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The Large Hadron Collider (LHC) project of CERN

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Abstract

The Large Hadron Collider (LHC) was approved by CERN's Council in December 1994 and a conceptual accelerator design published in October 1995. The LHC will provide proton-proton collisions of 7 TeV + 7 TeV with a luminosity of up to 10^{34} cm^{-2}s^{-1}, at two collision points and lead-ion collisions with a total centre of mass energy of 1148 TeV and a luminosity up to 10^{27} cm^{-2}s^{-1}. In this paper the status of the collider project will be described with emphasis on the latest developments. The experimental programme of the LHC is also in the process of being defined and is expected to include a dedicated heavy-ion detector, ALICE, and a specialised B-physics spectrometer, LHC-B, as well as the already approved, high luminosity, general purpose detectors, ATLAS and CMS. A description of the experimental areas foreseen for these experiments will be given.

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1 Introduction

The CERN Council of nineteen European countries approved the LHC project in December 1994. For financial reasons it was approved on the basis of a two stage machine with first colliding beams in 2004, but at a lower energy using a missing magnet scheme. Full energy would not be achieved before 2008. It was decided, however, that the detailed construction schedule would only be formally approved in 1997, when it will be known how many non-member countries have responded to the CERN Council's invitation to join the project. If the required funds were available it might be possible to have 7 TeV proton beams colliding much earlier than 2008.

The proposal now being prepared by the CERN management for presentation to Council at the end of this year follows this approach and will propose a single stage construction to achieve full energy collisions before the end of 2005. This plan reflects the progress which has been made in negotiating special agreements with non-member countries and the consequent financial plan. Recent work on the details of this schedule suggests that from a technical point of view this is perfectly feasible for the collider and the experiments, including the construction of new large experimental areas. It is assumed that LEP will stop at the end of 1999 although the schedule for LHC construction does not foresee any major interference with the LEP tunnel before October 2000. According to this schedule, while civil engineering starts in 1998 the main production run of cryomagnets only starts in 2001 following a two year period for a pre-series. An interesting milestone will be an injection test into the first two octants to be completed, from access point P2 to P4. According to the present planning this will take place before the end of 2003.

The conceptual design of the LHC has been considerably refined and a new design report published in October 1995 [1]. The detailed engineering is now underway and the first substantial contracts have been placed, notably for the civil engineering design consultants. The layout of Fig. 1 has been carefully adapted to accommodate the initial experimental programme. This will consist of the two general purpose detectors ATLAS [2] and CMS [3], both of which are now approved, a dedicated heavy-ion detector ALICE [4], and a specialised B-physics detector LHC-B [5]. The two high luminosity experiments will be placed opposite each other in new areas to be constructed at access points 1 and 5, while both ALICE and LHC-B will make use of existing experimental caverns, at P2 and P8 respectively.

2 Performance and parameters

The performance aims for the LHC remain almost identical to those previously reported [6], (see Table 1) although a number of design decisions have been taken to save money and increase performance margins, offering a greater chance of reaching design performance on the planned time scale. For example, the symmetric arrangement of the two high luminosity experiments combined with the increased bunch spacing of 25 ns is expected to help limit the so called "beam-beam effect". The electromagnetic forces which an individual proton suffers each time it passes through the other beam at a collision point are extremely non-linear and result in tune shifts and spreads which are difficult to control. These effects are expected to be the principal LHC performance limitation. The design luminosity per collision point remains 10^{34} cm^{-2}s^{-1}, but the ultimate value could be twice as high. A second, extremely important increase in the safety margins has been achieved by redesigning the magnet lattice in such a way as to increase the total length of the twin aperture dipoles fitted into the arcs of the LEP tunnel. For 7 TeV proton beams a magnetic field of only 8.4 T is now needed. This "version 4" optics is based on 23 regular

