The Large Hadron Collider LHC

Eberhard Keil
CERN, Geneva, Switzerland

ABSTRACT

The Large Hadron Collider Project LHC was approved by the CERN Council in December 1994. Commissioning with beam will start in the second half of 2005. The paper discusses the most important parameters, the general layout of the LHC octants, the status of the experiments ALICE, ATLAS, CMS and LHC-B, proton injection using the PS Booster, and the proton synchrotrons PS and SPS. Also described are the technical developments of the arc dipoles, the radio-frequency system, the vacuum chamber, cryogenics and the tests of half an arc cell.

I. INTRODUCTION

The LHC project was approved by the CERN Council in December 1994. A review of the project by Council will take place in June 1997. At that time a decision should be taken whether enough funds are available to construct the LHC in a single stage, as recommended by the LHC Management Board. The funds include contributions from non-member states. I assume for the remainder of the milestones that enough funds are available to construct the LHC in a single stage. By the end of 1999 most of the big contracts will have been placed, the prices will be known, and a final decision on the configuration can be taken. We assume that LEP will stop operation at the end of 1999. Dismantling LEP will start in October 2000 when the civil engineering work for LHC is advanced such that it becomes necessary to break into the tunnel, in particular for the ATLAS and CMS caverns. Injection tests are foreseen from October 2003. Commissioning with beam will start in the second half of 2005. The latest conceptual design report [1] for the LHC was issued in October 1995.

The remainder of this paper is organised as follows: Chapter II discusses the most important parameters, Chapter III the general layout of the LHC and the status of the experiments, Chapter IV the layout and optical functions of the low-β insertion near Pit 5. The proton injection into the LHC and the modifications to the injectors are described in Chapter V. Technical discussions of the super-conducting dipoles and their development are in Chapter VI. The radio-frequency system is discussed in Chapter VII, the vacuum chamber in Chapter VIII, cryogenics in Chapter IX, the tests of half an arc cell in Chapter X, and the civil engineering work in Chapter XI. The conclusions are in Chapter XII.

II. PARAMETERS

Tab. I shows several LHC parameters. The circumference C is that of LEP, and known to even more digits than shown. The maximum energy E is a round figure, achieved at the dipole field B listed. The bunch spacing s corresponds to 10 RF wavelengths. Together with the distance from the interaction point IP to the separating dipoles it determines the number of parasitic collisions, about 15 on either side of the IP. The bunch population N and the bunch radii σ_x and σ_y, shown at the interaction point IP, determine the beam-beam tune shift parameter ξ and the luminosity L. The full crossing angle Φ should be small to avoid the drop of luminosity at the head and tail of the bunches and the excitation of synchro-betatron resonances by the beam-beam collisions by having $\sigma_s\Phi \leq \sigma_y$, and large compared to the divergence σ'_y in order to achieve a good separation of the two beams at the parasitic collision points. The value of the beam-beam tune shift parameter ξ is determined from experience with other hadron colliders which were or are in operation [2]. The total beam-beam tune spread from the nearly head-on collisions and from all parasitic collision should be small enough to fit between nonlinear resonances of order up to twelve. Not all the space ℓ_{Q} between the IP and the magnetic front face of the nearest quadrupole is available to the experiments. At an assumed inelastic non-diffractive cross section for pp collisions $\sigma_{pp} = 60$ mb, the number of events in a single collision is $n_c = 19$.

