DOE/ER-0677

Department of Energy Assessment of the Large Hadron Collider

June 1996

U.S. Department of Energy
Office of Energy Research

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MASTER

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highest-energy proton collider of the present day, the Fermilab Tevatron. It will be a unique facility for basic physics research, providing the world's highest energies to probe the structure of matter and the forces that control it.

The LHC will be the latest and largest in a series of colliders built with superconducting magnets, beginning with the Tevatron at Fermilab, followed by HERA in Germany, and soon to be joined by RHIC at Brookhaven National Laboratory. The art and science of designing and building superconducting accelerator magnets has been advanced by R&D at numerous laboratories, including CERN. The LHC is building on proven technology.

The magnet systems constitute 62 percent of the estimated accelerator project cost, with the 1,232 main bending magnets (a "2-in-1" design with twin-bore magnets) representing over half the magnet systems cost. The overall main bending magnet design is well established, the scope complete, and the cost estimate adequate. However, several time-consuming iterations will still be needed to finalize the engineering details of the main bending magnets before production can begin. These state-of-the-art magnets are on the project's critical path, and it is important that a development effort continue to be focused on them.

The helium refrigeration system used to cool the magnets to superconducting temperatures will be the largest in the world. Based on experience with other facilities (including the Tevatron, the Tore Supra tokamak, the Continuous Electron Beam Accelerator Facility, and LEP), the LHC cryogenic design appears technically sound and a straightforward extrapolation of past experience. The committee concluded that the cryogenic costs (estimated to be 15 percent of the accelerator project) are reasonable, although CERN will have to work closely with industry to control the cost of the cryogenic transfer lines.

The facility will also depend on numerous other technical systems such as radio frequency power, vacuum, transfer lines, injection/ejection, beam cleaning, control, etc. While they are crucial to proper operation, and must be carefully designed and engineered, the cost of each system is relatively small. Together with installation, they amount to 15 percent of the estimated accelerator project cost. These systems are properly scoped and adequately costed.

By making optimal use of the existing LEP facilities, including underground enclosures, the amount of civil engineering is kept small. This work for the LHC is well defined for this stage of the project. Cost estimates are reasonable (including electricity and other services, civil engineering is estimated to be eight percent of the accelerator project cost), and the schedule supports the overall project schedule.

In summary, the LHC cost estimated by CERN is reasonable, generally being based on past experience and conservative estimating assumptions. The project greatly benefits from the use of existing CERN technical expertise, infrastructure, and accelerator systems. The overall construction schedule, with initial operation presently being planned for the year 2005, appears feasible, assuming that an adequate funding profile is available. There is considerable flexibility in the deployment of laboratory resources, giving added confidence that the project goals can be met.

Most important of all, the committee found that the project has experienced and technically-knowledgeable management in place and functioning well. This strong management team, together with the CERN history of successful projects, gives the committee confidence in the successful completion of the LHC project.

1. INTRODUCTION

1.1 Background

The Large Hadron Collider (LHC) will be a unique facility for basic research, providing the world's highest energies to probe the structure of matter and the forces that control it. This proton-proton colliding beam accelerator will be located at CERN, the European Laboratory for Particle Physics outside Geneva, Switzerland, in the 27-km tunnel presently containing the Large Electron Positron (LEP) collider.

In the aftermath of the termination of the Superconducting Super Collider (SSC) project, the High Energy Physics Advisory Panel (HEPAP) established a subpanel, chaired by Professor Sidney Drell, to address the future of the U.S. high energy physics program. A major element of the subpanel's considerations was to seek very broad input from the U.S. high energy physics community. Based on its evaluation, the subpanel concluded that an essential element to the program is "...significant participation at the highest energy frontier, for which the best current opportunity beyond the Tevatron is through international collaboration on the LHC at CERN." This led the subpanel to recommend a U.S. program that included:

> "... Significant participation in the LHC accelerator and detectors, both to provide research opportunities at the energy frontier and to ensure that U.S. physicists remain integrated in the international high-energy physics community...."

The report of the subpanel was endorsed by HEPAP and the basic recommendations were accepted by the Department of Energy (DOE). Subsequently, the broader U.S. high energy physics community, through the Report of the Committee on Long-Term Planning of the Division of Particles and Fields of the American Physical Society, stated that "In accord with the Drell Subpanel report, we believe that the LHC program will define the high-energy physics frontier and that participation by U.S. physicists in this effort is essential."

While international collaboration on detectors has a long and well established history, the frequency and extent of collaboration on the construction of accelerator facilities has been much more limited. The LHC is such a large project that it stretches the financial resources of the CERN member countries. In December 1994, the CERN Council approved construction of the LHC with the understanding that if no contributions were forthcoming from CERN non-member countries, it would have to be built as a two-stage project. The first stage would be a collider with energy

5 TeV per beam, ready for experiments in 2004, with an upgrade in the second stage to 7 TeV per beam in 2008. Given the presently anticipated contributions from the United States, Japan, and several other non-member countries, planning now assumes completion of the machine at the full 7-TeV energy in 2005, based on a new 10-year plan to be presented to the CERN Council for approval in December 1996.