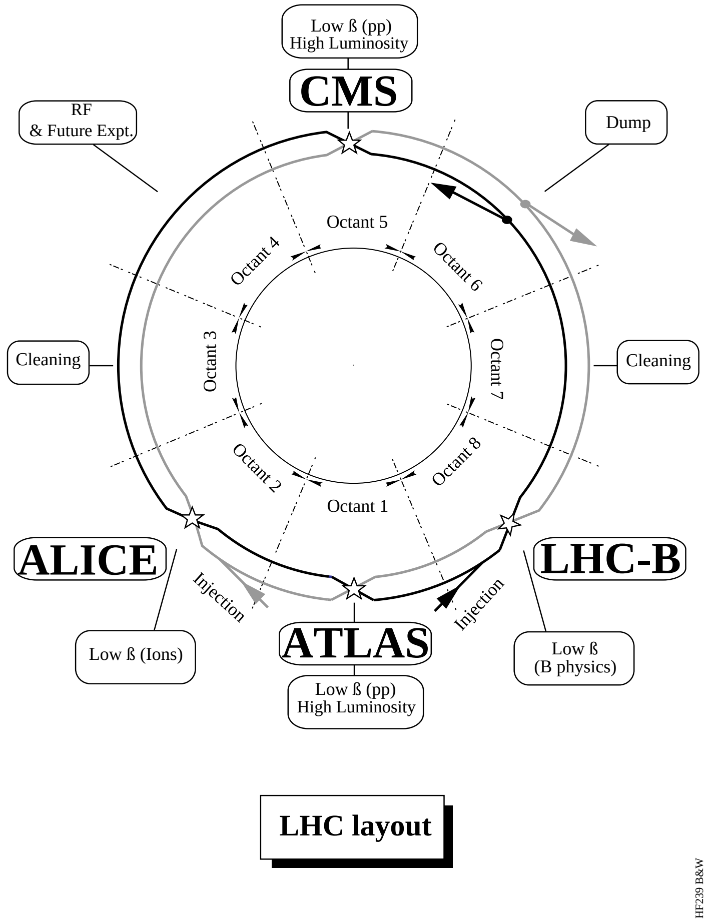

Figure 1: A schematic layout showing the assignment of the eight long straight sections of the LHC to experiments and utilities. The access points referred to in the text are in the centre of each octant, hence ATLAS will be at P1, ALICE at P2, CMS at P5 and LHC-B at P8.

lattice periods in each of the eight arcs. Each half-period consists of three two-in-one dipoles with magnetic lengths of 14.2 m and a two-in-one 3.1 m long quadrupole with a field gradient of 230 T/m. The coil aperture of these magnets is 56 mm. Further flexibility has been obtained by powering separately the dipoles and quadrupoles.

A number of multipole correctors are integrated into the short straight section containing the quadrupole and each dipole contains short sextupole and decapole correctors to compensate unwanted field harmonics. The nominal phase advance is 90 degrees per cell although a tuning range of a few units will be possible. This will also allow split vertical and horizontal tunes to help control betatron coupling.

Injection of 450 GeV protons from the CERN SPS will be immediately upstream of P2 for the clockwise rotating beam and P8 for the opposing beam. The whole chain of injectors already exists and recent beam studies have shown that the performance required is within reach. Indeed it is expected that commissioning of the LHC will profit from the availability of much lower emittance beams at lower intensities. These smaller cross-section beams are expected to allow useful luminosities of around 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to be reached, even if beam intensities are initially limited operationally by magnet quenches or for any other reason [7].

		Protons	Pb-Ions
Centre of mass total energy	TeV	14	1148
Magnetic field in bending magnets	T	8.4	8.4
Initial luminosity per collision region	$cm^{-2}\ s^{-1}$	10^{34}	2×10^{27}
Number of bunches per beam		2835	608
Bunch spacing	m — ns	7.5 — 25	37.4 — 124.8
No. of particles per bunch		10^{11}	9.4×10^{7}
Number of collision regions assumed		2	1
Beta parameter at interaction point	m	0.5	0.5
r.m.s. beam radius at collision point	μm	16	15
r.m.s. collision region length	cm	5.4	5.3
r.m.s. energy spread σ_E/E		1.1×10^{-4}	1.1×10^{-4}
Beam crossing angle	μrad	200	$\leq$100
Luminosity lifetime	h	10.0	6.7
Stored beam energy	MJ	334	4.8
Synchrotron radiation (per beam)	kW	3.6	

