The Large Hadron Collider

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REVIEW

The Large Hadron Collider

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The construction of the Large Hadron Collider (LHC) has been a massive endeavour spanning almost 30 years from conception to commissioning. Building the machine with the highest possible energy (7 TeV) in the existing large electron–positron (LEP) collider tunnel of 27 km circumference and with a tunnel diameter of only 3.8 m has required considerable innovation. The first was the development of a two-in-one magnet, where the two rings are integrated into a single magnetic structure. This compact two-in-one structure was essential for the LHC owing to the limited space available in the existing LEP collider tunnel and the cost. The second was a bold move to the use of superfluid helium cooling on a massive scale, which was imposed by the need to achieve a high (8.3 T) magnetic field using an affordable Nb-Ti superconductor.

Keywords: Large Hadron Collider; collider; accelerator

1. Introduction

In this paper, no attempt is made to give a comprehensive review of the machine design. This can be found in the Large Hadron Collider (LHC) Design Report [1], which gives a detailed description of the machine as it was built and comprehensive references. A more popular description of the LHC and its detectors can be found in Evans [2]. Instead, this is a more personal account of the project from approval to commissioning, describing some of the main technologies and some of the challenges encountered during its construction and commissioning.

2. Approval of the Large Hadron Collider

The LHC had a difficult birth. Although the idea of a large proton–proton collider at CERN had been around since at least 1977, the approval of the superconducting super collider (SSC) in the USA in 1987 [3] put the whole project into doubt. The SSC, with a centre-of-mass energy of 40 TeV, was almost three times more powerful than what could ever be built at CERN (the European

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Laboratory for Particle Physics). It was only the resilience and conviction of Carlo Rubbia, who shared the 1984 Nobel Prize in Physics for the discovery of the W and Z bosons, that kept the project alive. Rubbia, who became the Director General of CERN in 1989, argued that, in spite of its disadvantage in energy, the LHC could be competitive with the SSC by having a luminosity an order of magnitude higher than could be achieved with the SSC, and at a fraction of the cost. He also argued that the LHC would be more versatile. As well as colliding protons, it would be able to accelerate heavy ions to world-beating energies at little extra cost.

The SSC was eventually cancelled in 1993 [4]. This made the case for the building of the LHC even stronger, but the financial climate in Europe at the time was not conducive to the approval of a large project. CERN's largest contributor, Germany, was struggling with the cost of reunification and many other countries were trying to get to grips with the problem of meeting the Maastricht criteria for the introduction of the single European currency.

During the course of 1993, an extensive review was made in order to reduce the cost as much as possible, although a detailed cost estimate was particularly difficult to make since much of the research and development on the most critical components was still to be done. In December 1993, a plan [5] was presented to the CERN Council to build the machine over a 10 year period by reducing the other experimental programme of CERN to the absolute minimum, with the exception of the full exploitation of the large electron–positron (LEP) collider, which was the flagship machine of the decade.

Although the plan was generally well received, it became clear that two of the largest contributors, Germany and the UK, were very unlikely to agree with the budget increase required. They also managed to get Council voting procedures changed from a simple majority to a double majority, where much more weight was given to the large contributors so that they could keep control.

On the positive side, after the demise of the SSC, a US panel on the future of particle physics [6] recommended that 'the government should declare its intentions to join other nations in constructing the LHC'. Positive signals were also being received from India, Japan and Russia.

In June 1994, the proposal to build the LHC was made once more. Council adopted a very unusual procedure in which the vote on the Resolution was opened so that countries in a position to vote could do so, but neither the vote nor the Council Session was closed [7]. Seventeen member states voted to approve the project. However, because of the newly adopted double voting procedure, approval was blocked by Germany and the UK, which demanded substantial additional contributions from the two host states, France and Switzerland, claiming that they obtained disproportionate returns from the CERN budget. They also requested that financial planning should proceed under the assumption of 2 per cent annual inflation, with a budget compensation of 1 per cent, essentially resulting in a 1 per cent annual reduction in real terms.

In order to deal with this new constraint, CERN was forced to propose a 'missing magnet' machine in which only two-thirds of the dipole magnets needed to guide the beams on their quasi-circular orbits would be installed in the first stage, allowing the machine to run with reduced energy for a number of years, eventually upgrading to full energy. This would have been a very inefficient way of building the machine, costing more in the long run but saving some 300 million

Swiss francs in the first phase. This proposal was put to Council in December 1994. After a round of intense discussions between France, Switzerland, Germany and the UK, the deadlock concerning extra host-state contributions was broken when France and Switzerland agreed to make extra voluntary contributions in the form of a 2 per cent annual inflation adjustment, compared with the 1 per cent adjustment from the other member states. In the continuation of the 100th Session of Council, still open from the June meeting, the project was finally approved [8] for two-stage construction, to be reviewed in 1997 after the size of the contribution offered by non-member states interested in joining the LHC programme would be known. The tough negotiations with France and Switzerland were couched in diplomatic language in the *Considerata* of the Council Resolution 'The CERN Council...Notes with gratitude, the commitments of France and Switzerland to make voluntary contributions to help and accelerate the LHC project'.

There followed an intense round of negotiations with potential contributors. The first country to declare a financial contribution was Japan, which became an observer to the CERN Council in June 1995. The declaration from Japan was quickly followed by that from India and Russia in March 1996 and by that from Canada in December 1996.

A final sting in the tail came in June 1996 from Germany, which unilaterally announced that, in order to ease the burden of reunification, it intended to reduce its CERN subscription by between 8 and 9 per cent. Confining the cut to Germany proved impossible. The UK was the first to demand a similar reduction in its contribution in spite of a letter from the UK Science Minister during the previous round of negotiations stating that the conditions are 'reasonable, fair and sustainable'. The only way out was to allow CERN to take out loans, with repayment to continue after the completion of LHC construction.

In the December 1996 Council, Germany declared that 'a greater degree of risk would inevitably have to accompany the LHC'. The project was approved for single-stage construction with the deficit financed by loans. It was also agreed that the final cost of the project was to be reviewed at the half-way stage with a view to adjusting the completion date. With all contingency removed, it was inevitable that a financial crisis would occur at some time, and this was indeed the case when the cost estimate was revised upwards by 18 per cent in 2001. Although this was an enviable achievement for a project of such technological complexity and with a cost estimate from 1993 before a single prototype had been made, it certainly created big waves in Council. CERN was obliged to increase the level of borrowing and extend the construction period (which was necessary anyway on technical grounds for both the machine and detectors).

In the meantime, following the recommendation of the US panel, and in preparation for a substantial contribution, the US Department of Energy, responsible for particle physics research, carried out an independent review of the project [9]. It found that 'the accelerator-project cost estimate of 2.3 billion in 1995 Swiss francs, or about $2 billion US, to be adequate and reasonable'. Moreover, it found that 'Most important of all, the committee found that the project has experienced and technically knowledgeable management in place and functioning well. The strong management team, together with the CERN history of successful projects, gives the committee confidence in the successful completion of the LHC project.' In December 1997, at a ceremony in Washington, DC, in the splendid Indian Treaty Room of the White House Annex, an agreement was signed between the Secretary of Energy and the President of the CERN Council. More than 1300 American physicists are users of CERN today.

After a shaky start and a mid-term hiccup, the project has proceeded reasonably smoothly to completion. The LHC is a fine example of European collaboration and leadership in science.

3. A brief history of colliders

Colliding beam machines (storage rings), with two beams of particles circulating in opposite directions and colliding at a point on the circumference where particle detectors could be placed, were the dream of accelerator builders in the late 1950s, since the energy available for producing new particles scales as the beam energy and not as its square root, as in fixed-target experiments. In the early 1960s, the first machines started to appear at Stanford in the USA, Frascati in Italy and Novosibirsk in Russia. Instead of protons, these machines collided leptons (electrons or positrons). One great advantage in using electrons and positrons is that, when bent on a circular orbit, they emit light (synchrotron radiation). The dynamics is such that the emission of this radiation has a natural damping effect on the transverse dimensions, concentrating the particles into a very intense beam, essential if there is to be a reasonable probability of two particles colliding instead of the beams just passing through each other without interacting. It is also desirable that the beams can circulate for many hours while data are collected. During this time, the particles are subjected to perturbations due to imperfections in the guide field or the electromagnetic field of the other beam that can cause them to become unstable. Synchrotron radiation also plays an important role in combating these external perturbations owing to its natural damping effect. However, the emission of synchrotron radiation makes the particles lose energy, which has to be replaced by the acceleration system. Essentially, the beams have to be permanently accelerated in order to keep them at constant energy. The energy lost at each revolution increases dramatically (with the fourth power) as the energy of the machine increases, eventually making it impossible for the accelerating system to replace it. In spite of its usefulness, synchrotron radiation naturally limits the maximum achievable energy of the machine. The way around this is to revert to particles that emit much less radiation.

In the late 1960s, a very bold step was taken at CERN with the construction of the first proton storage rings, called the intersecting storage rings (ISRs), which started operation in 1969. The advantage of protons is that they do not emit synchrotron radiation of any consequence since the energy loss per revolution varies as the inverse fourth power of the mass of the particle, and protons are 2000 times heavier than electrons. The disadvantage is that they have to operate without the benefit of the strong damping provided by synchrotron radiation. Indeed, many accelerator physicists doubted that proton storage rings would work at all.