Table I: LHC Parameters

Circumference C	26659	m
Energy E	7	TeV
Dipole field B	8.4	T
Bunch spacing s	25	ns
Bunch population N	10^{11}	
Bunch radius $\sigma_x = \sigma_y$	16	μm
Bunch length σ_s	75	mm
Beam-beam parameter ξ	0.0034	
Luminosity L	10	nb^{-1}s^{-1}
Full crossing angle Φ	200	μr
Distance to nearest quadrupole ℓ_{Q}	± 23	m
Events/crossing n_c	19	

III. LAYOUT AND EXPERIMENTS

The layout of the LHC is shown in Fig. 1. The pits are at the centres of the octants. The two LHC rings cross in Pits 1, 2, 5, and 8. The circumferences of the two rings are the same, since both rings have four inner and four outer arcs. The two large experiments, ATLAS and CMS, are diametrically opposite in Pits 1 and 5, respectively. Both are approved experiments with a cost ceiling of 475 MCHF each. Technical proposals were published in 1994 [3, 4]. The LHCC expects technical proposals for the subsystems. The heavy-ion experiment ALICE will be in Pit 2. The technical proposal for the core experiment [5] was published in 1995. The LHCC is waiting for the technical proposal for the muon arm. The LHC-B experiment is dedicated to

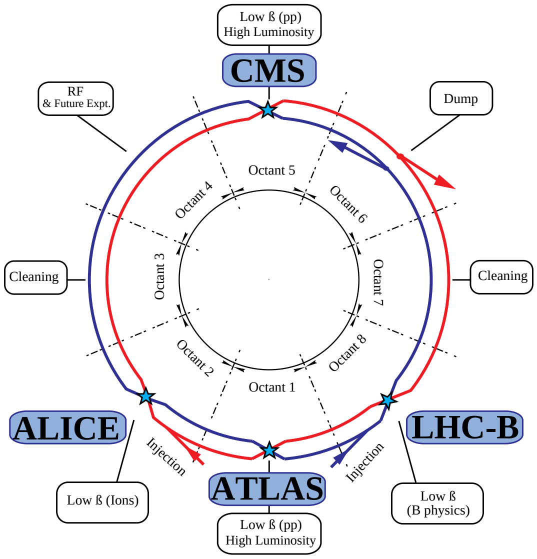

Figure 1: Layout and Experiments

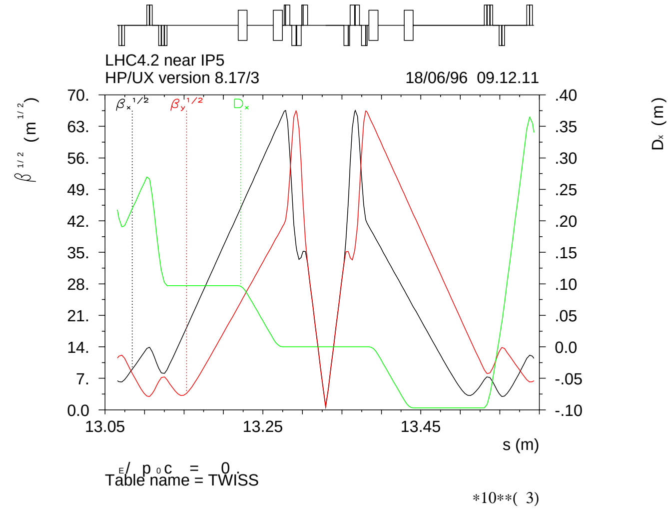

Figure 2: Layout and Optical Functions near Pit 5. The interaction point is close to the centre of the abscissa. The diagram above the graph schematically shows the horizontally focusing (defocusing) quadrupoles as rectangles above (below) the axis, and the separating dipoles as centred rectangles. The curves are the square roots of the horizontal and vertical amplitude functions in black and red and the horizontal dispersion in green.

the study of CP violation and other rare phenomena in the decay of Beauty particles. It uses colliding beams and a forward detector, contrary to the HERA-B experiment which uses a single beam and a gas jet target. A letter of intent [6] has been submitted to the LHCC. The LHCC wants an R&D programme for the detector. The two beams are injected into LHC into outer arcs upstream of Pits 2 and 8. The beam cleaning insertions to steer the beam halo into staggered sets of collimators rather than the super-conducting magnets are in Pits 3 and 7. Pit 4 houses the RF system. Pit 6 is reserved for the beam dumping system.