Table 1: Main LHC parameters

3 Engineering layout

The layout of machine utilities and experiments to be installed in the eight straight sections of the LHC has now been frozen with most of the decisions emerging during cost optimisation (Fig. 1). The two high luminosity general purpose detectors ATLAS and CMS will be installed opposite each other in new underground areas at P1 and P5. ALICE will be installed in the existing LEP experimental facilities at P2, while the spectrometer of LHC-B will be installed at P8. In order to make best use of the existing cavern at P8 it is planned to displace the normal collision point by 11.2 m in which case the 18 m long spectrometer of LHC-B will just fit into the cavern presently occupied by the LEP experiment DELPHI. The optics of the insertion were easily adapted to this displacement and the effect of the asymmetry on the beam-beam effect has also been studied. Only at these four points (P1, P2, P5 and P8) will the LHC beams, which are side by side with a separation of 194 mm in the arcs, cross over from the inner to the outer arc or vice versa. At the other four points, machine utilities can be installed without the need to bring the beams into a common vacuum pipe, thus avoiding the need for expensive bending magnets.

The insertions required to focus the beams down to a beta* of 0.5 m at the collision points have not fundamentally changed and are similar in all four experiments although the space between the inner triplets is slightly more at P1 and P5 than at P2 and P8. The design of the large single aperture high gradient magnets of the inner triplet has advanced well and earlier this year an industrially built short model using a graded coil with an aperture of 70 mm wound from NbTi cable achieved the required gradient of 250 T/m when cooled to 1.9 K. Progress has also been made on the engineering of this very important region both from the point of view of the machine requirement to align the magnets correctly and maintain their stability and measures to control the energy deposition by secondary particles from the interaction region. Definition of the shielding at the interface of the machine and experimental area, required to reduce backgrounds in the muon chambers of the detectors while allowing access during shutdowns, has also advanced.

The insertions with machine utilities have all been redesigned around two parallel beam lines. The straight sections around P3 and P7 will be used for the very important beam cleaning sections; systems of collimators which will ensure that all particles which fall outside the dynamic aperture of the machine in any of the six dimensions of phase space, will be safely removed and absorbed in suitable shielding. If these halo particles were to be allowed to circulate until they struck the vacuum pipe near superconducting magnets they would deposit their energy in the coils and cold masses of the magnets causing superconducting to normal transitions, or "quenches". The efficiency to be achieved in these cleaning sections is of order 99.9%, as the LHC halo is expected to be fed by 10^9 protons per second, while as few as 10^6 may cause a quench.

Two beam halo cleaning insertions are foreseen, both using a FODO lattice of classical magnets with a dogleg at either end where the beam separation is increased from 194 to 224 mm. These insertions will be equipped with two stage collimator systems consisting of three scattering blocks at each stage, designed to remove the betatron halo in P3 and off-momentum particles in P7. The doglegs are required to prevent off-momentum particles from inelastic interactions in the collimator blocks being lost in the adjacent superconducting machine elements.