In the end, the ISR was a big success for the machine builders and an essential step on the road to the LHC. The machine eventually reached 31 GeV per beam, compared with the few giga-electronvolts available from the lepton beams at that

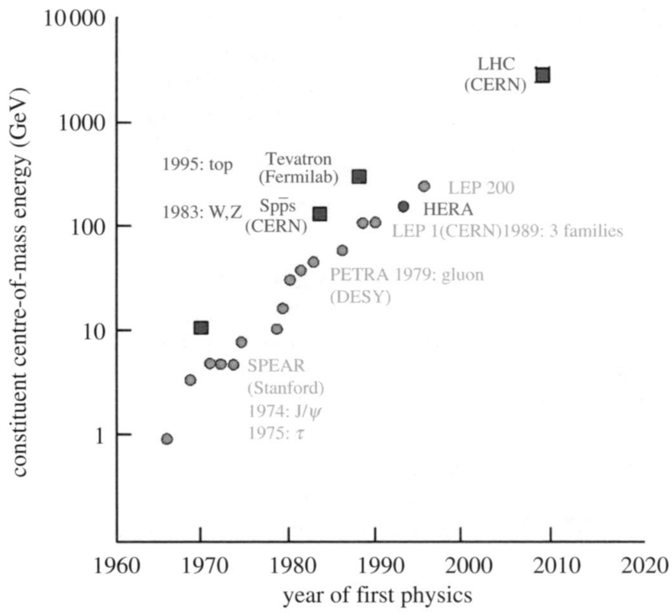

Figure 1. The history of colliders. Circles indicate the lepton machines. Squares indicate the Hadron machines, including three of the four constructed at CERN. The energy available in the quarks or gluons is about one-fifth of the beam energy. Circle labelled ‘HERA’, e–p collider; all other circles, $e^+ e^-$ collider; square, Hadron collider. (Online version in colour.)

time. The accelerator physicists learned how to build proton storage rings that overcame the lack of synchrotron radiation damping. Early ISR experiments were not so successful because they mainly looked at forward angles, whereas the most important physics was at large angles. This was an important lesson learned from the ISR. The first modern four-pi detector was the mark 1 detector used in SPEAR at Stanford, CA, in 1973. With this experience, the experimentalists learned how to build detectors that worked in the difficult environment of a proton–proton collider.

Another step on the road to the LHC was taken during the long period of LEP collider construction. During this time, Carlo Rubbia proposed that the super proton synchrotron (SPS), built in the 1970s as a ‘fixed target’ machine, could be turned into a hadron collider using the newly discovered technique proposed by Simon Van de Meer at CERN and first demonstrated experimentally by Wolfgang Schnell in the ISR of accumulating and cooling antiprotons produced in CERN’s oldest machine, the CERN proton synchrotron (PS). Since protons and antiprotons have the same mass but opposite charge, they could be accelerated in opposite directions in the single vacuum chamber of the SPS. Collisions at 273 GeV per beam produced the first W and Z bosons, the mediators of the weak nuclear force responsible for radioactive decay in the two (then) massive detectors christened UA (for underground areas) 1 and 2, purpose built for their detection.

The proton–antiproton collider (PPBAR) also provided the essential remaining information needed for the design of the LHC and its detectors. For the LHC machine, it elucidated the main factors that would limit its performance, and the two detectors UA1 and UA2 served as prototypes for the much larger LHC

Figure 2. The Large Hadron Collider. (Online version in colour.)

detectors. Indeed, the nucleus of the teams designing the two large LHC detectors, ATLAS and CMS, comes from these earlier collaborations.

Across the Atlantic, a further bold step was taken with the construction of the world's first large superconducting synchrotron, the Tevatron at Fermilab. This machine showed that superconducting magnets, which inevitably have a poorer field quality than conventional magnets, could operate in storage ring mode. The Tevatron took over the energy frontier from PPBAR in 1987 (figures 1–3).

4. The design of the Large Hadron Collider

The fact that the LHC was to be constructed at CERN, making the maximum possible use of existing infrastructure to reduce cost, imposed a number of strong constraints on the technical choices to be made.

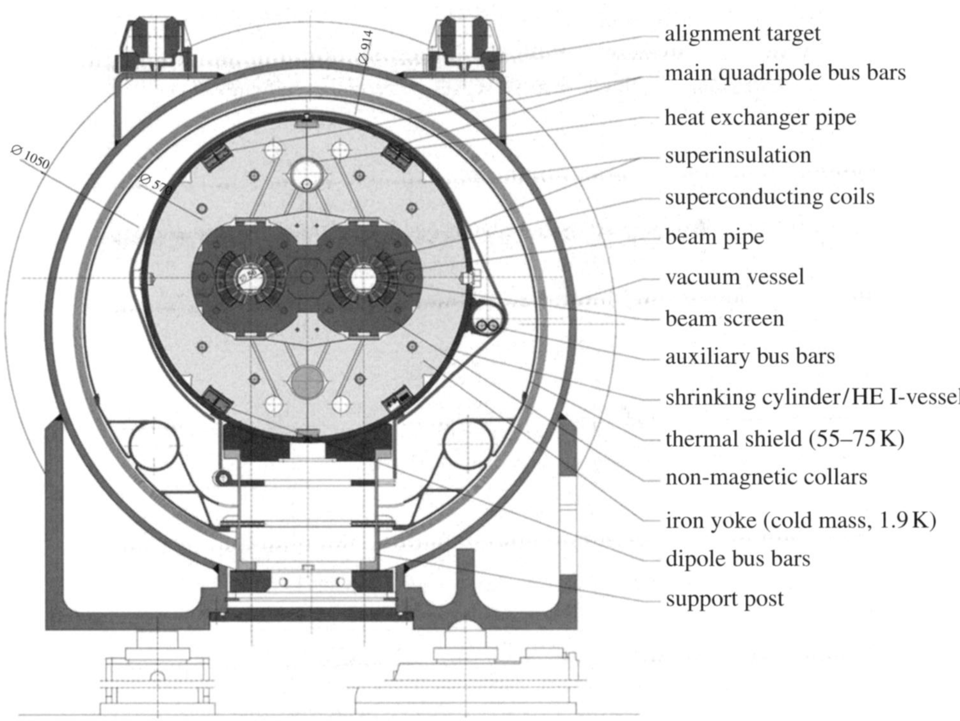

Figure 3. A cross section of the two-in-one LHC bending magnet. The two rings are concentrated inside a single vacuum vessel to save space (and money). (Online version in colour.)

The first of these was the 27 km circumference of the LEP collider tunnel. The maximum energy attainable in a circular machine depends on the product of the bending radius in the dipole magnets and the maximum field strength attainable. Since the bending radius is constrained by the geometry of the tunnel, the magnetic field should be as high as possible. The field required to achieve the design energy of 7 TeV is 8.3 T, about 60 per cent higher than that achieved in previous machines. This pushed the design of superconducting magnets and their associated cooling systems to a new frontier.

The next constraint was the small (3.8 m) tunnel diameter. It must not be forgotten that the LHC is (just like the ISR) not one but two machines. A superconducting magnet occupies a considerable amount of space. To keep it cold, it must be inserted into an evacuated vacuum vessel called a cryostat and well insulated from external sources of heat. Owing to the small transverse size of the tunnel, it would have been impossible to fit two independent rings into the space. Instead, a novel and elegant design with the two rings separated by only 19 cm inside a common yoke and cryostat was developed. This was not only necessary on technical grounds, but also saved a considerable amount of money, some 20 per cent of the total project cost.

Finally, the re-use of the existing injector chain governed the maximum energy at which beams could be injected into the LHC.

Table 1. Magnet types.

type	number	function
MB	1232	main dipoles
MQ	392	arc quadrupoles
MBX/MBR	16	separation and recombination dipoles
MSCB	376	combined chromaticity and closed orbit correctors
MCS	2464	sextupole correctors for persistent currents at injection
MCDO	1232	octupole/decapole correctors for persistent currents at injection
MO	336	Landau dumping octupoles
MQT/MQTL	248	tuning quadrupoles
MCB	190	orbit correction dipoles
MQM	86	dispersion suppressor and matching section quadrupoles
MQY	24	enlarged-aperture quadrupoles in insertions
MQX	32	low-beta insertion quadrupoles

5. Magnets and cryogenics

At the heart of the LHC is the superconducting magnet system and associated cryogenics. Table 1 lists all of the superconducting magnets in the machine. As well as the main dipoles and lattice quadrupoles, there are a large number of other magnets for orbit and chromaticity correction, higher multi-poles to control persistent currents and the special quadrupoles and dipoles in the low-beta insertions. There are also a number of strong octupoles to provide Landau damping of coherent instabilities if needed.

The main dipoles need to operate at a much higher field (8.3 T for 7 TeV energy) than in any previous machine. This high field level can be obtained with two types of superconductor. The ductile alloy niobium–titanium and the intermetallic compound Nb_3Sn are the only materials that can be used for such magnets today. Nb_3Sn could reach the required performance in supercritical helium at 4.5 K, but it is mechanically brittle and costs at least five times as much as Nb-Ti. It is, therefore, excluded for large-scale series production. The only alternative is Nb-Ti, but it must be cooled to 1.9 K below the lambda point of helium to get the required performance. This requires a very innovative cryogenic system.

The superconducting cable is made of strands of wire, about 1 mm in diameter and composed of one-third superconducting material and two-thirds copper. The Nb-Ti filaments are 6–7 µm in diameter and precisely positioned with 1 µm separation in the copper matrix. They are produced by multiple co-extrusion of Nb-Ti ingots with copper rods and cans. The strands and multi-strand cable are shown in figure 4.

It is of interest to make the dipoles as long as possible to reduce the number of units and interconnects, and therefore the cost, and also to maximize the filling factor, reducing the magnetic field required for a given energy. A number of practical factors, including the road transport of magnets and facility of installation, put an upper limit on their length. The final magnets have a magnetic length of 14.3 m with a physical length of 15 m. The regular lattice period is 106.9 m with six dipoles and two 3 m long quadrupoles per

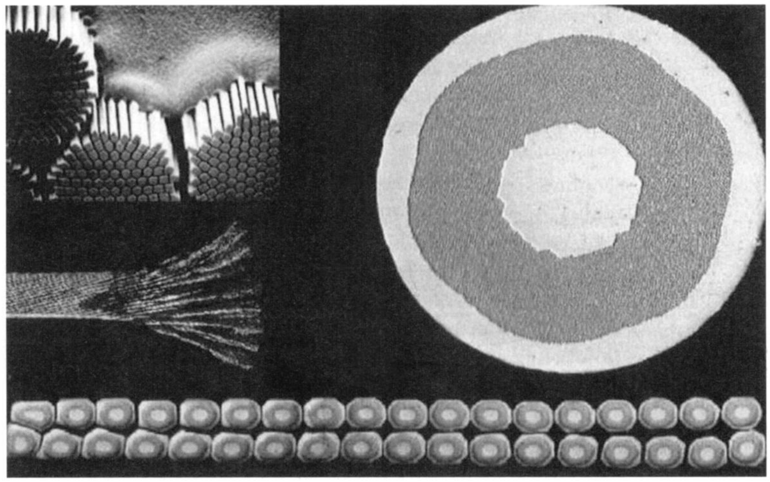

Figure 4. LHC superconductor and cable. (Online version in colour.)

