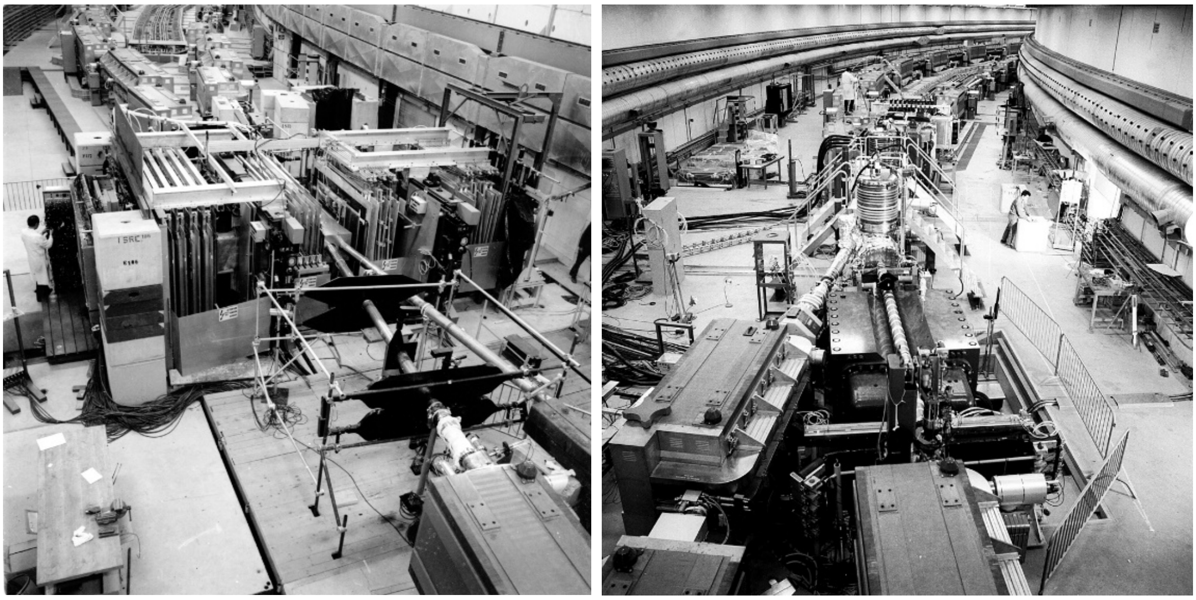


Figure 2. Physics Interaction points 1 (**left**) and 8 (**right**).

2.1. Lack of Diagnostics in ISR Due to Coasting Beam

High-precision beam diagnostics are crucial for particle colliders, enabling measurement of particle count, beam size, and position. Beams are grouped into highly charged packets called bunches, which interact with electromagnetic fields. Diagnostics detect the electromagnetic signals induced by these charged bunches as they pass, allowing evaluation of beam properties such as proton count, bunch position, and length.

The ISR was a "storage" ring. This meant it took a batch of (20) bunches from the injector PS, accelerated them to the storage aperture in the ISR and then "let them go". Each batch of bunches were "let go" by switching off the RF acceleration system to allow the RF system to capture and accelerate the next batch. This meant that the stored beam in the ISR was a "coasting" rather than a bunched beam. Hence none of the normal e-m beam diagnostics devices could be used to measure the parameters of the coasting beam. This was a huge disadvantage for efficient operation for physics.

At the start of ISR operation, operators could "see" the coasting beam using only two devices: a real-time transverse profile monitor and a DC current monitor [1]. The profile monitor employed a thin sodium gas curtain at one azimuthal position, where circulating protons ionized the gas, enabling a camera to capture the beam's cross-section. Meanwhile, the precise DC current monitor measured the total beam current, including both bunched and unbunched components.

2.2. Stacking

High currents in the ISR were built through momentum "stacking," accumulating about 200 PS batches across its large momentum aperture. Each cycle captured 20 PS bunches at −2% injection momentum, accelerated them to +2% by changing RF frequency, then debunched the beam by switching off the RF. The maximum single beam current reached an impressive 57 amperes.

2.3. Phase Displacement Acceleration

Phase displacement occurs when an RF "bucket" (phase stability area) traverses a debunched beam [2]. The particles in the debunched beam travel around the unstable trajectories associated with the bucket. Traversing a debunched beam from high momentum to low momentum produces an increase in the average momentum of the debunched beam by an amount equal to the phase space area of the phase displacing buckets. A useful analogy is the release of droplets of mercury (RF buckets) into a cylindrical container containing some water (coasting beam). The mercury droplets go from high energy to low energy and the water energy is increased by displacement.

Since the ISR circumference was larger than the PS, the maximum possible momentum was also higher (31.4 compared to 26.6 GeV/c). In the quest for higher collision energies, it was decided to attempt to increase the momentum of the accumulated beam in the ISR from 26.6 to 31.4 GeV/c. However, the small ISR RF (16kV maximum) system could only capture a tiny amount of the coasting which had a 3% momentum spread. Hence phase-displacement was the only option. The phase-displacement technique required several hundred traversals of the coasting beam by the RF system.

So, in our relative ignorance of the problems (space charge, changing tunes, chromaticity, orbits, RF noise effects, absence of diagnostics...) we decided to attempt to phase-displace high intensity stacks of protons. Initially the progress was very slow and frustrating, but after some better understanding and a few breakthroughs, 31.4 GeV/c became the preferred high luminosity operational momentum of the ISR during the latter years of operation. In the last years of ISR operation, beams of more than 30 amperes were accelerated by phase displacement to 31.4 GeV/c.

2.4. Schottky Scans

The Schottky noise spectra [3] result from the discrete nature of the particles in the beam. A sensitive high frequency longitudinal pick-up with long-term signal processing, could produce a signal proportional to the longitudinal phase space density of the debunched beam. Figure 3 shows the first Schottky scans taken operationally in the ISR. The three scans shown were taken at beam currents of 10, 15 and 19.2 amperes. The horizontal axis is the longitudinal frequency and allows evaluation of the beam $\Delta p/p$.

Soon after discovering longitudinal Schottky scans, transverse pickups were used to measure the transverse Schottky scans which gave information about the "tune" values in the stacked beams.