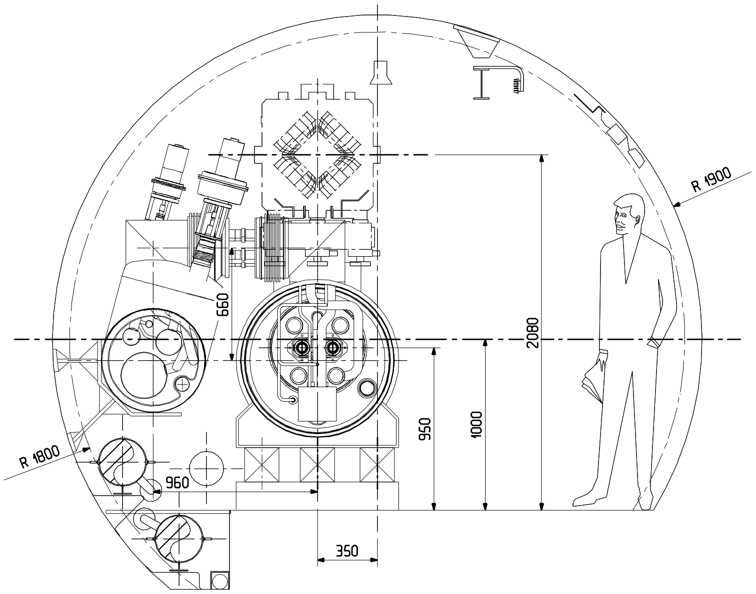

Figure 2: A cross-section of the machine tunnel with the twin aperture superconducting magnet of the LHC installed below a LEP quadrupole. The separated cryogenic feed-line and connecting valve box, new developments, can be seen on the left.

This very efficient beam cleaning will also mean that the LHC experiments should have very little problem with beam induced background and indeed preliminary estimates suggest that background from beam losses of any sort, including beam gas collisions will be at the level of a few percent of backgrounds generated by a collision luminosity of

10^{34} $\mathrm{cm^{-2}s^{-1}}$. As an example the peak rates of muons from all beam loss sources in the muon chambers of CMS will not exceed a few muons $\mathrm{cm^{-2}s^{-1}}$ [7, 8].

The RF accelerating system, consisting of eight 400.8 MHz superconducting cavities per beam, will be installed in a special insertion at P4. The beams will be separated to be 420 mm apart so as to allow the installation of separate superconducting cavities for each beam. Initially only one set of cavities common to the two beams was foreseen, but a separate system on each beam reduces the beam loading effects on the cavity power couplers and gives a considerably increased operating flexibility. In particular it will allow the LHC to collide protons against heavy ions, if required. The cavities have been placed at the ends of the straight section in such a way as to leave the central region clear for an additional collision region and experiment if necessary. Since the beams do not cross at P4 a scheme with additional bending magnets to bring the beams together into one vacuum chamber and back out again will be required if collisions are needed for an additional experiment.

At the end of LHC colliding beam runs the beams, which will have total energies of up to 334 MJ, must be safely extracted and absorbed in external beam dumps. The beam abort system will be installed at P6 where it will require the full straight section to reliably and cleanly extract each beam with a system of horizontally deflecting fast kicker magnets and a vertically deflecting double Lambertson septum magnet in the centre of the straight section. A 3 μs gap left in the bunch train of each beam will be sufficient for the rise time of the kickers and with the proper synchronisation will ensure that no particles strike the septum. The dump blocks will be placed in special caverns alongside the arc tunnel some 750 m downstream of the septum magnet. To limit the local energy deposition in the carbon core of the dump blocks to reasonable values the 80 μs long bunch train will be swept over the front face of the block by a pair of orthogonally deflecting kicker magnets.

4 Magnets and cryogenics

The dipole field of 8.4 T required for a beam energy of 7 TeV is fairly comfortably below the values being routinely achieved in industrially produced prototypes of the main bending magnets. The R & D programme for these magnets, which have twin-apertures and use niobium-titanium alloy superconducting cable cooled to 1.9 K, still has some time to run, but the design team is now very confident that all 1232 of the final dipoles will achieve 9 T, providing a margin with respect to routine operation which is vital if the collider is to operate reliably with good efficiency for particle physics experiments.

As a result of a highly successful first “string test”, in which two and now three of the first 10 m long dipole magnets and a prototype quadrupole are being operated together in a 45 m long “string”, very similar to a half-cell of the regular lattice, there have been a number of changes made to the mechanical and cryogenic layouts of the LHC. In order to avoid having to excavate new underground equipment caverns, all cryogenic equipment has been clustered into existing structures at the even numbered points. Systems tests on the string have shown that this will be perfectly feasible, with a separate cryogenic feed line. It had previously been thought that the most economic solution would be to integrate all feed-lines into the magnet cryostat, but a separate line (Fig. 2) which now becomes possible and economic, has many obvious engineering and operational advantages. In particular because it separates the cryogenic system from the magnet system and therefore simplifies installation and commissioning.