IV. INTERACTION REGION NEAR PIT 5

The mimic diagram at the top of Fig. 2 shows the LHC layout schematically for the straight section of about 500 m length in the neighbourhood of Pit 5. The low-β interaction point IP5 and CMS are close to the centre. On either side of IP5 is a quadrupole triplet, actually consisting of four quadrupoles, schematically shown as rectangles above the horizontal axis for horizontally focusing quadrupoles, and below for vertically focusing quadrupoles. Because of the antisymmetry designed into LHC, the first quadrupole of the triplet focuses horizontally on the left, and defocuses on the right, and similarly for all other quadrupoles. The distance between IP5 and the magnetic front faces of the nearest quadrupoles is ± 23 m. The centred rectangles behind the first triplet are the dipole magnets which first separate the two beams, and then make them parallel again at the correct distance of 194 mm at 1.9 K between the two apertures of most LHC magnets. Just before the end of the straight section there is a second triplet, consisting of seven quadrupoles. The curves in Fig. 2 show the optical functions $\sqrt{\beta_x}$ in black, and $\sqrt{\beta_y}$ in red. They are proportional to the horizontal and vertical beam radii. The antisymmetry of LHC makes them swap values when passing through IP5. Their values at IP5, $\beta_x = \beta_x = 0.5$ m, are too small to show clearly. Their maximum values in the first triplet are quite large. The green curve shows the horizontal dispersion D_x. It is matched to $D_x = D_x' = 0$ at IP5, and has asymmetric nonzero values behind the first separating dipoles. The layout and optical functions near Pit 1 are the same as those near Pit 5. The layout and optical functions near Pits 2 and 8 are very similar.

V. INJECTION

The proton bunches for LHC are injected first into the PS booster which operates with just one bunch in each of the four rings. For this, the PS booster will be equipped with two new RF systems, one operating at $h = 1$ and the other at $h = 2$, superimposed such that the bunches are made longer and the direct Laslett space charge detuning is reduced. The four bunches from the four booster rings are injected into the PS. Then the PS booster cycles again, and another batch of four bunches is injected into the PS, and accelerated to 26 GeV. At that energy, the PS beam is adiabatically debunched, and captured by a new RF system, operating at $h = 84$ and 40 MHz. From this moment onwards, the bunches have the LHC bunch spacing of 25 ns. Three of these PS beams are successively injected into the SPS, filling only 3/11 of the SPS circumference, and accelerated by a new RF system at 80 MHz with a circumferential voltage of 0.7 MV to 450 GeV. Just before ejection towards the LHC, another new RF system at 400 MHz with a circumferential voltage of 6 MV is adiabatically turned on to match the SPS bunches to the LHC buckets. One such cycle takes about 16.8 s. Repeating this sequence twelve times fills one of the LHC rings, and takes about three minutes. The acceleration in the LHC from 450 GeV to 7 TeV takes about 20 minutes.