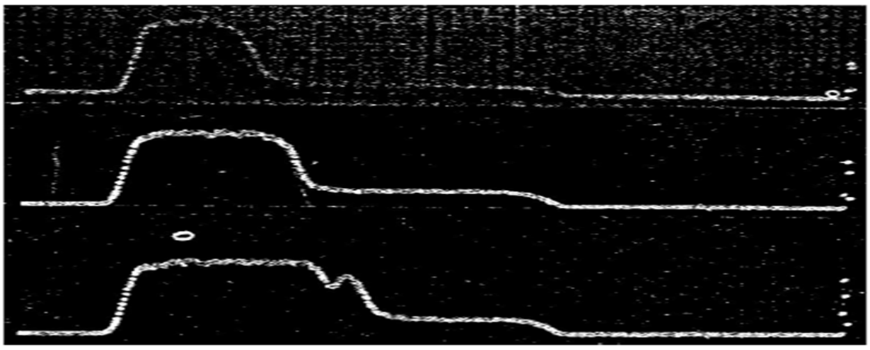


Figure 3. Longitudinal Schottky scans.

Schottky scans revolutionized ISR operation by providing the only quantitative beam diagnostics during long stable-beam fills, sometimes lasting up to five days. While the sodium curtain offered visual but non-quantitative cross-section views, Schottky scans enabled evaluation of longitudinal density versus $\Delta p/p$ using current meter data. Identifiable "markers" in the beam, initially at stack edges and later placed via phase displacement, allowed precise tune measurements at discrete momentum offsets, enabling continuous tracking of the tune "working line" throughout physics runs.

2.5. Stochastic Cooling

The first ISR Schottky scans sparked interest in damping particle oscillations via stochastic cooling. The technique was tested by Wofgang Schnell [4] that followed the initial idea proposed by Simon Van Der Meer [5]. Schnell's team built a test system demonstrating this concept. At the ISR the most sensitive measurement of transverse beam size was obtained through the normalized luminosity, inversely related to the beam "height".

Figure 4 shows the results of the first ever conclusive observation of stochastic cooling (in an ISR machine physics experiment [4]).

The inverse normalized luminosity (effective beam height) is shown over a 13-h period with stochastic cooling turned on and off every few hours. The effect is small but very significant: stochastic cooling worked! Very soon afterwards a similar system was designed for the Initial Cooling Experiment (ICE) with spectacular results as shown in Figure 5.

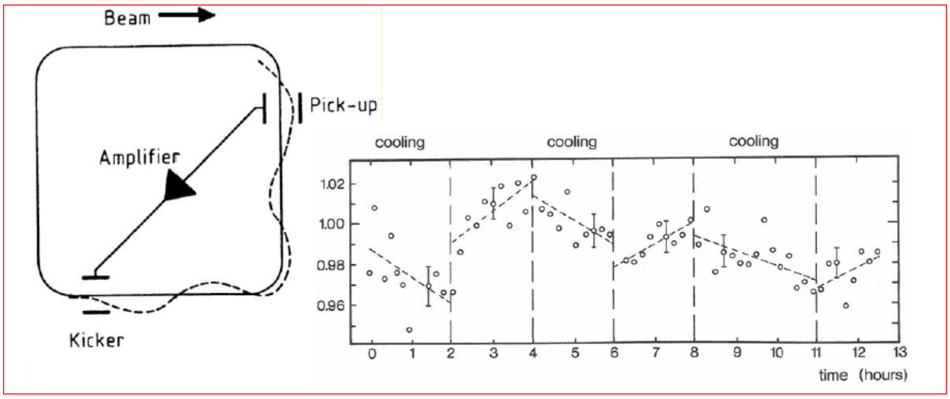


Figure 4. First observation of stochastic cooling.

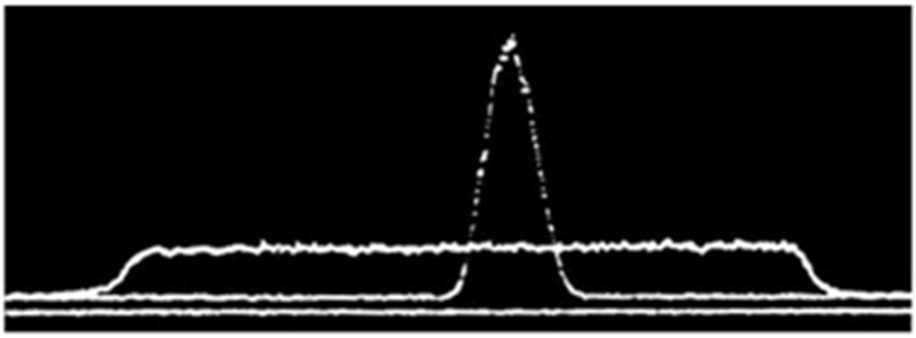


Figure 5. Fast momentum cooling in ICE.

2.6. The Legacy of the ISR

Although not known for discoveries, the ISR was a pioneering project as the first proton-(anti)proton collider, answering key questions and inspiring future collider designs. It also served as an excellent training ground for accelerator physicists. Below is a list of its most important lessons and legacy.

- Type of collider detectors

Before the ISR particle detectors were highly specialized, some looking at small angle events, others focused on high transverse momentum events etc. After the ISR all detectors were general-purpose "4π" systems aiming at collecting the maximum number of simultaneous events produced in the collisions. An immediate consequence of this was the UA1 and UA2 detectors for the SP$\overline{\text{P}}$S.

- Experimental proof of stochastic cooling.

Although the two previously mentioned legacies had, in my opinion, the greatest impact, the complete list of contributions to accelerator physics, operations, and engineering is long and impressive. Many of these have been successfully implemented by more modern accelerators. In an arbitrary order of importance or priority the legacies from the ISR are:

- A fantastic training ground for accelerator physicists and engineers.
- Safe operation of beams with high destructive stored energy.
- Background control by collimation.
- Absolute luminosity calibration using "Van der Meer scans".
- Longitudinal phase space stacking of protons.
- Production and maintenance of ultra-high vacuum in the presence of high intensity. beams (clearing electrodes, electron cloud, etc.).
- Space charge tune compensation.
- Impact of non-linear resonances driven by machine imperfections.
- Pulsed beam-beam effects (Overlap knock-out resonances).
- Instabilities and impedance.
- Phase displacement acceleration and deceleration.
- Proton-antiproton collisions: demonstrated for the first time.
- High precision, low noise, power converters.

- Low beta insertions.
- Computer control of acceleration in colliders.
- Optics measurements and corrections.
- Stacking and phase displacement of different particle species, protons, anti-protons, alfas, deuterons etc.

3. The CERN SPS Proton—Antiproton Collider

3.1. The Importance of Stochastic Cooling

Luminosity in a collider requires small beam sizes, but the antiproton beam for the SP$\overline{\text{P}}$S was naturally much larger than needed. Stochastic cooling, proven in the ISR for one plane, had to be extended to all three dimensions for success. The 1977-approved Initial Cooling Experiment (ICE) demonstrated 3D cooling by 1978, leading to the green light for the SPS proton–antiproton project. Following ICE's success, the Antiproton Accumulator (AA) was built rapidly (1979–1980) with strong stochastic cooling to prepare antiprotons for collisions.