The string test is now operating routinely at fields of 9 T and is continuing to give very valuable information on the operation of the cryogenic, powering, control and vacuum systems. The string can be ramped up to full design current and down again in less than one hour and repetitive cycling is being interleaved with other tests. It is hoped to achieve two thousand cycles, equivalent to about ten LHC years, for the systems involved. A second phase string test using the next generation of long prototypes and a separate cryoline and hence even closer to the final LHC configuration is now being planned for 1998.

The most visually obvious difference in the proposed tunnel cross-section (Fig. 2) results from the decision to place the heavy LHC cryostats on the floor of the tunnel and reinstall, when required, the much lighter LEP magnets above them, in an arrangement better adapted to a second stage electron-proton collider.

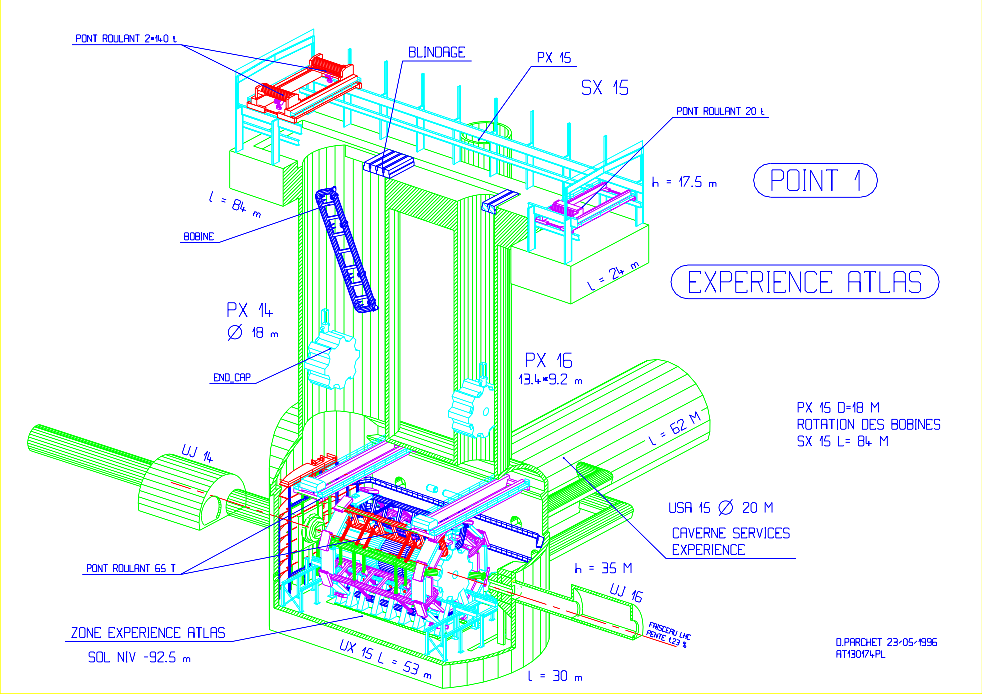

Figure 3: The new cavern and surface building at P1 for ATLAS

5 Experimental areas

Some of the first excavations and construction work will be for the new experimental areas at P1 and P5. The cavern and surface facilities needed for ATLAS are illustrated in Fig. 3, where it can be seen that a recent decision to lower the coils of the barrel toroid individually and in an almost vertical orientation has allowed the reduction of the largest access shaft to only 18 m diameter. This has reduced construction costs and simplified the engineering, reducing risks of unforeseen expenses or delays. The assembly of the toroids in the underground cavern also reduces the need for on-site halls; another substantial cost saving. Installation of the ATLAS magnet system will take longer than initially foreseen, but as the underground cavern can be completed three years before commissioning in 2005, adequate time should be available.