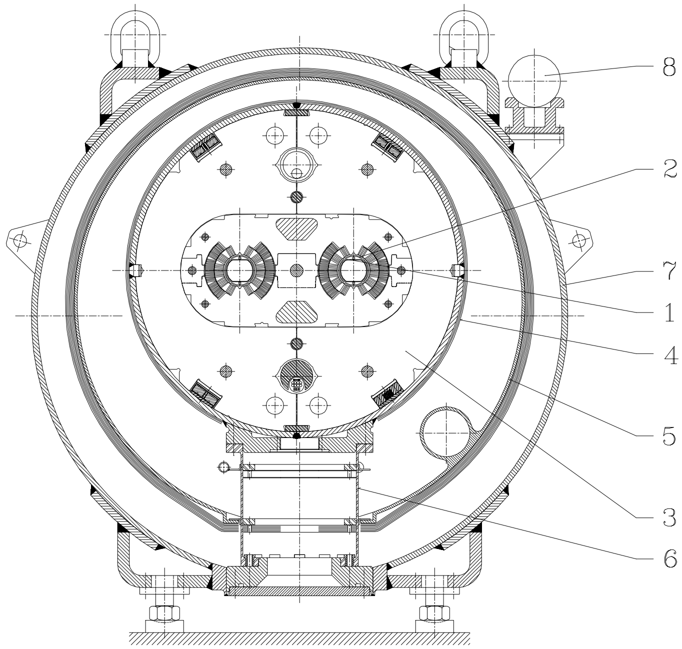

Figure 3: Cross Section of Dipole Magnet and Cryostat. 1. Beam screen, 2. Cold bore, 3. Cold mass at 1.9 K, 4. Radiative insulation, 5. Thermal shield at 55 to 75 K, 6. Support post, 7. Vacuum vessel, 8. Alignment target

VI. DIPOLES

The LHC dipoles occupy about 2/3 of the circumference. Fig. 3 shows their cross section [7]. The two apertures are in the same iron yoke and cryostat because the space in the tunnel does not allow two independent magnets and because a 2:1 design is cheaper. The space between the two apertures was increased from 180 to 194 mm in order to make their fields more independent and to reduce the collaring forces during their manufacture. Contrary to earlier designs, the cryogenic distribution line is no longer in the magnet cryostat. Only the cooling pipes with gaseous He at 50 K and 4.2 K for the intermediate heat shields, and the heat exchanger pipe at 1.9 K remain in the magnet cryostat. Its outer diameter was reduced to 914 mm. Cooling to this low temperature of 1.9 K is necessary to achieve the dipole field $B = 8.4$ T with super-conducting NbTi cable. The non-magnetic collars are made of aluminium. The field quality and its consequences for the LHC performance, in particular the dynamic aperture, are hotly debated between the magnet designers and my colleagues in accelerator physics [8].

So far, industry built seven and we tested six long dipole prototypes with 50 mm coil aperture and a length of 10 m, the nominal length when the orders were placed. The three best magnets, which had their first quench above 8.4 T and trained rapidly up to 9.6 T, are in the test string. The last one is being tested. Two prototypes with 56 mm coil aperture and the nominal magnetic length of 14.2 m are being constructed. The first magnet will be assembled in industry, the second at CERN, using collared coils produced in industry. The cold mass of the first of these magnets is expected in March 1997. Tests are foreseen in June 1997. A further four 10 m dipoles with 56 mm coil aperture are also in the pipeline, because the tooling for 10 m dipoles exists at several companies. In parallel to the long magnets, a programme of 1 m models is under way at CERN [9]. Its aim is studying the influence of individual coil parameters on the magnet behaviour with a fast turn around rate and qualifying possible design solutions. So far, eight single-aperture models were produced, at a rate of about one per month. The models tested so far show that at 2 K a field of 8.9 T can be reached for the first natural quench. Common to all models is a gradual training above this field level. A twin-aperture model with the same cross section as the long dipoles, now being fabricated in industry, will be completed and tested by the end of 1996. The cable insulation with polyimide tape was decided. Research and development programmes are under way on the super-conducting cable to increase the uniformity of the inter-strand contact resistance and on current leads made of high T_c super-conductors.

VII. RF SYSTEM

The RF system is housed near Pit 4. There are now two separate RF systems for the two rings instead of a common one. Separating dipoles increase the distance between the two LHC rings to 420mm, such that the vacuum chamber for one ring passes outside the helium tank, but inside the cryostat insulation vacuum of the RF cavities for the other ring. Transient beam loading dominates the design of the RF system, caused by the high beam current and the presence of long gaps in the circulating beam. Having two RF systems makes the control of transient beam loading much more robust, especially at injection where it is needed most. The complete RF system for one ring consists of eight single cell, wide beam tube aperture cavities, grouped by pairs in common cryostats. The mechanical design of the cryostats, largely dominated by the cavity tuning requirements (strong axial forces, absence of vibrations) is under revision. The main RF couplers and the higher-order-mode (HOM) couplers are located on the wide beam tubes, near the cavities. The outer diameter of the main coupler coaxial line has been increased, compared to that of LEP, to avoid more of the dangerous multipacting zones. The design of the HOM couplers is dominated by their power extraction capability, rather than by beam instability requirements. Nevertheless beam feedback systems, longitudinal and transverse, are essential to guarantee LHC performance. Four 200 MHz copper cavities are used as longitudinal kickers. Electrostatic deflectors are used for the transverse planes.