3.2. Conversion of the SPS to the SP$\overline{P}$S

The SPS had been built as a proton synchrotron; not as a collider. The following upgrades were required if the SP$\overline{\text{P}}$S project was to be successfully operated as a $p\bar{p}$ collider.

- A new beam line was needed, to transfer the antiprotons from the PS to the SPS, and a new injection system for counterclockwise injection was added in the SPS.
- The SPS had been built for an injection energy of 14 GeV/c. The proton transfer line, TT10, and the injection system had to be upgraded to 26 GeV/c.
- To provide sufficient beam lifetime for stored beams, the vacuum system had to be improved by two orders of magnitude, from the design vacuum of the SPS (200 nTorr) to better than 2 nTorr,
- To increase the luminosity, tight focussing low-beta insertions were needed in straight sections 4 and 5 for the UA2 and UA1 experiments
- Beam diagnostics had to be improved to measure the beam parameters with the very low beam intensities, and new devices added, such as directional couplers for independent observation of protons and antiprotons.
- To reduce the beam-beam effect, high voltage electrostatic deflectors were required to separate the beams, in 9 of the 12 crossing points,
- The RF system had to be upgraded with reduced "RF noise".
- New transfer lines to and from the AA and from the PS to the SPS (TT70) were required.

The first proton–antiproton collisions were recorded in summer 1981, with the first physics run producing 0.2 nb^{-1} of integrated luminosity by the end of the year. Although initially low, the luminosity was sufficient to discover the W and Z bosons in 1982–1983, earning Carlo Rubbia and Simon van der Meer the 1984 Nobel Prize. Key to this success were the large 4π detectors absent at the ISR. The performance of the accelerator was improved with the Anti-proton Collector (AC), boosting antiproton density and shortening cooling times. Beam energy rose from 273 GeV (1982–1985) to 315 GeV (1987–1991), when the program ended. The SP$\overline{\text{P}}$S was a highly ambitious and successful CERN project.

3.3. The Legacy of the SP$\overline{P}$S

Before its commissioning, doubts existed about operating a hadron collider with bunched beams due to beam–beam effects and RF noise. Although low-intensity bunched beams were tested in the ISR, the SP$\overline{\text{P}}$S proved such concerns unfounded for future colliders. Proton and antiproton orbits were separated using a "Pretzel" shape with electrostatic separators—a method later used at LEP and LEP2. Additionally, civil engineering experience from building large experimental caverns at SP$\overline{\text{P}}$S aided construction for LEP and LHC.

4. The Large Electron Positron Collider (LEP)

Over the past decades electron positron colliders have been ideal tools for studying mesons (J/ψ, Υ) and leptons (τ). Although the actual discoveries have often occurred at proton machines, the precise and easily tunable beam energy, as well as the well defined initial state, are big assets of electron positron colliders.

Following the prediction of the existence of two massive vector bosons, the neutral Z^0 and the charged $W^{\pm}$, LEP was designed with the aim of discovering and studying those bosons, which were, however, first observed at the SPS proton-antiproton collider in 1982. With LEP it was possible to measure the properties of these bosons with excellent precision. A very important early result was that there are three types of light neutrinos and thus three fundamental fermion families. The precise determination of the standard model parameters from the LEP data allowed a prediction of the top mass and limits on the expected mass range for the standard Higgs boson.

Design studies of the LEP machine started at CERN in 1976 and the first practical design was published in 1978. The proposed machine had a cost-optimized energy of 70 GeV per beam and measured 22 km in circumference. After extensive discussions during the autumn of 1978 it was decided to embark on the design of a somewhat larger machine, 30 km in circumference, with a cost-optimized energy of about 90 GeV per beam. The energy of both these machines could be extended by using super-conducting RF cavities, were these to become available, to 100 GeV and above.

Studies of the 30 km machine were completed during 1979 and a design report was issued in August of that year. These studies covered not only machine design but also the design and development of the components of LEP. A much cheaper design for the main magnet system was developed, as well as a more economical system for the RF accelerating system using a storage cavity scheme. At the same time, it was decided to increase the effort on the development of super-conducting RF cavities for LEP by setting up a small team at CERN and establishing a collaboration with other European laboratories. The basic feature of the final design was a machine with a large circumference which could be installed in stages to match the particle physics requirements and new technological developments.

4.1. Beam-Beam Effect

Before LEP, electron-positron colliders struggled with beam-beam effects. Drawing on ISR experience, I developed a Monte Carlo simulation to track a large number of particles over many revolutions to study this impact on LEP. Thanks to CERN's upgraded computing power, I overcame past limitations. After extensive development and debugging, the simulation successfully matched experimental data from smaller colliders.

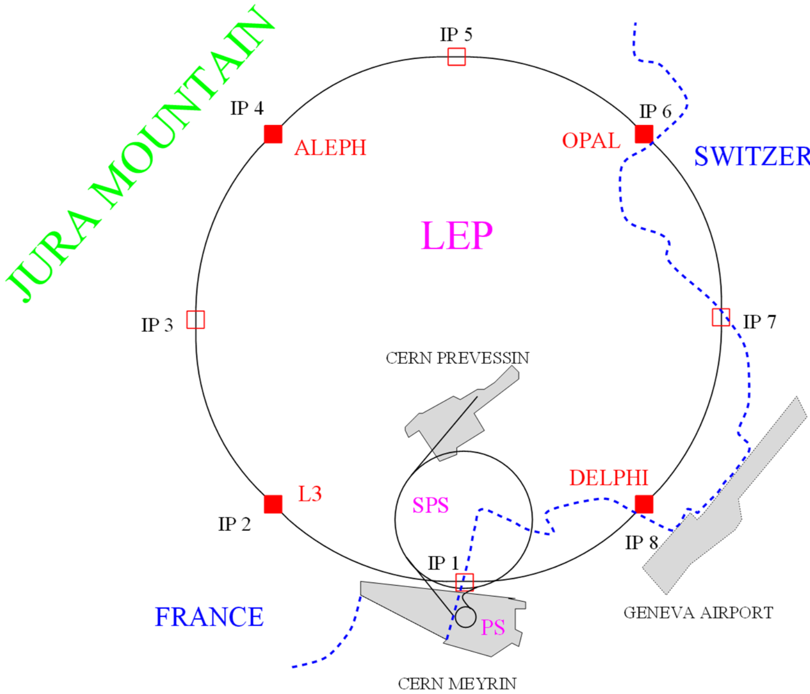
Insertion: a Proton-Proton Collider in the LEP Tunnel.