One of the very first surface building to be visible will be the very large assembly hall at P5 for the CMS solenoid (Fig. 4). This hall will be large enough and available early enough for the complete construction and testing of the 14,000 ton solenoid on

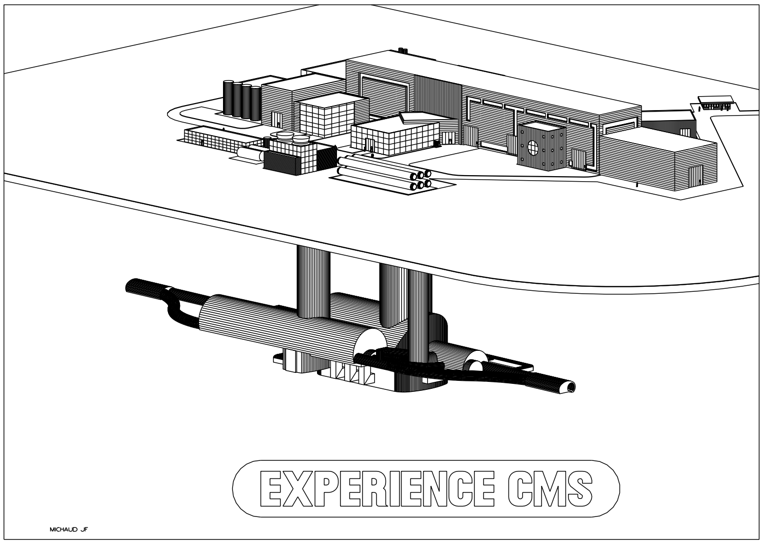

Figure 4: A schematic of the surface assembly hall and underground caverns to be constructed at P5 for CMS

the surface. When the underground cavern becomes available, early in 2003, the magnet will be lowered in only seven major pieces using a temporary gantry crane. Once all the heavy pieces are installed 100 m underground, not only will the crane be removed but the assembly hall will be reduced in height and length by almost 30% in each case. This will reduce the environmental impact considerably and make the final hall comparable to those on the LEP sites.

At both P1 and P5 the new excavations include service caverns to house equipment and racks close to the detectors with sufficient radiation shielding to allow permanent access. In order to minimise the additional shielding extensive modelling of the 14 TeV collisions and self-shielding of the detectors has been carried out [10, 11] using FLUKA [12]. For both ATLAS and CMS the radiation protection shielding is dominated by the continuous dose rates resulting from a collision point with a luminosity of 10^{34} cm^{-2}s^{-1}, but the self-shielding of the detectors is considerable and taking it into account has led to considerable economies.

Elsewhere the shielding is generally determined by an accidental beam loss which has also been studied [13], in the many different configurations which occur around the ring . The reinforcement of the 1 m equivalent of concrete shielding, which is adequate for LEP, up to at least 4 m equivalent, is one of the more difficult aspects of reusing the LEP tunnel for a new hadron machine. In fact the groups responsible for the different systems of the machine have all accepted that access underground, during operation with beams, will not be possible. All underground equipment must operate reliably and remotely with access only possible between runs. This is clearly unacceptable for the experiments, but permanent access to counting rooms has not been easy to arrange, in particular, for the existing caverns at P2 and P8.

ALICE will use the P2 cavern with almost no modification. It will, however, be necessary to add a substantial shield around the beam line under the existing counting rooms in the shaft PX25 (Fig. 5). As the machine cryogenics will be installed in a new cavern at the foot of the existing, but unequipped shaft, PGC2, use will also be made of the new zone to give improved access to the muon-arm side of the detector and to house cryogenics, alignment and other equipment. The plans for the installation of the LHC-B