VIII. VACUUM CHAMBER

Fig. 4 shows one of the beam apertures. The coil aperture is now 56 mm. Just inside, still at 1.9 K, is the vacuum chamber with outer and inner diameters of 52 and 49 mm, respectively, made of stainless steel. Just inside the vacuum chamber is the beam screen which now has a racetrack shape with an inner horizontal diameter of 44 mm and a height of 36 mm. The purpose of the beam screen is absorbing the synchrotron radiation power, about 0.2 W/m from one nominal beam, at 5 to 20 K, using gaseous helium flow through the cooling pipes shown in Fig. 4, since the heat load at 1.9 K would be excessive. The beam screen is supported every 1.7 m. The synchrotron radiation photons will desorb gas molecules from the beam screen which will then be deposited on the screen by cryopumping. To avoid building up a gas layer on the beam screen, and deteriorating the vacuum, the beam screen has pumping slots in the straight top and bottom parts through which the desorbed gases can diffuse to the vacuum chamber walls where they are cryopumped again, but this time at 1.9 K where vapour pressure effects are negligible and the risk of being desorbed by the synchrotron radiation is absent. The electro-magnetic impedance of these slots has been the subject of intense studies [8, 10]. The beam screen is made of a high Mn content stainless steel to give a low magnetic permeability, and coated on the inside with 50 μm of copper in order to reduce its resistive impedance and associated heat load.

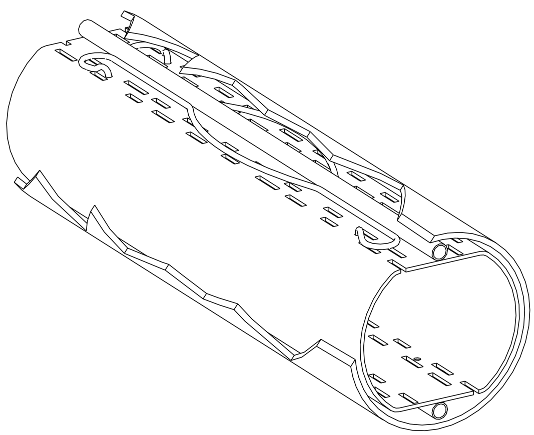

Figure 4: Cut-away drawing of the LHC vacuum chamber, perforated beam screen, cooling pipes and support springs.

IX. CRYOGENICS

The super-conducting magnets are immersed in a bath of super-fluid He at 1.9 K, pressurised at about 1 bar. The heat is transferred by heat exchangers, consisting of a tube containing flowing saturated He II, and running through a half cell of the LHC arcs. It was checked in the string tests, that the liquid and gaseous He may flow in the *same* or in the *opposite* direction in this tube. The LHC tunnel is inclined with respect to the average vertical by at most 14.2 mr. Allowing He flow in either direction avoids the complication of changing the orientation of the cooling loop whenever the tunnel slope changes sign. Contrary to earlier designs, the cryogenic fluids are supplied by a separate cryogenics line which runs along the tunnel walls and is connected to the cryostats every half cell. The cryogenics supply line is fed from the four even-numbered pits where much equipment is available from LEP2 [12].

In collaboration with CEA in France, key technologies for high-capacity refrigeration at 1.8 K are being developed [11]. This includes very low pressure heat exchangers, cold volumetric and hydrodynamic compressors to be used as components of practical and efficient thermodynamic cycles. Prototypes of such machines from European industry were tested in the laboratory.