> *(LEP Note 440 April 1983)*
>
> *By mid-1981, the first $p\bar{p}$ collisions were observed in the $SP\bar{P}S$ at CERN. It was now very clear that ISABELLE (BNL) was obsolete, and that the USA was pursuing a much higher energy collider (SSC).*
>
> *Following an invitation to represent CERN at an SSC meeting in the US, I began to think about the 27 km tunnel we would have in Geneva and what sort of proton collider we could imagine installing there.*
>
> *After some calculations and discussions, Wolfgang Schnell and I co-authored "LEP" note 440 entitled "Preliminary performance estimates for a LEP proton collider", which was published in April 1983 [7]. This was a short, 16-page report that provided performance estimates and limitations for the design of a proton collider in the LEP tunnel. As far as I am aware, this was the first document to address performance issues of the LHC. It raised many of the points that were subsequently part of the LHC design: 8 TeV per beam, beam–beam limitation (arguing the case for a twin-ring accelerator), twin-bore magnets and the need for magnet development, problems with pile-up (multiple collisions per bunch-crossing) and impedance limitations.*
>
> *We continued, and wrote additional "LEP" notes (450, 460, and 470) on the parameters for other sub-systems for the LHC and then abandoned this subject to return to the design of LEP.*
>
> *Nevertheless, these reports were never cited in any of the reports from the CERN LHC study group.*
>
> *However, Burt Richter (Nobel Laureate 1976) referred to the LEP notes in 2014 [8]*
>
> *"The Myers/Schnell paper started informal discussions at CERN that became more serious when the SSC was initially approved by the U.S. Congress, and turned into a major design effort when the SSC was cancelled by the U.S. Congress in 1993…."*

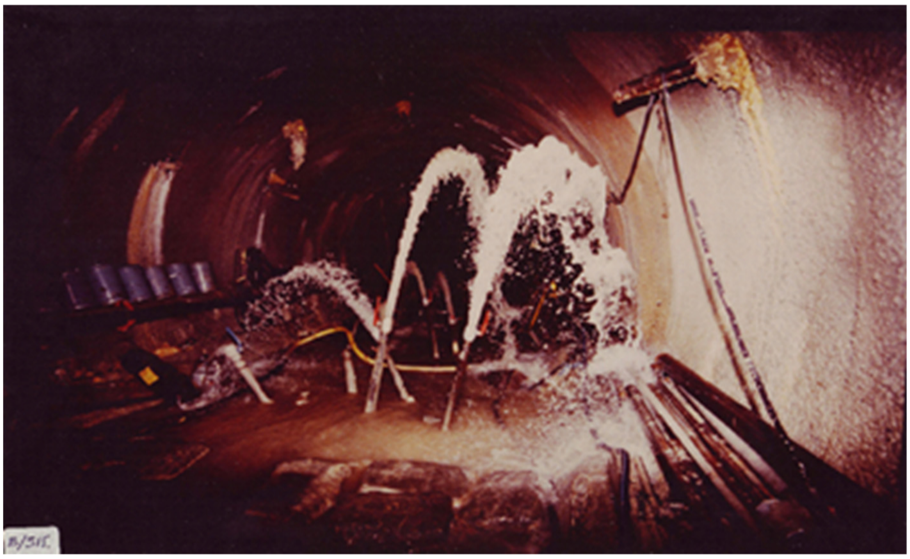
4.2. 1985 Start of LEP Construction

The construction of the LEP tunnel started in 1985 following a standard public enquiry in France (Figure 6a shows the layout of LEP).

LEP's tunnel, then the longest built, faced disaster just 2 km in when unsuitable rock required blasting, causing a high-pressure underground river that delayed work for six months (Figure 6b). After many failed attempts, a solution was found by June 1987, allowing tunnel completion and accelerator installation. This incident complicated the original smooth construction schedule and served as a tough lesson for future collider tunnels.



(**a**)



(**b**)

Figure 6. (**a**) Layout of the LEP ring, the 4 experiments and the LEP injectors. (**b**) Photo of water input to LEP tunnel.

4.3. 1988 LEP Octant Test

The first major task was the controversial octant test—passing a positron beam through the first eighth of the accelerator. Despite skepticism from CERN leadership, octant 8 was completed by July 1988, shortly after finishing difficult Jura excavation. On 12 July, four positron bunches traveled 2.5 km successfully. Early beam measurements revealed harmful betatron coupling caused by a nickel magnetic layer inside the vacuum chamber—a crucial defect discovered a year before the first full beam circulation.

4.4. 1989 First Circulating Beam in LEP

At 23:45, on 14 July 1989, the beam made its first turn on the first attempt. Soon afterwards the beam was circulating many turns, and we were ready to fine-tune the multitude of parameters needed to prepare beams for physics. The beams were brought into first collisions on August 14. After ten agonising minutes, we heard the long-awaited comment: "We have the first Z^0!" A period of machine studies followed, allowing big improvements to be made in the collider's performance (on 14 July 1989—the 200th anniversary of the seizure of the Bastille).

4.5. LEP Operations

LEP remains the highest energy electron-positron collider ever built. It was commissioned in 1989 and finished operation in November 2000. During this period, it was operated in different modes, with different optics, at different energies, all with excellent performance. In the end, LEP surpassed all design parameters. It provided a large amount of data for the precision study of the standard model, first on the Z resonance, and then above the W pair threshold. Finally, with beam energies above 100 GeV, a tantalizing glimpse of what might have been the Higgs boson was observed.

4.5.1. LEP Performance

Performance at LEP was divided naturally into two regimes: 45.6 GeV per beam running around the Z boson resonance and high energy running above the threshold for W pair production. A summary of the performance through the years is shown in Table 2 below [9–12].

Table 2. Overview of LEP performance from 1989 to 2000. Note E_b is the energy per beam, k_b the number of bunches per beam and ζ is the peak luminosity. $\int \zeta dt$ is the luminosity integrated per experiment over each year and I_{tot} is the total beam cur- rent 2 $k_b I_b$. The luminosity C is given in units of $10^{30}cm^{-2}\ s^{-1}$.

Year	$\int \zeta dt$ (pb^{-1})	E_b (GeV/c2)	k_b	I_{tot} (mA)	ζ
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5–86	4	4.2	35.6
1997	73.4	90–92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98–101	4	6.2	100
2000	233.4	102–104	4	5.2	60

In the regime on or around the Z resonance, performance was constrained by the beam-beam effect which limited the bunch currents that could be collided. The beam-beam effect blew up beam sizes and the beam-beam tune shift saturated at around 0.04. Optimization of the transverse beam sizes was limited by beam-beam driven effects such as “flip-flop”. The main breakthroughs in performance at this energy was an increase in the number of bunches. First with the Pretzel scheme (8 bunches per beam) commissioned in 1992, and then with the bunch train scheme (up to 12 bunches per beam) used in 1995. The optics (phase advance and tunes values) were also changed in attempts to optimize the emittance and the beam-beam behaviour.