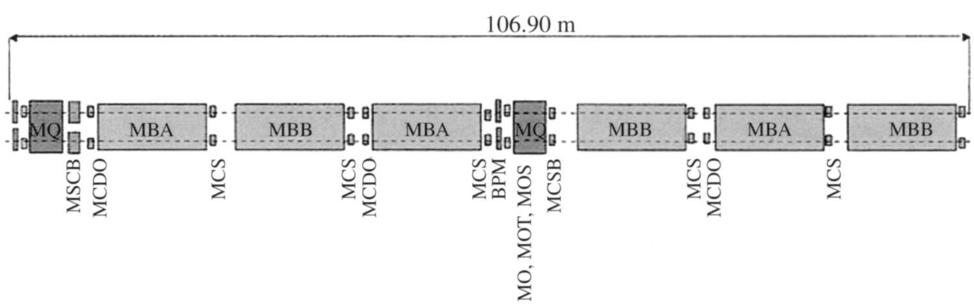

Figure 5. The regular lattice. (Online version in colour.)

period. The ends of the dipoles contain the small octupole and decapole correctors to control unwanted multi-poles, especially in the 'snapback' regime at the start of acceleration when persistent currents cause strong nonlinearities (figure 5).

In addition to these small correctors, each lattice period contains a sextupole to correct the chromaticity as well as a dipole for orbit correction. Depending on its location in the machine, each period contains an additional corrector, either a trim or skew quadrupole or a Landau octupole.

The mechanical forces in the dipole are very large, up to 300 tonnes m^{-1} pushing the coils outwards at full power. These forces are contained by strong non-magnetic steel collars surrounded by an iron yoke and a stainless steel cylinder (figure 6).

Series production of dipoles and quadrupoles has been a monumental task. All superconducting cables and many mechanical components were supplied to the cold mass assemblers (three for the dipoles and one for the quadrupoles) by CERN in order to ensure uniformity of production and also to allow control of the distribution of contracts between countries. The cold masses were assembled into

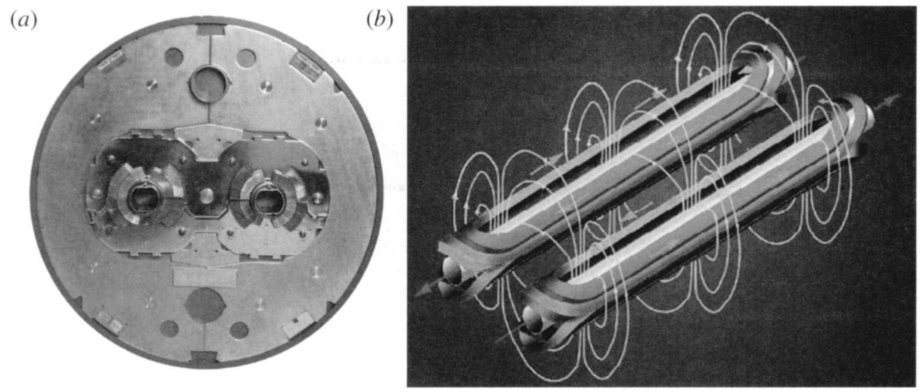

Figure 6. (*a*) Cross-sectional model of the LHC dipole without the cryostat. (*b*) Magnetic coupling between the two apertures. (Online version in colour.)

their cryostats at CERN. All magnets were tested at 1.9 K before installation in the tunnel. From start to finish, production, from cable to fully tested magnets, took about 6 years.

The total mass to be cooled to 1.9 K is 37 000 tonnes, requiring approximately 80 tonnes of superfluid helium to be maintained at 1.9 K during the entire period of operation. The main reason for operating in superfluid is to extend the operating range of the Nb-Ti superconductor. However, operating below the lambda point brings its own advantages and challenges. The rapid drop in the specific heat of the conductor at low temperature makes it imperative to use the special properties of superfluid helium in the best possible way. The insulation between turns in the coil has been designed to be porous so that, with its low viscosity, the helium can permeate the windings where it buffers thermal transients owing to its high specific heat (2000 times that of the conductor per unit volume). The excellent thermal conductivity of the fluid (peaking at 1.9 K and typically 1000 times that of oxygen-free high-conductivity (OFHC) copper) enables it to conduct heat without mass transport with no need for fluid circulation or pumps.

The magnets operate in a static bath of superfluid at atmospheric pressure using an unconventional cooling scheme. The bath is continuously cooled through a linear heat exchanger tube made out of cryogenic-grade copper and extending the full 107 m length of each cell (figure 7). The pressure inside the heat exchanger is 15 mbar. Helium expanded into the tube through a Joule–Thomson (JT) valve is cooled to 1.9 K. The static helium in the magnets is then cooled by latent heat of vaporization of the small quantity of superfluid inside the heat exchanger. This scheme has been shown to work beautifully, keeping the LHC temperature stable for weeks on end.

At 7 TeV, even protons start to produce synchrotron radiation. The power emitted is about 4 kW per beam, which is much too low to provide synchrotron radiation damping but is quite a nuisance since it must be absorbed on the cold surface of the beam pipe. One watt at 1.9 K corresponds to a kilowatt at room temperature, which cannot be accepted by the refrigerators. Therefore, the beam vacuum chamber contains a liner cooled to 20 K in order to intercept the heat load with better thermodynamic efficiency.

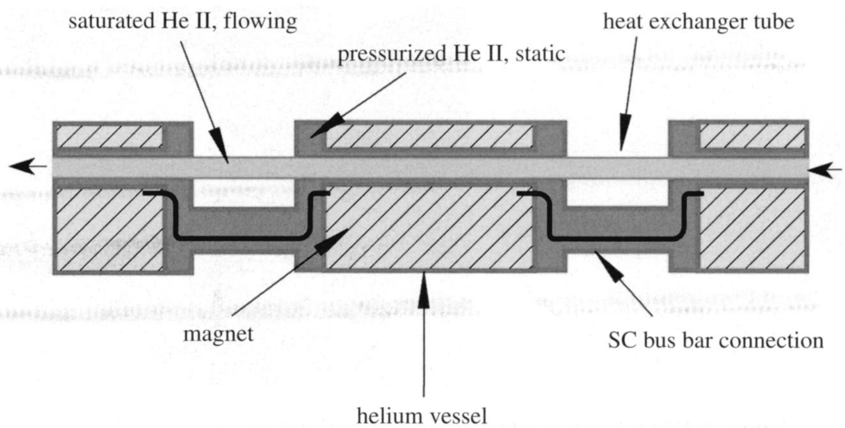

Figure 7. Schematic of the LHC magnet cooling system. (Online version in colour.)

6. Machine layout

In parallel with the approval of the LHC machine, proposals for the experimental programme were being examined by the LHC Experiments Committee (LHCC), whose job was to give advice to the CERN management and through it to Council. Unlike the machine, the detectors have considerable independence. Only 20 per cent of their funding comes through CERN. The rest comes from collaborating institutes all around the globe. However, it is the responsibility of CERN to provide the infrastructure, including the caverns in which the experiments are housed. Eventually, the LHCC proposed approval of two large general purpose detectors, ATLAS and CMS, as well as two smaller more specialized detectors, ALICE for heavy-ion physics and LHCb for the study of matter–antimatter asymmetry.

(*a*) *Civil engineering*

The first job was to decide where these detectors were to be located. The LHC ring is segmented into eight identical arcs joined by eight 500 m long straight sections (LSSs), labelled from 1 to 8. Four of these LSSs (at points 2, 4, 6 and 8) already contained experimental caverns in which the four LEP detectors were located. These caverns were big enough to house the two smaller experiments. However, ATLAS and CMS required much bigger caverns, so excavation had to start while the LEP collider was still running, the four even points therefore being excluded. Point 3 lies in a very inhospitable location deep under the Jura Mountains and, for various reasons, point 7 could also be excluded. There remained point 1, conveniently situated opposite the CERN main campus and diametrically opposite to point 5, the most remote of all. Needless to say, there was considerable pressure from both ATLAS and CMS collaborations to get the more convenient point 1. In the end, geology prevailed. Sample borings showed that point 1 was much better suited for the larger cavern required for ATLAS. CMS was allocated point 5. ALICE re-used the large electromagnet magnet of one of the old LEP experiments at point 2 and LHCb was assigned the cavern at point 8 (figure 8).

Figure 8. Excavation of ATLAS. The cavern is the largest ever built in the type of rock encountered in the Geneva basin. (Online version in colour.)

The excavation of the large caverns at points 1 and 5 posed different problems. At point 1, the cavern is the largest ever excavated in such ground conditions. The work also had to continue while the LEP machine was still operating. At point 5, although the exploratory borings showed that there was a lot of ground water to be traversed when sinking the shaft, the speed of water flow took us by surprise. Extensive ground freezing was necessary to produce an ice wall around the shaft excavation.

An additional complication at point 5 was that, during the preparation of the worksite, the foundations of an ancient Roman farm (fourth century AD) were discovered. Work was immediately stopped so that the mandatory archaeological investigation could be made. Articles of jewellery and coins minted in London, Lyon and Ostia, the ancient harbour city 35 km southwest of Rome, were found. The coins minted in London were dated AD 309–312. One striking feature easily seen from the air (figure 9) is the precise alignment of the villa with respect to the boundaries of the present-day fields. This is evidence that the 'cadastre', or land registry of today, is derived from the time of the Roman occupation.