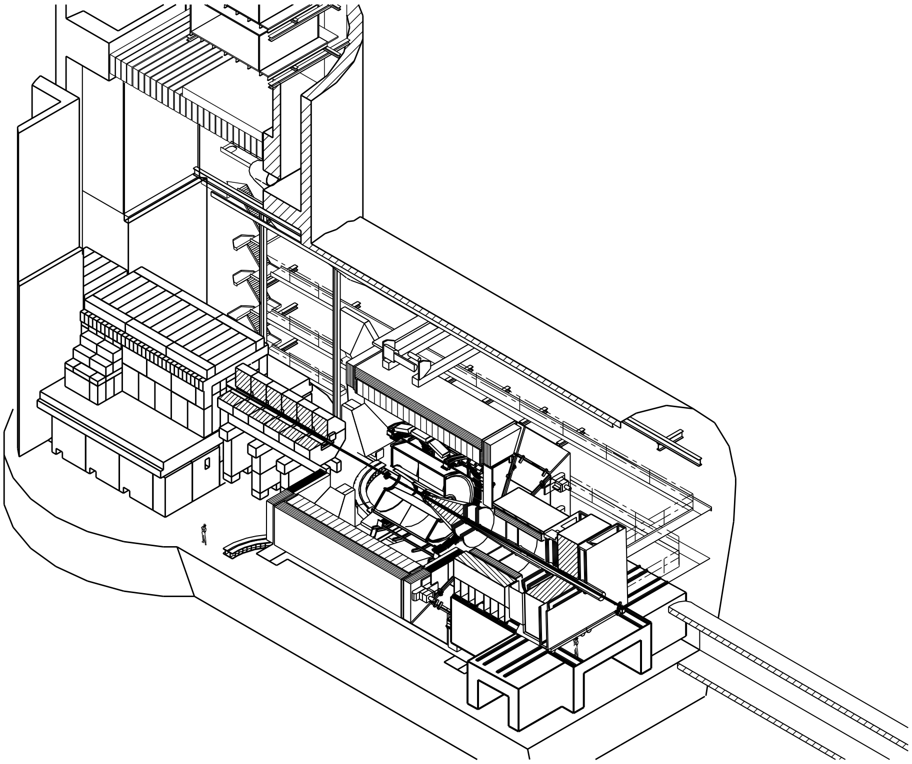

Figure 5: Adaptation of the existing cavern and magnet at P2 for ALICE

spectrometer in P8 are still at a very early stage and the solution to the same access and shielding problem has not yet been chosen. One possibility is to close off the "garage" side of the LEP experimental cavern with a four metre thick concrete wall and install behind it the electronics racks for LHC-B in the mobile barracks of the LEP experiment DELPHI. (Fig. 6)

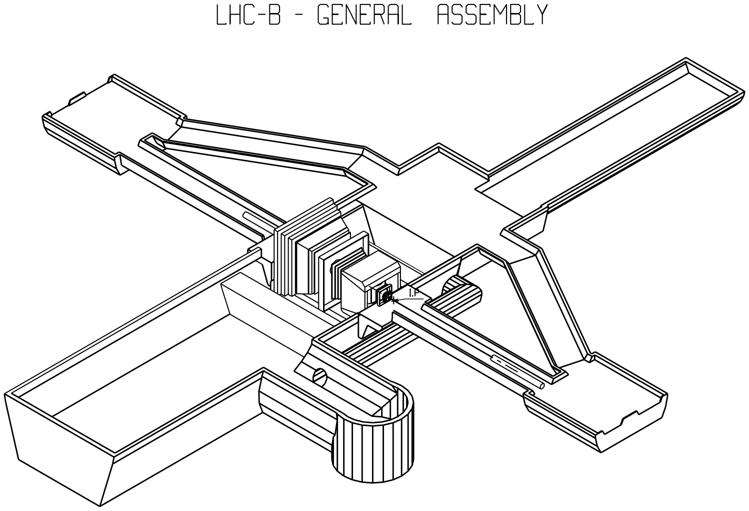

Figure 6: A possible scheme for the installation of the LHC-B spectrometer in the existing cavern at P8

6 Conclusion

The details of the new underground caverns, surface buildings and services are now being finalised and the engineering is in the hands of the design consultants. An environmental impact report will be ready very shortly for presentation to the relevant authorities of France and Switzerland before the end of this year. As explained above the exact timetable for the construction of the LHC has not yet been approved by the CERN Council, but all preparations are well on target for colliding beams and first physics runs before the end of 2005.

Acknowledgements

This status report is based on the work of the very many colleagues who are now working on the LHC project, both on the collider and experiments, at CERN and worldwide.

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