With the increase in energy to above the W pair threshold, the beam-beam limit increased, and the challenge was to develop a low emittance optics with sufficient dynamic aperture to go to the 100 GeV regime. Luminosity production was maximized by increasing the bunch current to the limit while operating with four bunches per beam and rigorous optimization of vertical and horizontal beam sizes.

Between 1996 and 2000, LEP’s beam energy increased from 80.5 to 104.4 GeV. At these energies, strong damping and photon emission reduced beam blow-up, allowing higher bunch currents and record beam-beam tune shifts above 0.08 at all four collision points. Superconducting cavities were pushed beyond design to provide over 3.6 GV accelerating voltage per turn. The progression in accelerating voltage can be seen in Figure 7. LEP surpassed all design goals, with peak luminosity nearly four times higher than expected. The design and achieved values for a number of crucial LEP performance parameters are summarized in Table 3.

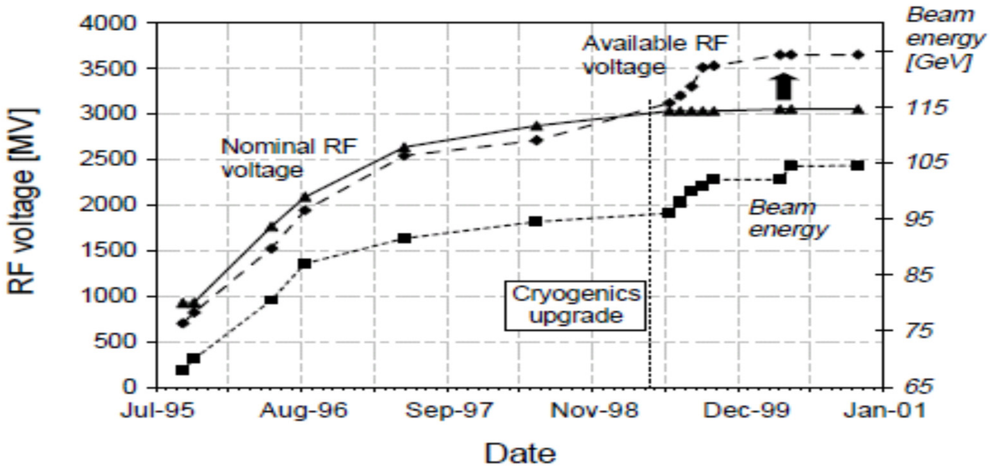


Figure 7. RF voltage per turn over the years.

Table 3. LEP Performance parameters.

Parameter	**Design** (55/95 GeV)	**Achieved** (40/98 Gev)	
Bunch current	0.75 mA	1.00 mA	
Total beam current	6.0 mA	8.4/6.2 mA	
Vertical beam-beam parameter	0.03	0.045/ 0.083	× 10
Emittance ratio	4.0%	0.4 %	× 1.4/3.7
Maximum luminosity	16/27 10^{30} cm^{3}s^{-1}	23/ 100 10^{30} cm^{3}s^{-1}	
IP beta function b_x	1.75 m	1.25 m	
IP beta function b_y	7.0 cm	4.0 cm	

4.5.2. Competition from the USA

There was also fierce competition from the more innovative Stanford Linear Collider (SLC) in California. But LEP got off to a fantastic start and its luminosity increase was much faster than at its relatively untested linear counterpart.

4.5.3. Performance Summary

LEP's performance was fundamentally limited by the beam-beam interaction, which directly affects luminosity. While the highest tune shift before LEP was 0.045, LEP achieved a record 0.083 at high energies, thanks to very fast synchrotron damping time.

4.6. LEP2

In 1995, the LEP2 upgrade began, allowing beam energies above the WW threshold (161 GeV). As LEP2 Project Leader from 1996, I oversaw the construction of 288 superconducting cavities. LEP2 exceeded design goals in luminosity and beam energy, reaching 104.4 GeV per beam with over 3.5 GV RF voltage to offset synchrotron losses. Continuous improvements raised luminosity by increasing bunch intensity and tightening beam focus, though performance was ultimately limited by beam-beam nonlinear forces. The luminosity performance of LEP over the eight-year period 1993–2000 [13] is shown in the Figure 8 below. This performance was impressive given that the operational mode was changed every single year.

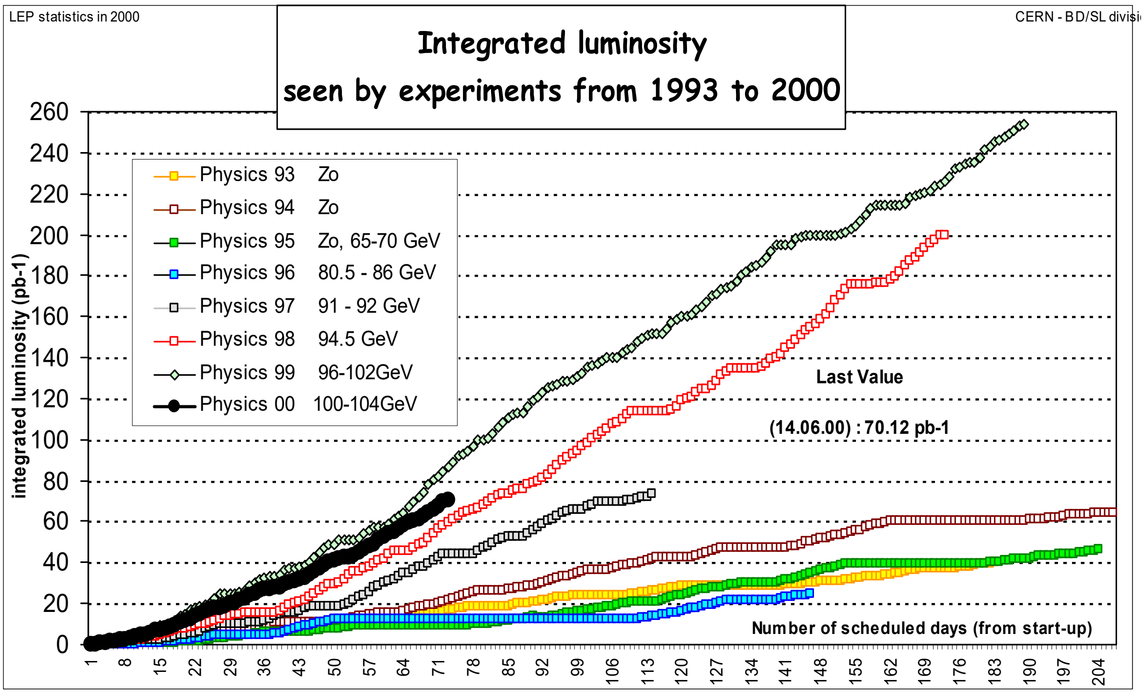


Figure 8. LEP daily integrated luminosity from 1993 to 2000.