A third civil engineering work package was the construction of two 2.6 km long tunnels connecting the SPS to the LHC and the two beam dump tunnels and caverns (figures 10 and 11).

(*b*) *Machine utilities*

It takes more than just magnets to make a particle accelerator. Once the four straight sections were allocated to the detectors, the other four could be assigned to the essential machine utilities.

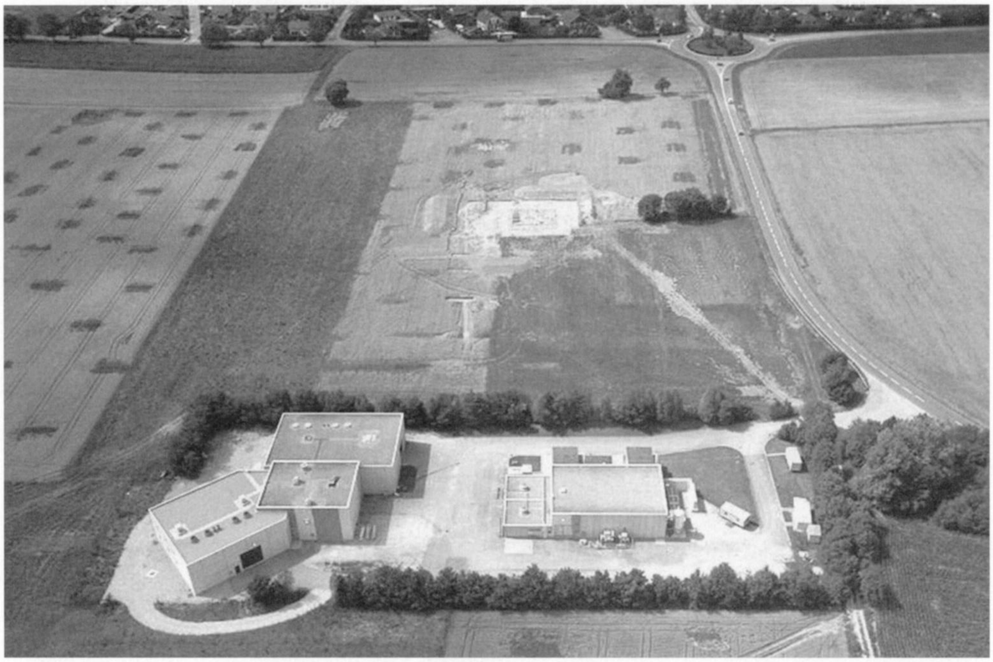

Figure 9. Aerial view of point 5 in 1998. In the bottom of the picture are the original buildings from the LEP collider. The foundations of a Roman farm from the fourth century can be seen top-centre. Note how its walls are aligned perfectly with the boundaries of the surrounding fields. (Online version in colour.)

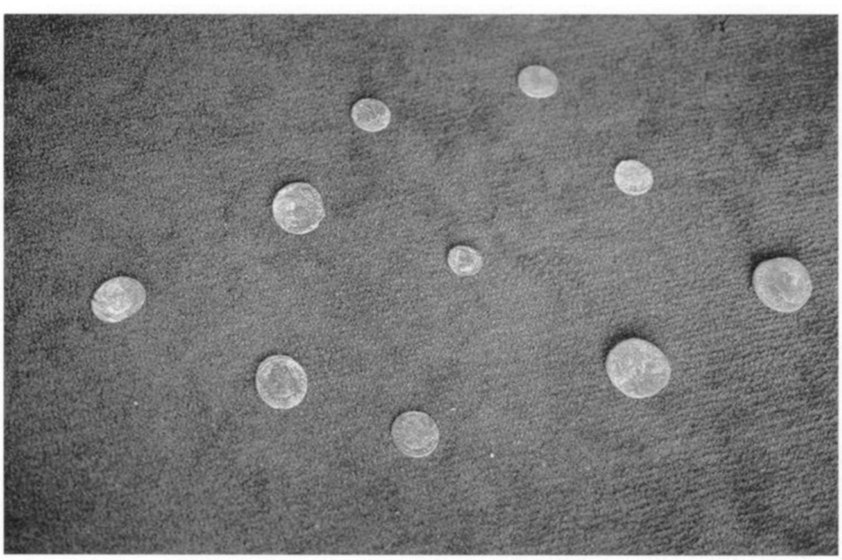

Figure 10. Roman coins found during archaeological excavations at point 5. The larger coins are from the Emperor Maxence minted in Ostia between AD 309 and 312. The smaller coins are from the Emperor Constantin minted in London and Lyon between AD 313 and 315. (Online version in colour.)

Figure 11. An underground river made the excavation of the shaft of the CMS cavern very difficult. A ring of pipes carrying liquid nitrogen was used to form a wall of ice inside which the shaft was excavated and lined with concrete. (Online version in colour.)

Figure 12 shows a schematic layout of the LHC ring. The two beams cross from one ring to the other at the four collision points 1, 2, 5 and 8; elsewhere, they travel in separate vacuum chambers. They are transported from the SPS through two 2.6 km long tunnels. Owing to the orientation of the SPS with respect to the LHC, these tunnels join the LHC ring at points 2 and 8. It was, therefore, necessary to integrate the injection systems for the two beams into the straight sections of the ALICE and LHCb detectors.

Clockwise from point 2, the long straight section at point 3 lies deep below the Jura Mountains. It contains no experimental cavern from the LEP days and, moreover, it is known from experience of excavating the LEP tunnel that the geological conditions in this region are very poor. Cracks and fissures in the rock allow water to percolate from the very top of the mountain, more than 1000 m high, producing a large static water pressure. In view of this, it was decided that no additional civil engineering for tunnel enlargement would be allowed in this region. It was therefore assigned to one of the two collimation systems, which could be fitted into the existing tunnel.

Collimation is essential in a collider. As the beams are stored for many hours, a halo of particles slowly builds up around the core, mainly owing to nonlinearities in the magnetic field or to the interaction of one beam with the other (in a lepton machine, this halo would be damped by synchrotron radiation). If it were left uncontrolled, eventually particles would hit the vacuum chamber wall, producing

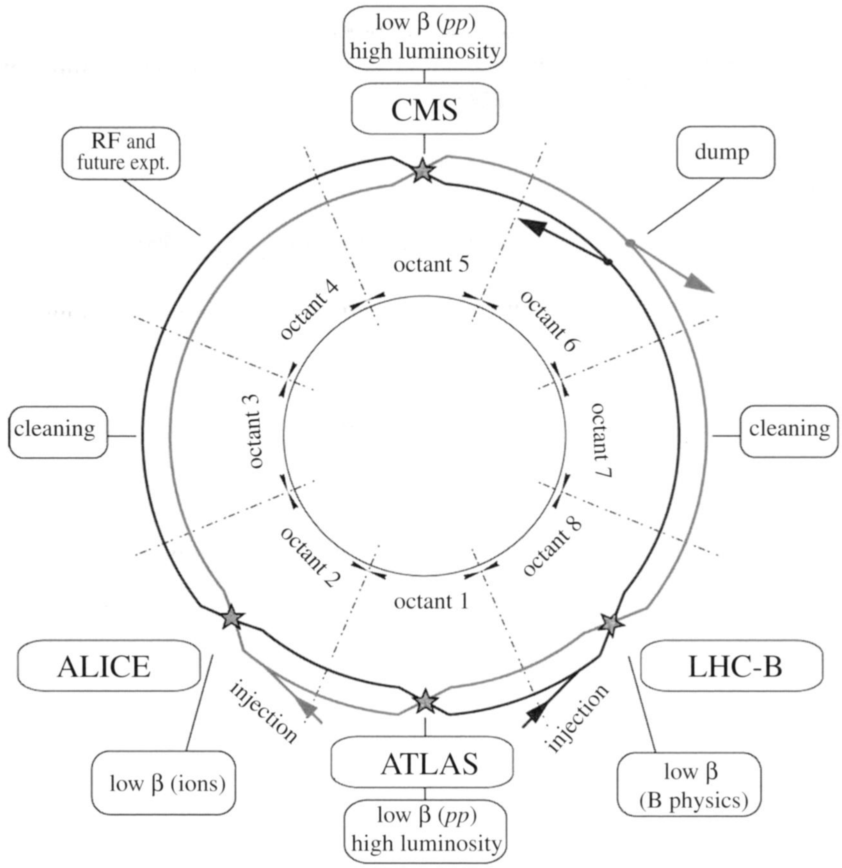

Figure 12. Schematic of the machine layout. (Online version in colour.)

unacceptable background in the detectors and risking a *quench* (a transition from the superconducting state owing to the accompanying temperature rise) in some of the magnets. Collimators are specially designed motorized blocks that can be driven into the machine aperture to 'clean' the beam by removing the halo locally. The collimators constitute the primary aperture restriction in the machine.

Point 4 is assigned to the all-important radio frequency (RF) acceleration system. Acceleration is obtained by a longitudinal oscillating electric field at a frequency of 400 MHz in a set of resonant cavities. The electric field in the cavities is very high, in excess of 5 million volts per metre. Once again, superconductivity is very useful here. The cavities are made of copper but there is a thin film of niobium deposited on the inside surface. When cooled with liquid helium, this film becomes superconducting, enabling currents to flow in the cavity walls without loss.