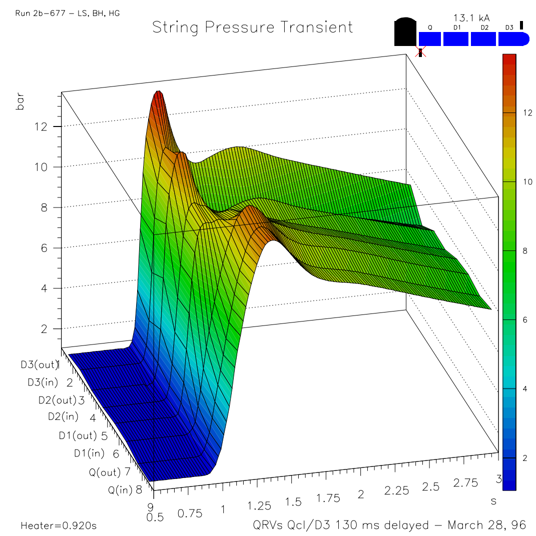

Figure 5: Pressure rise in dipole string tests during a quench. The right axis is the time in seconds. The left axis shows several points along the string. The ordinate is the pressure in bar.

X. STRING TESTS

The LHC test string [13] consists of a quadrupole of 3 m length and three dipoles of 10 m length each, the cryogenic equipment needed to supply the magnets with cryogenic fluids and gases, the cryogenic valves and short circuits for the electrical bus-bars, the power converters for the magnets, and control and diagnostic equipment. The test string has been in operation for eighteen months, with more than 6000 hours at 1.8 K. It was cycled 1210 times, simulating several years of routine LHC operation. Its purpose is the experimental validation of the cryogenic cooling scheme and the development of the quench detection and magnet protection systems. The 1.8 K cooling with super-fluid helium was tested in steady state conditions and during transients. Much was learned on quench detection and magnet protection from the 11 natural and 64 provoked quenches so far; 35 of them occurred at or above the nominal field. In addition, there were about 15 quenches in the magnets *before* they were installed in the string. The temperature increases during ramping upwards at 10 A/s and downwards at 130 A/s were 6 mK and 50 mK, respectively, small enough not to quench the magnets. Simulating a heat load due to particle losses at 1 W/m caused temperature increases less than 30 mK. The pressure rise during quenches was measured for various configurations of pressure relief valves, and for various delays in opening them, and is shown in Fig. 5. This made us reduce the number of pressure relief valves from four to two in a half cell. The delays in opening the pressure relief valves are long enough that commercially available valves can be used. The string is installed on a slope simulating the slope of the tunnel.

By reversing the flow of liquid He, the flow of liquid and gaseous He in the *same* and *opposite* direction was tested, and both were found to be possible. This makes the layout of the cooling loops independent of the local slope of the tunnel.

XI. NEW CIVIL ENGINEERING

The new civil engineering needed for the LHC is shown in red in Fig. 6. The existing LEP tunnel and associated underground building is shown in bright grey. The new civil engineering is concentrated around the interaction points. New caverns and access shafts are needed for the ATLAS and CMS experiments in Pits 1 and 5. The ATLAS cavern is so large that the CERN Main Building would fit into it. Less work is needed in Pits 2 and 8 where caverns and shafts already exist. New transfer tunnels are needed from the SPS to the LHC; TI2 for the clockwise and TI8 for the anti-clockwise beam, respectively. The transfer lines will be equipped with room temperature magnets. The tunnels for the beam dumps near Pit 6 are also new.