Insertion: 2000, The Last Year of LEP2 Operation: On the verge of a great discovery?

LEP's days were never fated to dwindle. Early on, CERN had a plan to install the Large Hadron Collider in the same tunnel, in a bid to scan ever higher energies and be the first to discover the Higgs boson. However, on 14 June 2000, LEP's final year of scheduled running, the ALEPH experiment reported a possible "Higgs" event during operations at a centre-of-mass energy of 206.7 GeV. On 31 July and 21 August ALEPH reported second and third events corresponding to a supposed reconstructed Higgs mass in the range 114–115 GeV/c^2.

LEP was set to stop in mid-September, with two reserve weeks for new Higgs-like events. ALEPH requested a two-month extension but was granted one month, boosting data by 50% and increasing their signal excess to 2.6σ by October. L3 soon reported a missing energy candidate. LEP's collision energy was pushed to the limit, and by November ALEPH's excess grew to 2.9σ. A one-year extension was requested but met gridlock due to concerns over delaying the LHC by up to three years, potential Higgs discovery at Fermilab's Tevatron, and practical issues like resource shifts and costs.

The impending closure of LEP, when many of us were sure that we were about to discover the Higgs, was perceived likethe death of a dear friend by most of the LEP-ers.

The CERN Research board met again on 7 November and again there was deadlock, with no unanimous recommendation, the vote being split 8-8. The next day CERN Director-General Luciano Maiani announced that LEP had closed "for the last time". It was a deeply unpopular decision, but history has shown it to be correct, the Higgs being discovered at the LHC 12 years later, with a mass of not 115 but 125 GeV/c^2.

When LEP was finally laid to rest most of the LEP protagonists went into deep mourning, and we met one last time for an official wake (see Figure 9).

LEP was the highest-energy e^+e^- collider ever built, leaving a vital legacy for current and future colliders. Its unmatched data quality, luminosity, and energy calibration set the standard and serve as the benchmark for all future e^+e^- ring collider designs. The legacy of LEP can be listed below:

- The physics data on the Z and W (luminosity, energy, energy calibration).
- The ultra-precise beam energy determination.

- Operation at record beam-beam tune shifts
- The experience in running a very large collider.
    - Technical requirements to control a large-scale facility.
    - Operational procedures for high efficiency.
    - Orbit optimization in long machines
    - Alignment, ground motion and emittance stability in deep tunnels.
- Designing and efficiently operating a large SC RF system
- Impedance and Transverse Mode Coupling Instability (TMCI) evaluation in large colliders.
- Flexibility in beam optics designs with changed in the betatron phase advance per cell ranging from 600/600 to 1020/900 and 1020/450.
- Strong reminder of the need for quality beam instrumentation and controls for efficient commissioning.
- The use of the personnel experience and expertise gained in LEP/LEP2 to prepare beam commissioning and operation of the LHC collider
- Avoid tunnelling in non-solid rock terrain

LEP's experience running a large collider was invaluable for LHC preparation, highlighting the importance of shutdown planning, maintenance, and remote repairs. Its real-time beam monitoring was essential for LHC's safe, efficient operation, and expertise with superconducting and cryogenic systems greatly benefited LHC performance.

Figure 9. Last beam dump in LEP.

4.7. Moving Focus and Personnel to the LHC

The closure of LEP allowed massive redeployment of skilled and experienced CERN staff from LEP2 to the LHC design.

With the new focus from the closure of LEP, the design of the LHC gathered real momentum.

5. The Large Hadron Collider

5.1. 2008: the LHC Start Up on 10 September and the Terrible Accident of 19 September

September 10 was a fantastic day for CERN and LHC. Protons circulated in the ring very smoothly and everybody was happy. The LHC's start-up attracted massive global media attention, making it difficult to operate amid crowds on the first beam day—a momentous occasion for CERN. However, on 19 September 2008, just nine days after the initial success, during the test of sector 3–4, the last octants of magnets intended to be brought at 9.3 kA a treal disaster did happen. At 8.7 kA a resistive zone developed in the dipole bus-bar magnet interconnects. This caused a thermal runaway in one of the magnet interconnects, followed by electrical arc and sudden helium release. Several magnets and the whole vacuum system were damaged over 400 m.

The accident brought intense media scrutiny after the initial euphoria. As it happened, however, another even more important disaster took place only days before the LHC accident: the bankruptcy of Lehman Brothers (announced 15th September, just three-four days before the LHC accident!).

This was the largest bankruptcy filing in the history of the US with Lehman holding over $600 billion in assets, and of course took most of the journalists' attention. From a media point of view, the LHC accident went by unnoticed, luckily for CERN!

Post-Mortem of the Accident

An inquiry by CERN specialists [14] indicated several causes of the substantial damage to the machine:

- There was an absence of solder on the offending magnet interconnect giving a contact resistance of 220 nΩ (design ~1 nΩ).
- There was poor electrical contact between the superconducting (SC) cable and the copper stabilizing busbar.
- The fault detection of the interconnect was not sensitive enough. If the fault detection had been more sensitive, the accident would have been prevented.
- The pressure relief ports were under-dimensioned for an accident of this magnitude.
- The anchorage of the magnets to the tunnel floor was inadequate.

One of the sources of heat can be the movement of the coils, which can create friction. Another potential source of heat is the proton beam itself, which can deposit a huge amount of energy

The LHC accident occurred because the magnet protection system didn't work. There was a resistance runaway, and the energy wasn't transferred out of the magnets fast enough.

The damage inside the tunnel was impressive but horrific: many large heavy components had been blasted out of their places by the force of the "explosion". We were very concerned about inspecting the magnets due to their weight and their precarious positioning after the accident. For the repair, replacing the magnets was of course much more complicated than installing them for the first time, because they had to be extracted from the full tunnel, in the restricted space with little room for manoeuvre.

5.2. Chamonix 2009: The Repair

Following the initial investigation of the resulting damage, a crash programme was set up to repair and consolidate the LHC. The teams included many CERN partners, collaborators, detector people as well as the accelerator sector.

Two external panels were created, the first on Technical Risk was headed by Don Hartill from Cornell, and the second on Quench Protection headed by Jay Theilacker from Fermi National Accelerator Laboratory. Most of the members of these panels participated in the Chamonix meeting.

5.3. Chamonix January 2010: Restart

After the Christmas break it was time for the Chamonix retreat once again. This time we had, amongst others, two very hot topics; the beam energy scenario for the LHC and a project proposal to replace the injector chain of the LHC by a new superconducting linac and an upgraded Proton Synchrotron.