With each revolution, the beam is given a small increase in energy as long as the field is pointing in the right direction. To achieve this, the frequency of the RF must be a precise harmonic of the revolution frequency so that, each time a particle comes around, the field is pointing in the same direction. As the energy slowly increases, the magnetic field must also rise to keep the beams in the centre

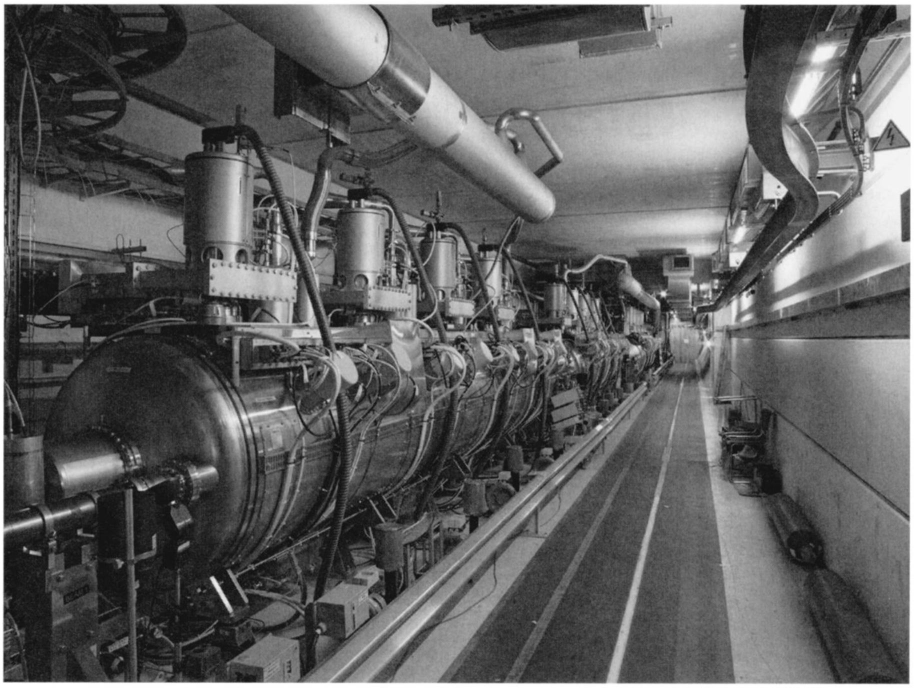

Figure 13. The superconducting radio frequency cavities at point 4. (Online version in colour.)

of the vacuum chamber since the magnetic field required to bend a particle on a constant radius is proportional to its energy. The RF system needs considerable infrastructure and profits fully from the space available in the old LEP cavern at point 4 (figure 13).

At 7 TeV with nominal intensity, the stored energy in one of the beams is 350 MJ, equivalent to more than 80 kg of TNT. If, for any reason, this beam is lost in an uncontrolled way, it can do considerable damage to machine components, resulting in months of down-time. It is therefore essential to have a system that can reliably extract the beams very quickly and deposit them on special absorber blocks. This 'beam-dump' system is located at point 6. A set of special magnets can be pulsed very rapidly to kick the whole beam out of the machine in a single turn. The extracted beams are transported 700 m in an evacuated pipe and deposited on absorber blocks specially designed to take the enormous power.

The beam dump can be triggered by many sources, for instance if an excessive beam loss on the collimators is detected or if a critical power supply fails. It is also used routinely during operation; when the intensity in the beams falls too low the beams are 'dumped' by the operators in order to prepare the machine for the next filling cycle.

Finally, point 7, like point 3, contains a second collimation system.

The long straight sections each side of the four detectors house the equipment needed to bring the beams together into a single vacuum chamber and to focus them to a small spot with a radius of about 30 μm at the collision points inside the detectors. This requires special elements and is a prime example of international collaboration in the machine construction. The superconducting magnets required

Figure 14. The 'inner triplet' in the long straight sections left of point 1 (ATLAS). The cryostats contain quadrupole magnets which focus the beams to a 30 μm spot at the interaction point. (Online version in colour.)

to focus the beams were built in the USA and Japan, with the Japanese magnets shipped to the USA for integration into their cryostats before delivery to CERN. The special dipoles used to bring the two beams to the same orbit were built in Brookhaven in the USA, and the current feed boxes for all superconducting elements in the straight sections come from Fermilab. Other equipment in these long straight sections comes from India and Russia (figure 14).

7. First cool down

The year 2008 was very eventful for the LHC. During the first half of the year, the whole machine was cooled down (figure 15). From room temperature to 80 K, the helium circulating in the magnets was cooled by vaporizing liquid nitrogen in a heat exchanger. In total, 1200 tonnes of liquid nitrogen was needed for a single sector, the whole process taking about 10 days with 60 trucks, each containing 20 tonnes of liquid nitrogen, arriving every 4 h. Between 80 and 4.5 K, the helium refrigerators were used. Finally, the cold compressors producing helium at 15 mbar pressure were switched on to reduce the temperature to the operating value of 1.9 K.

8. First commissioning

By 10 September 2008, seven of the eight sectors had been successfully commissioned to 5.5 TeV in preparation for a run at 5 TeV. Owing to lack of time, the eighth sector had only been taken to 4 TeV. Beam commissioning started by

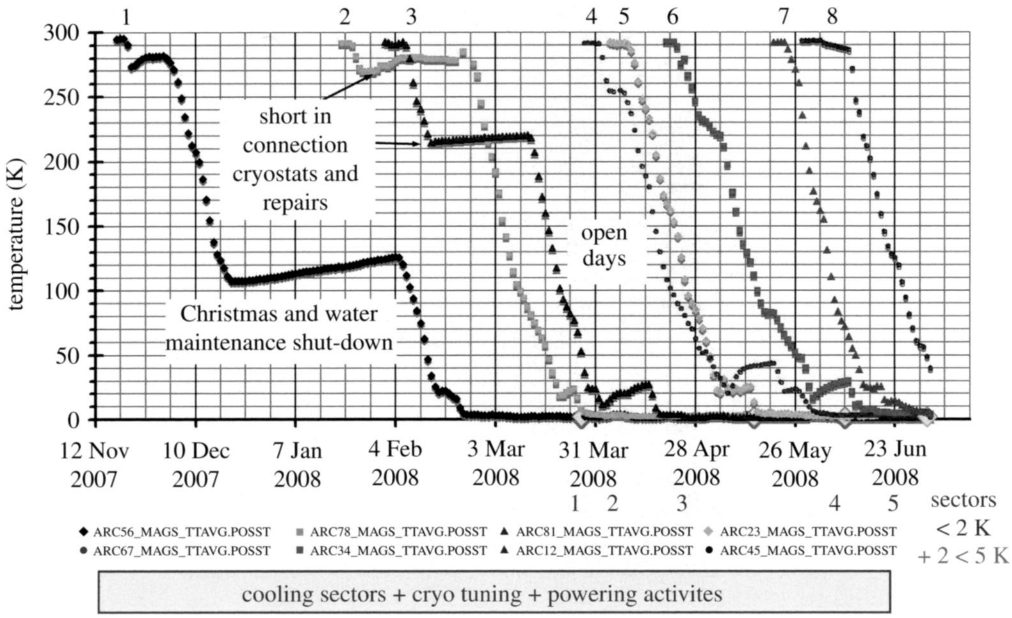

Figure 15. Cooling down of the LHC sectors. (Online version in colour.)

threading beam 2, the counter-clockwise beam, around the ring, stopping it at each long straight section sequentially in order to correct the trajectory. In less than an hour, the beam had completed a full turn, witnessed by a second spot on a fluorescent screen intercepting both injected and circulating beams (figure 16).

Very quickly, a beam circulating for a few hundred turns was established (figure 17). The decay in intensity was due to the de-bunching of the beam around the ring since the RF system had not yet been switched on. Figure 18 shows the RF capture process. Each horizontal line on the mountain range display records the bunch intensity every 10 turns. Without the RF, the beam spreads around the ring (de-bunches) as it should in about 250 turns, or 25 ms. Figure 18*b* shows the first attempt that was made to capture the beam, but, as can be seen, the injection phase was completely wrong. Adjusting the phase allowed a partial capture, but at a slightly wrong frequency (figure 18*c*). Finally, adjusting the frequency resulted in a perfect capture (figure 18*d*).

The closed orbit could then be corrected. Figure 19 shows the first orbit correction where, remarkably at this early stage, the root mean square (r.m.s.) orbit is less than 2 mm. It can be seen that, in the horizontal plane, the mean orbit is displaced radially by approximately 1 mm, indicative of an energy mismatch of about 0.9 parts per thousand.

9. The accident

Commissioning proceeded rapidly with a circulating beam in the other ring until, on 18 September, a transformer failed at point 8, taking down the cryogenics in that sector. Since it was impossible to circulate the beam, attention turned to bringing the last remaining sector up to 5 TeV like the others. On 19 September,

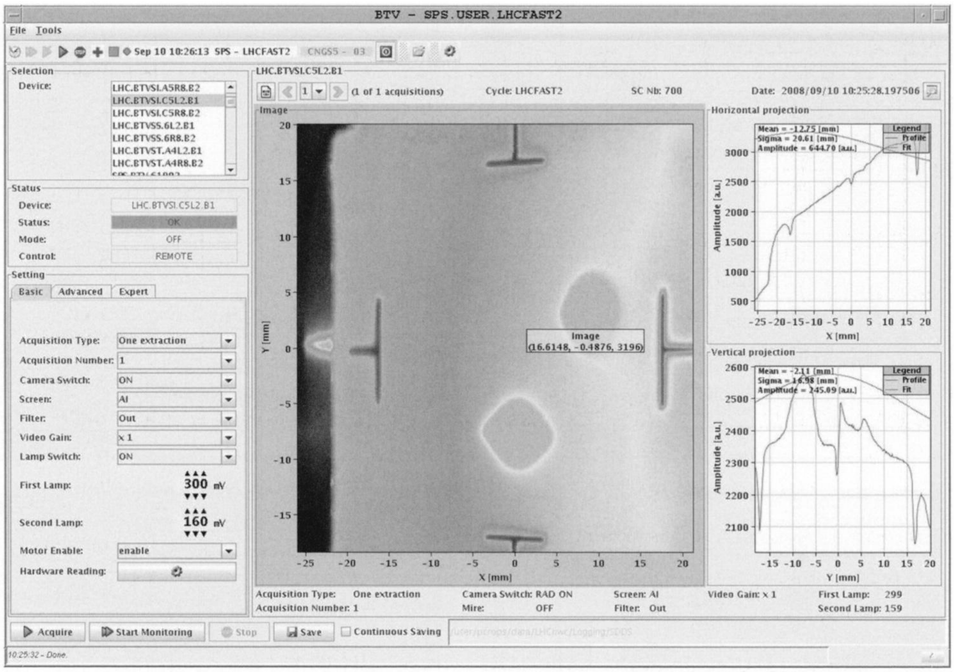

Figure 16. Beam on turns 1 and 2. (Online version in colour.)