XII. CONCLUSIONS

Since the publication of [1] progress was made in many areas of the LHC design. There still are many ongoing studies of which I only mention a few. My colleagues in accelerator physics study the effects of the errors of the magnetic fields in the super-conducting magnets on the dynamic aperture, mostly by computer simulation, i.e. tracking. These errors are caused by the arrangement of the coils, by fabrication tolerances, amplified by the 2:1 design, and by persistent currents at the injection field of only about 0.5 T. etc. We are also concerned about designing an LHC lattice which is robust enough to be operated with ease. Apart from the dipoles, other magnets need to be built. The insertion quadrupoles are particularly challenging, because the large beam size and the high sensitivity of the beam to their errors. Studies of the super-conducting cable continue to find a cable which is mechanically stable and has a high and uniform inter-strand contact resistance.

XIII. REFERENCES

[1] The LHC Study Group, LHC – The Large Hadron Collider – Conceptual Design, CERN/AC/95-05 (LHC) (1995).

[2] E. Keil, Beam-Beam Effects in Electron and Proton Colliders, Particle Accelerators **27** (1990) 165.

[3] ATLAS: Technical Proposal for a General-Purpose pp Experiment at the Large Hadron Collider at CERN, CERN/LHCC/94–43 (1994).

[4] CMS: The Compact Muon Solenoid – Technical Proposal, CERN/LHCC/94–38 (1994).

[5] ALICE – Technical Proposal for A Large Ion Collider Experiment at the CERN LHC, CERN/LHCC/95-71 (1995).

[6] LHC-B: A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation, CERN/LHCC/95-5 (1995).

[7] N. Siegel, Status of the Large Hadron Collider and Magnet Program, presented at the Applied Super-conductivity Conference 1996, Pittsburgh/USA, 26 to 30 August 1996.

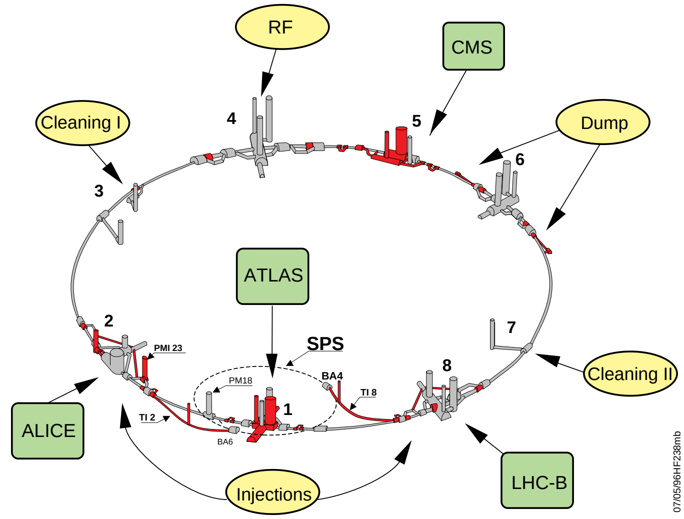

Figure 6: New Civil Engineering. The existing LEP tunnel, experimental halls and access shafts are shown in bright grey. The new experimental halls for ATLAS and CMS with their access shafts, the new transfer tunnels and the new beam dump tunnels are shown in red (or dark grey in the printed version).

[8] J. Gareyte, Accelerator Physics Issues of the LHC, EPAC 1996 (LHC Project Report 10, June 1996).

[9] N. Andreev *et al.*, The 1m Long Single Aperture Dipole Coil Test Program for LHC, EPAC 1996 (LHC Project Report 25, July 1996).

[10] F. Ruggiero, Single-Beam Collective Effects in the LHC, CERN SL/95-09 (AP) (1995).

[11] Ph. Lebrun, L. Tavian, G. Claudet, Development of Large-Capacity Refrigeration at 1.8 K for the Large Hadron Collider at CERN, Proc. KRYOGENIKA'96, Praha (1996) 55 (LHC Project Report 6, May 1996).

[12] V. Benda *et al.*, Conceptual Design of the Cryogenic System for the Large Hadron Collider (LHC), EPAC 1996 (LHC Project Report 12, July 1996).

[13] A. Bézaguet *et al.*, The LHC Test String: First Operational Experience, EPAC 1996 (LHC Project Report 32, July 1996).