For the LHC, two energy scenarios were compared. The first was to run at 3.5 TeV/beam to accumulate as much data as possible at this energy, and to delay the consolidation of the whole machine for 7 TeV/beam in the foreseen Long Shutdown 1 (LS1).

The second option was to run until the second half of 2010 then do the minimum repair on splices to allow 5 TeV/beam in 2011 (7 TeV/beam comes much later).

The discussion on the choice of these two options was heated and emotional. Indeed, some people openly disagreed with either of the two options and insisted that LHC had been tested and proven up to 5 TeV per beam and operation in 2010 should be at this energy. They dismissed and ignored the measurements and simulations which clearly showed that operating at 5 TeV was highly risky. Like most of my colleagues, I was totally convinced that this 5 TeV proposal was not only risky but foolhardy. I was also convinced that if we ever had a second accident like that of 2008, CERN's long-term future would be jeopardised. Fortunately, common sense prevailed, and the experiments agreed to follow the first of the official proposals which was the lower risk for data taking.

As a result of measurements done, some years later, during LS1, it was clearly shown that if we had decided to run LHC at 5 TeV in 2010 we would almost certainly have provoked another serious accident (Insertion).

The second major topic was the replacement of the injector system for the LHC. This was the second phase of a larger project under the previous DG (R. Aymar) which had also included replacement of the existing LINAC2 by a new LINAC4. I was not in agreement with these projects as I could not justify them from the LHC performance point of view. I had asked the injector specialists for a clear objective comparison of the performance limits for the LHC, between an upgrade of the injector systems and their replacement. The result was very clear: the proposed replacement was highly more resource intensive, much riskier and would not give any clear performance improvement in the LHC when compared with the much simpler less risky upgrade of the existing and well tested present injectors. The LHC Injector Upgrade (LIU) was born as a result. As always, Chamonix had been a tough but very useful and productive retreat.

First LHC 7 TeV Collisions after the Repair 2010:

(from CERN Bulletin 06-07/2010)

The first collisions at 7 TeV centre-of-mass energy were recorded on 30 March 2010. During 2010, operation was continuously divided between machine studies to increase the luminosity and physics data taking.

We had already suffered from the stored energy in the magnet system which produced the accident in 2008, however many of us were more concerned about the stored energy in the beams. Although the amount of stored energy in the beams was much lower than that in the magnets, the type of energy in the beams was potentially much more risky and destructive.

The LHC beam protection system is the most intricate accelerator protection system ever developed. It has literally thousands of beam abort triggers and relies on very stringent control of the optics of the machine, both locally and globally. The collimation system is part of the machine protection system and must intercept almost the totality of any beam losses if they are to protect the rest of the machine. When the collimators are well set up and the hierarchy of losses is correct, the vast majority of all losses are localized at the collimator.

The rate of progress was impressive, nevertheless before each step was taken to increase the intensity and hence the stored beam energy, all machine protection systems were validated up to the new higher level.

5.4. 2011–2012 LHC Operation

We continued to operate the collider in 2011 and were now increasing the performance much more rapidly (see Figure 10 comparing 2010 performance with 2011: note the different vertical scaling).

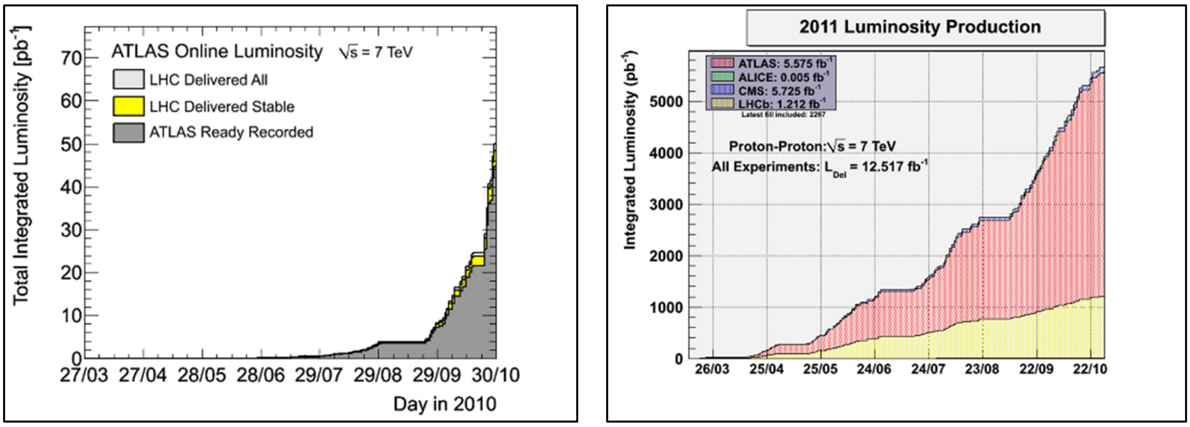
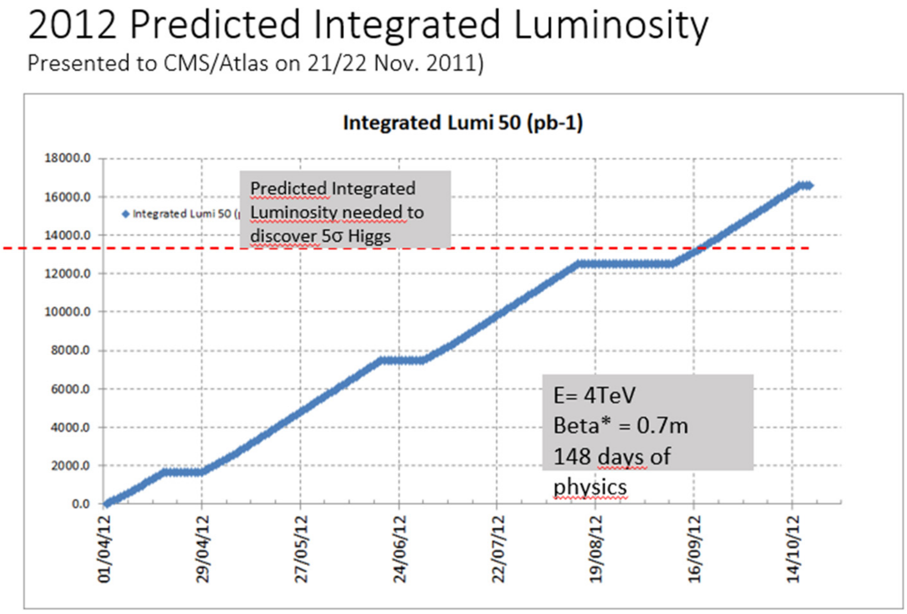
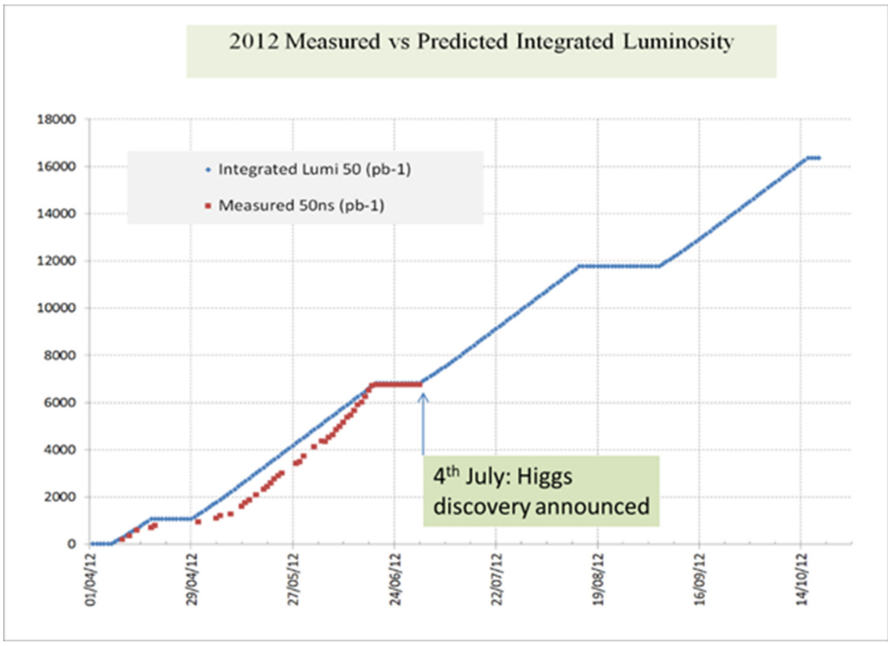