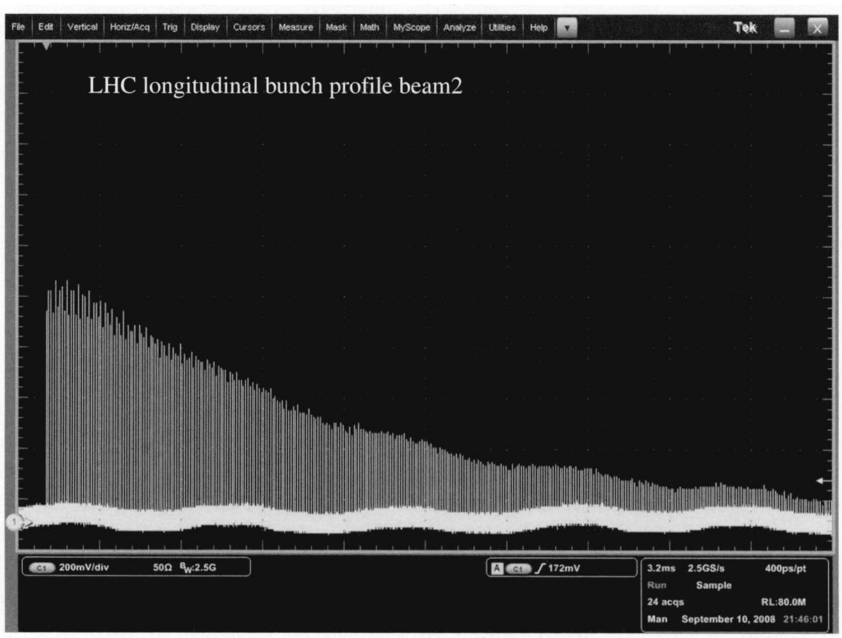

Figure 17. A few hundred turns. (Online version in colour.)

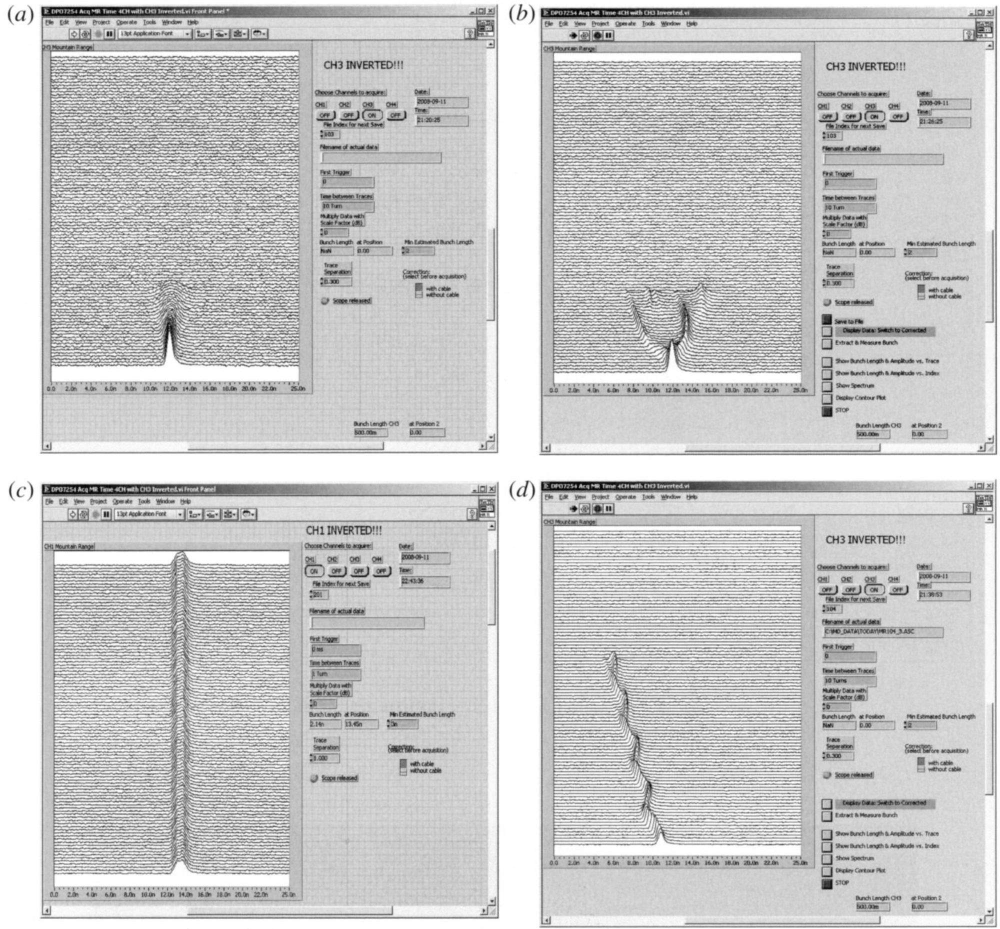

Figure 18. (*a*) No RF, de-bunching in approximately 25 × 10 turns, i.e. approximately 25 ms. (*b*) First attempt at capture, at exactly the wrong injection phase. (*c*) Capture with corrected injection phase but wrong frequency. (*d*) Capture with optimum injection phasing, correct reference. (Online version in colour.)

the last remaining circuit was being ramped to full field when, at 5.2 TeV, a catastrophic rupture of a bus bar occurred causing extensive damage in sector 34. These bus bars are connected by induction brazing with three layers of tin/silver solder in a copper box. Initially, it was foreseen to clamp these bus bars mechanically as well as with the solder, but this was discarded on the grounds that it would increase the hydraulic impedance in the interconnect region and therefore reduce the effectiveness of conduction cooling in the superfluid helium.

A fact-finding commission was established which concluded that the most probable cause of the accident was too high a resistivity in one of the 10 000 superconducting bus bar joints owing to the omission of the solder. In a normal machine, this would have caused minor damage. However, the joint rupture resulted in an arc piercing the helium vessel. The resultant high pressure in the

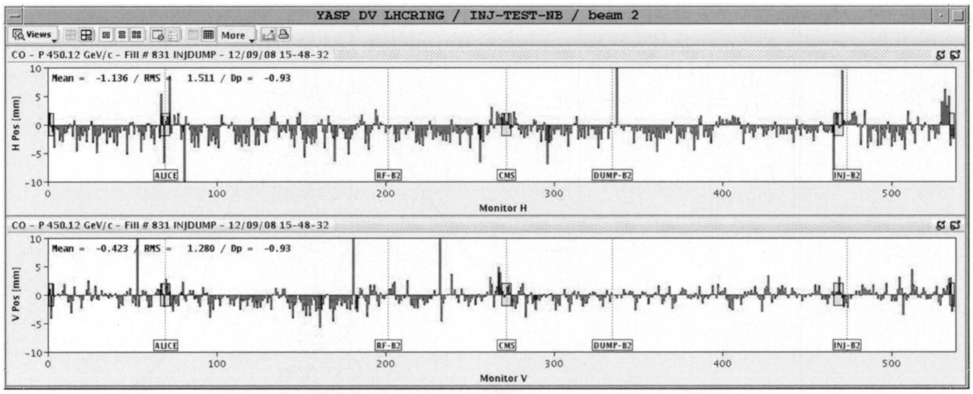

Figure 19. Corrected closed orbit on B2. Energy offset of approximately −0.9 parts per thousand owing to the capture frequency. (Online version in colour.)

insulating vacuum and the volume of helium gas was too high for the rupture discs to take, resulting in overpressure and displacement of magnets off their jacks. In total, 14 quadrupoles and 39 dipoles needed replacing.

10. The search for further defects

An urgent priority after the accident was to sift through data gathered during the event to see if any precursors to the accident could be detected, in particular any anomalous temperature increase in the affected area. Detecting temperature rise in the superfluid helium is made difficult for two reasons. The first is the enormous thermal conductivity of superfluid helium (figure 20). This provides good cooling of joints initially, but, since it is a quantum liquid, the thermal conductivity is a function of heat flux density (figure 21); therefore, as the heating increases, the cooling capacity quickly collapses, especially in the region of the splices with high hydraulic impedance.

The other reason why it was impossible to observe a temperature rise was the configuration of the superfluid cooling circuits themselves. Figure 22 shows one cryogenic cell containing two 107 m long periods of the machine. The primary superfluid flows through bayonet heat exchangers, the flow rate being controlled through JT valves (CV910 in the diagram). These valves are in a servo loop, which keeps the temperature constant.

It was obviously very important to find a way to be sure that there were no more bad joints in the machine. Two methods were developed. The first of these relied on calorimetry. With the servo loops open, the valves could be adjusted to just balance the static heat in-leak. Under these conditions, it was shown that a calibrated heat in-leak of 10 W through a resistor could be detected and, by measuring the rate of temperature rise in the cell (figure 23), the original 10 W could be reconstituted purely calorimetrically. Note the temperature axis with 5 mK ticks! Once this calibration was made, a sector was powered to 5 kA with the JT valves in an open loop adjusted to balance the static heat load. The normal signal to be expected during a current cycle is a slight

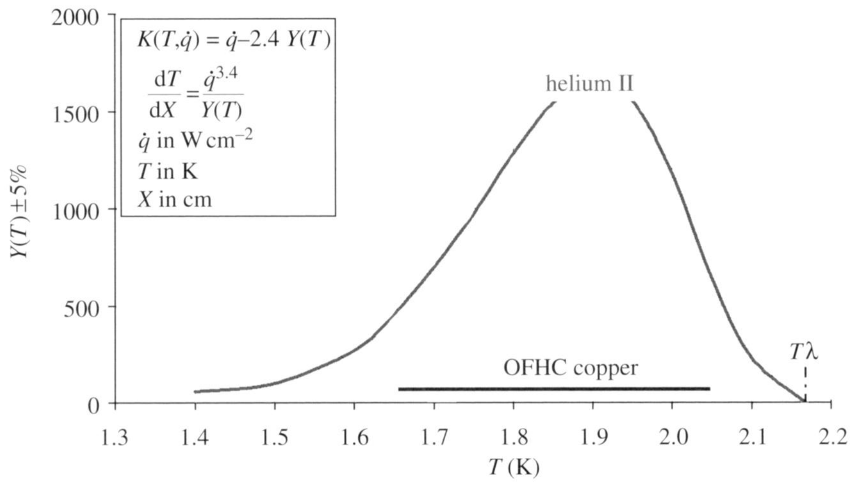

Figure 20. Equivalent thermal conductivity of He II. (Online version in colour.)

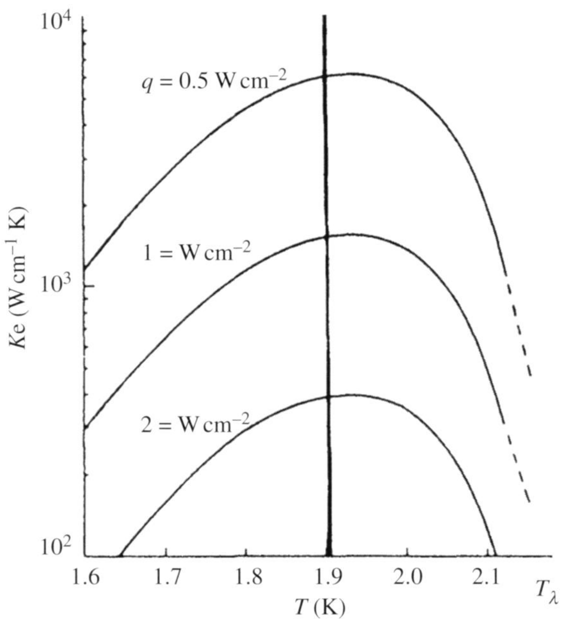

Figure 21. Effective thermal conductivity of He II.

heating during ramp and de-ramp owing to eddy currents and slow cooling on flat top. Figure 24 shows a cell in which this was not the case. The slow monotonic heating on flat top was consistent with a 100 nΩ resistance somewhere in the cell.

Every magnet is equipped with a card containing an analogue-to-digital converter and a buffer memory in order to measure voltages, usually on a trigger due to a quench. It was realized that these cards could also be used to

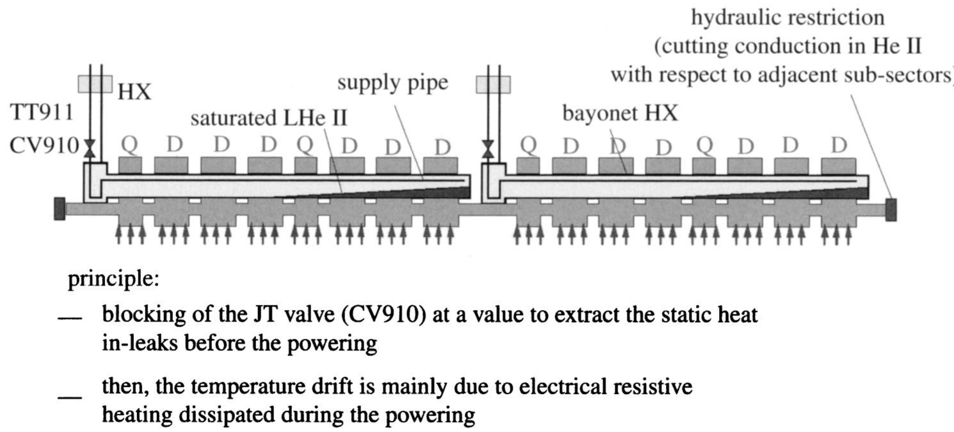

Figure 22. Sub-sector magnet cooling scheme. The system normally operates in a closed loop with the valve CV910 varied to keep the temperature constant. HX, heat exchanger. (Online version in colour.)

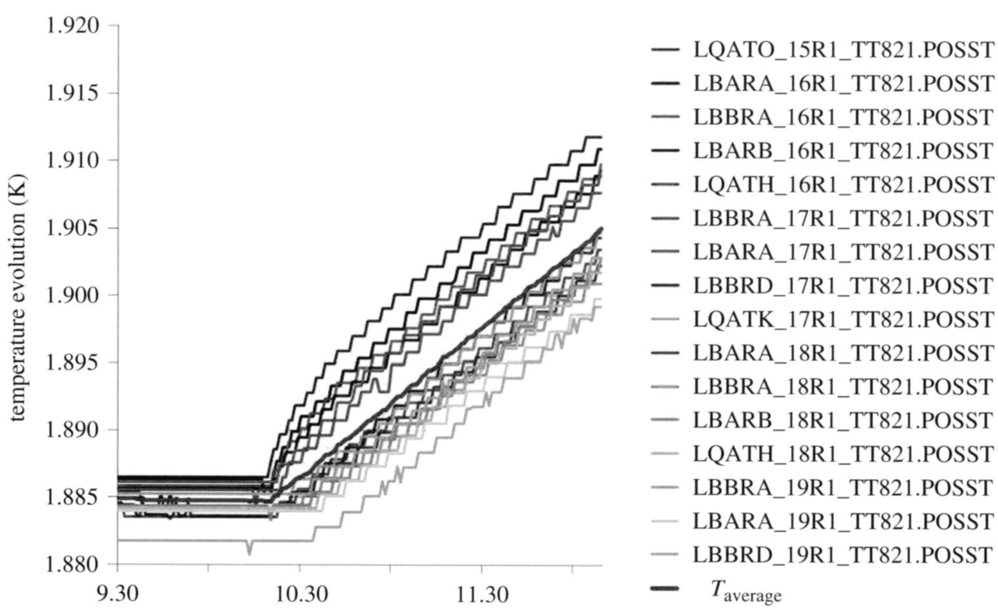

Figure 23. Experimental validation: temperature evolution. (Online version in colour.)

improve the signal-to-noise ratio in measuring voltages under DC conditions by averaging, thereby opening up the possibility of making ohmic measurements across each splice. Figure 25 shows just such a measurement of all the joints in the dipole chains of sectors 67 and 78 during a stepwise current ramp to 5 kA. In sector 67, there is one anomaly visible with a resistance of 47 nΩ. It was possible to locate exactly which splice was responsible. Both the 100 nΩ splice previously mentioned and the 47 nΩ splice were inside magnets which had

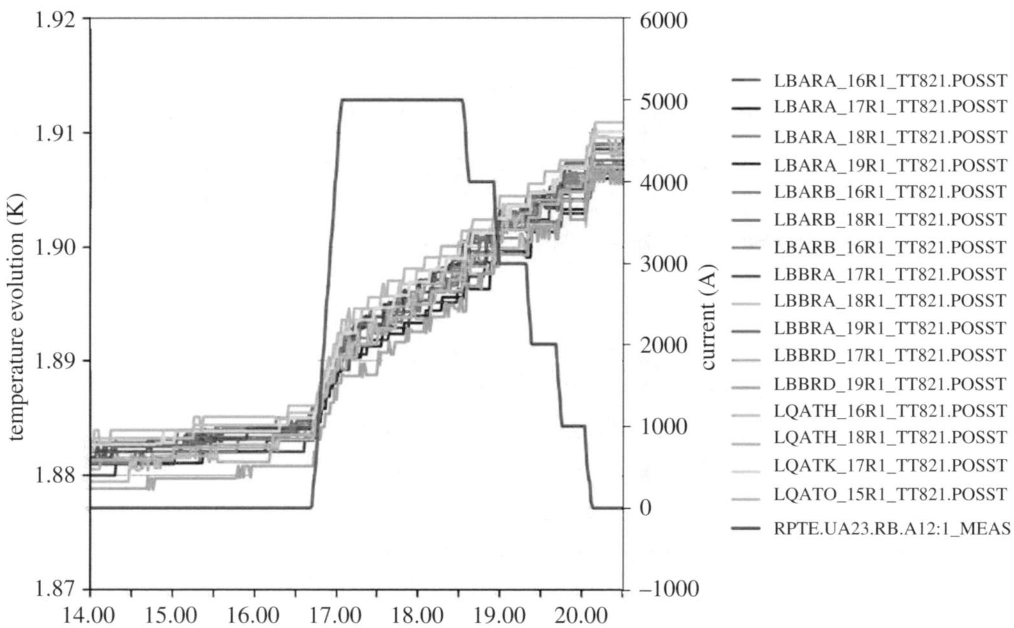

Figure 24. Powering example: 15R1 powering at 5000 A. The continuing rise in temperature during flat top indicates a resistive element of 100 nΩ. (Online version in colour.)

already been tested to full current. They have both been removed and the bad splices confirmed. No other such splices have been detected anywhere else in the machine.

However, during the removal of damaged magnets, it was discovered that, in some instances, solder had been leaking out of the interconnect joints during brazing, weakening the joints in case of a (very unlikely) bus bar quench. Consequently, it was decided to operate the LHC at reduced energy until additional consolidation can be made during a shutdown. This consolidation will consist of strengthening the interconnects, increasing the number of rupture discs in sectors where it has not already been done and reinforcing the jacks at the vacuum barriers so that they can take higher differential pressure in case of a very unlikely further incident of this kind.