Figure 10. Plots show the daily progress in performance of the LHC in 2010 and 2011, reaching a maximum of 44 in 2010 and 6000 in 2011.

During the second half of 2011, the physics world was waiting for 2012; the last year of LHC operation before the long shutdown. The looming question was: will the LHC discover the Higgs boson or prove that it doesn't exist? I ran my performance simulation code with the parameters foreseen for running in 2012. The results shown in Figure 11a indicated that the luminosity needed to discover the Higgs boson would be reached during 2012. I presented these results to the CMS and ATLAS collaborations on 21/22 November 2011 respectively.



(**a**)



(**b**)

Figure 11. (**a**) Prediction of Integrated Luminosity for 2012. (**b**) Plot of predicted integrated luminosity in blue and measured in red.

Operation of the LHC restarted in April 2012 and I was carefully watching the performance every day. Initially the preformance was lagging my predictions, but then during May the slope changed and by the start of the 2nd technical stop on 17 June, the actual performance was exactly as predicted (see Figure 11b).

It was now fairly clear that we would reach the threshold for Higgs' discovery before the end of the 2012 run. It normally takes some weeks or months before the experiments can analyse all of the events they have recorded, so I was more than surprised to hear the rumours in late June that the data had been analysed and there were signs of a Higgs' discovery. The annual high energy physics conference was scheduled for 4th July in Melbourne and a video link had been set up from the main CERN auditorium to allow the LHC results to be transmitted to the physics world. Everyone in the high energy physics' world was waiting with bated breath. The main auditorium had to be locked to stop the summer students camping out for days beforehand in the conference room and blocking it for anyone else. I arrived at CERN at 5am on the morning of the 4th July and the queue for a place in the main auditorium was already long. Fortunately I had a reserved seat so I did not need to join the queue.

The main auditorium was packed to capacity long before the start of the presentations, with many legendary physicists including Peter Higgs as well as most of the living previous CERN DGs.

CMS had won, by the toss of a coin, to be the first to present. Joe Incandela nervously started his presentation and then, after some explanations on how they analysed the data, showed the small bump which was the five sigma signal for the discovery of the Higgs'. Everyone present stood up and applauded for minutes. Then Joe came over to me sitting in the front row and shook my hand and thanked the accelerator team. After Joe, Fabiola Gianotti made the presentation on behalf of the ATLAS experiment: again a five sigma signal and the auditorium erupted.

CERN was now triumphant having produced perhaps the most important physics result of the past century.

After the euphoria of the Higgs' discovery the collider resumed operation with a new approval for a run extension of nearly two months at the end of the year. The final integrated performance at the previously planned end of run was almost exactly at the level of the predictions. (see left plot in Figure 12).

During the first three years of operating LHC, (see right plot in Figure 12) the performance increased (in inverse pico-barns, pb^{-1}) from 44 in 2010, to 6000 in 2011 and then to 23000 in 2012 [15,16]. An incredible collider!

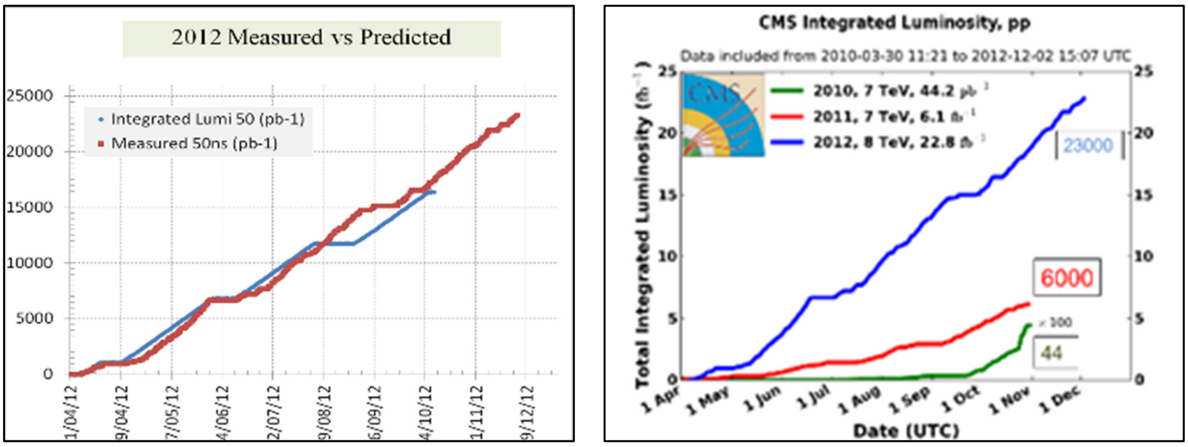


Figure 12. LHC performance in 2012 (predicted and achieved) and over 2010 to 2012.

Conflicts of Interest

The author declares no conflict of interest.

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