11. Re-commissioning

The repairs and hardware re-commissioning took until November 2009. In the short time available until the end of that year, beams were accelerated to energy of 1.18 TeV, equivalent to a dipole current of 2 kA, and a small amount of physics data collection was done. On 30 March 2010, the first collisions were obtained at a centre-of-mass energy of 7 TeV. Since then, operating time has been split between machine studies and physics data collection.

The collimation system works very efficiently. Figure 26 shows a loss map around the ring obtained by provoking beam loss. The losses are located precisely where they should be, with a factor of 10 000 difference between the losses on the collimators and those in the cold regions of the machine.

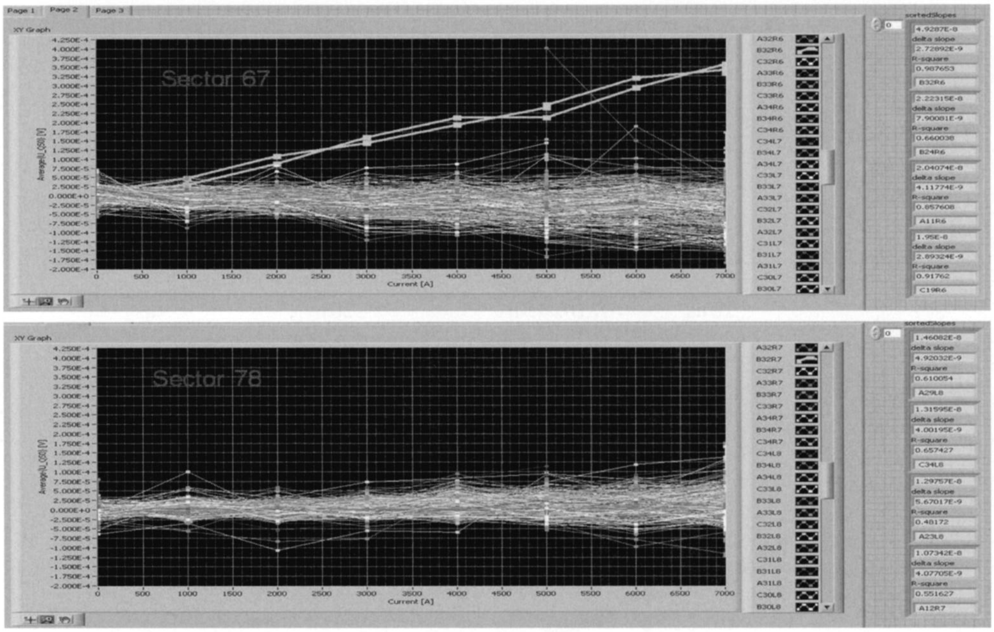

Figure 25. Snapshots in sectors 67 and 78 of all 154 dipoles during a current ramp to 5 kA—B32.R6 with a high (47 nΩ, top trace) joint resistance between the poles of one aperture. (Online version in colour.)

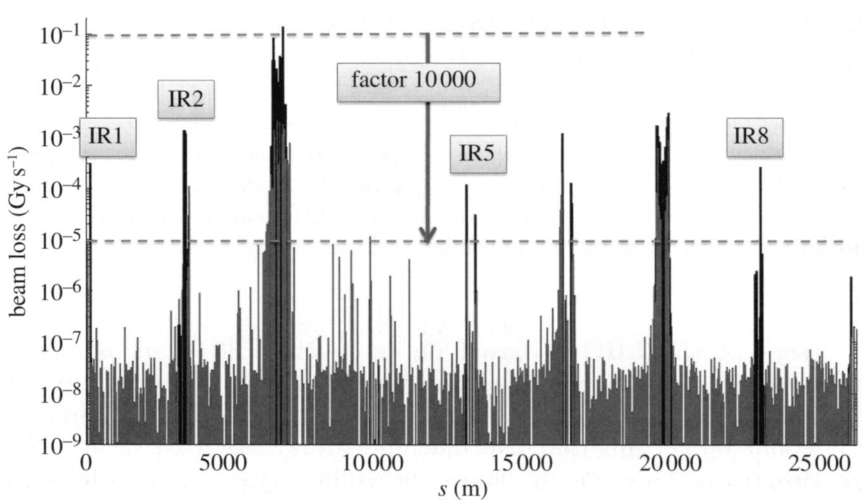

Figure 26. Loss maps for collimation. The peaks are at the locations of the primary collimators and secondary aperture restrictions. Blue lines, cold; black lines, collimator; red lines, warm. (Online version in colour.)

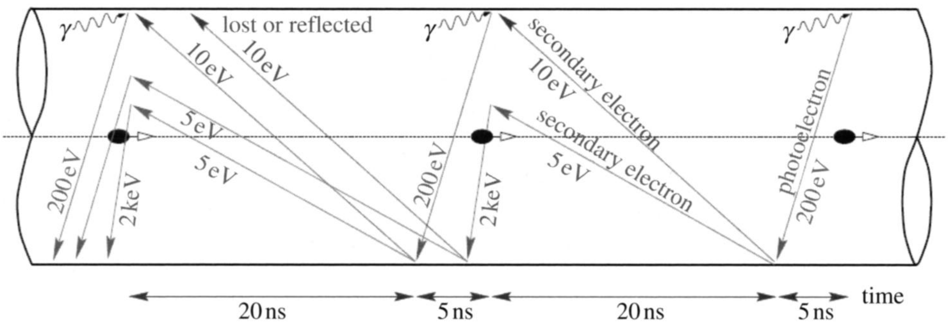

Figure 27. The electron cloud effect. (Online version in colour.)

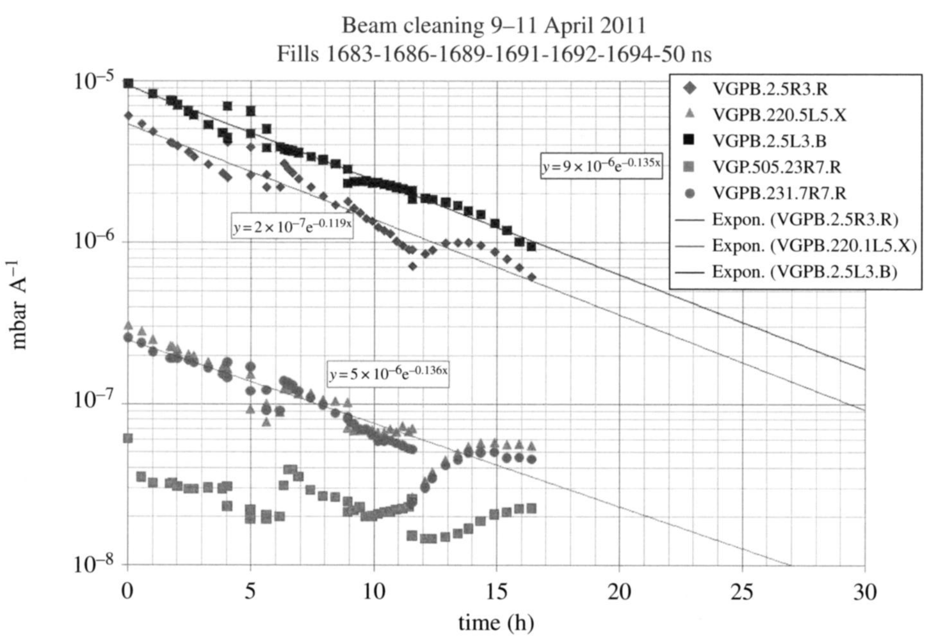

Figure 28. Improvement in vacuum pressure during 'scrubbing'. (Online version in colour.)

The design of the LHC is based on more than 30 years of accumulated knowledge of the behaviour of hadron storage rings. However, one new effect never before observed in hadron machines needed to be brought under control before it could be certain that the machine would reach its design objectives. This is the so-called electron cloud instability (figure 27), where electrons liberated by synchrotron radiation photons or ionization of residual gas are accelerated towards the wall of the beam tube owing to the electric field of the bunched beam. Secondary electrons can be resonantly amplified by following bunches, resulting in a thermal load on the cold beam pipe and instability. The cure foreseen was the conditioning of the beam pipe (scrubbing) by the electron cloud in order to reduce the secondary emission yield. Figure 28 shows the result of a 16 h scrubbing run, where the beams are allowed to circulate with an intensity just above the threshold of the electron cloud instability.

The reduction in electron activity can be observed as an order of magnitude reduction in vacuum pressure. After this treatment, the machine could operate at high intensity with a bunch separation of 50 ns.

The machine's performance at this early stage is very impressive. A single beam lifetime of more than 1000 h has been observed, an order of magnitude better than expected, proving that the vacuum is considerably better than expected and also the noise level in the RF system is very low. A nominal bunch intensity of 1.1×10^{11} has been achieved and the β^* at the experimental collision points squeezed to 1.5 m. The closed orbit can be kept to better than 1 mm r.m.s. with very good reproducibility. The number of bunches per beam is now being increased with the luminosity routinely exceeding $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

12. Conclusions

Building the LHC has been a huge task spanning more than 15 years from approval to operation. Initial commissioning with the beam went extremely smoothly. Circulating and captured beam were achieved in a record time. The two-in-one structure of the magnets works exactly as predicted. The machine's optics already look extremely good with the closed orbit corrected to less than 1 mm r.m.s. It has been shown that 'scrubbing' efficiently reduces the secondary emission yield of the beam screen to a point where the electron cloud instability can be controlled.

The unfortunate splice incident created a lot of damage that had to be repaired. Two powerful diagnostic tools have been developed to detect bad splices and to allow a permanent monitoring during operation.

The machine is now running for physics at reduced energy. Some further consolidation will be needed before it can be pushed up to full potential. This will be done in a long shut-down once an adequate amount of data at 7 TeV are collected.

The LHC is the most complex scientific instrument ever constructed. It has taken 15 years to build and many problems have been encountered on the way. These have all been overcome, thanks to the resourcefulness and resilience of the people who built it, both inside CERN and in our collaborating laboratories around the world. Now the machine is moving into its operational phase. I am confident that an equally competent team will exploit it to its full potential in the coming years.

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