Given the interest in the LHC from U.S. scientists, it is natural for the United States to collaborate on the accelerator project. The DOE believes that helping to build the LHC is in the best interest of the U.S. scientific program for three reasons:

- It will help advance the schedule for the availability of the facility at full energy by several years, thus benefiting all participating scientists.
- The U.S. contributions will help U.S. laboratories stay at the cutting edge of accelerator technology for future activities.
- Participation furthers the cause of international scientific collaboration.

Both the management of CERN and the LHC detector collaborations have welcomed U.S. help with the LHC accelerator and detectors. Informal discussions and planning for U.S. participation by many members of the scientific community began shortly after the SSC project was terminated in late 1993, and first formal negotiations between CERN and the U.S. Government were held in January 1996. The assessment described in this report is an important step in this process.

1.2 Charge to the DOE Assessment Committee

In a February 27, 1996, memorandum (Appendix A), Dr. James F. Decker, Deputy Director of the DOE Office of Energy Research, established a DOE Assessment Committee with the following charge:

> ". . . Because of the potential size of the U.S. investment in the LHC project, its importance to CERN, its impact on the U.S. High Energy Physics program, and its importance to U.S. participation in future international science projects, the Office of Energy Research will need to be able to substantiate to the Congress, and to elements of the Administration, that its investments in the LHC project are reasonable and able to achieve expected results.

Therefore, I request that you assemble a project team to assess: the cost estimate for the LHC machine, understand the basis for these elements, identify uncertainties, and judge the overall validity of the estimate, and the proposed schedule and related issues. . . ."

1.3 Membership of the Committee

The committee was chaired by Daniel R. Lehman, Director of DOE's Division of Construction Management Support, Office of Energy Research. It was organized into six subcommittees with members primarily drawn from DOE national laboratories and the DOE Office of Energy Research. In addition, the committee included observers from DOE and the National Science Foundation, support personnel, and a report coordinator. The committee membership and subcommittee structure are shown in Appendix B.

1.4 The Assessment Process

This assessment had long been planned and agreed to as part of the U.S.-CERN discussions. Development of a mutually agreeable agenda was carried out with the close cooperation of Lyn Evans, Gilbert Drouet, and others at CERN. The committee would like to express its thanks for the cooperation and hospitality received from its CERN hosts.

The assessment took place April 22-26, 1996, at CERN. The first day was largely devoted, in plenary session, to project-overview presentations by members of the CERN LHC staff. These presentations were based on the design described in *The Large Hadron Collider, Conceptual Design* ("Yellow Book," CERN/AC/95-05 (LHC), 20 October 1995), and the *LHC Cost Estimate–Accelerator* (AC-DI/GFD/95-12, November 1995).

On the second and third days, members of each subcommittee met with their LHC counterparts to discuss the details of the scope, cost, schedule, and management of each system. The presentations were well prepared and the discussions were highly informative. Members of the committee also toured the CERN magnet fabrication and test facilities, as well as the LEP tunnel. The next two days focused on subcommittee working sessions, committee deliberations, and the drafting of this report. The draft report was reviewed by CERN staff for accuracy on points of fact. The preliminary results of the assessment were discussed with CERN management and staff at a closeout session on the afternoon of April 26.

Comparison with past experience on similar projects was the primary method for assessing technical requirements, cost estimates, schedules, and adequacy of management structure. Although this project requires some extrapolations, similar accelerator projects provide a relevant basis for comparison. In the United States, these include the Fermilab Tevatron, the SSC, the Continuous Electron Beam Accelerator Facility (CEBAF), and the Brookhaven Relativistic Heavy Ion Collider (RHIC) projects. In Europe, experiences with the Intersecting Storage Rings (ISR), Super Proton Synchrotron ($S\bar{p}pS$), and LEP colliders at CERN and the HERA collider in Germany are relevant.

2. OVERVIEW OF DESIGN

2.1 Background

The LHC will be a particle accelerator facility built at CERN in the 27-km tunnel presently containing the LEP electron-positron collider. Powerful superconducting magnets will guide two counter-rotating beams of protons around the tunnel and bring them into collision inside sophisticated detectors. The detectors will be used to observe and record the particles produced by the energy of the collisions. These flashes of energy, concentrated into a very small space, are expected to produce new, massive particles as well as probe the forces of nature under extreme conditions.

At 7 TeV, the proton beams will have over seven times the energy of the world's present highest energy accelerator, the Tevatron at Fermilab. Unlike the Tevatron collider, which has a single beam pipe containing both a proton beam and an antiproton beam, the LHC will require two separate beam pipes. This is because the two LHC beams both have a positive charge and the two counter-rotating beams need oppositely directed magnetic fields. While this requires separate magnetic channels for the two beams, it allows the higher beam intensities, and thus higher interaction rates, that can be obtained with protons compared to antiprotons. Because of space limitations in the LEP tunnel, as well as cost considerations, both beam pipes are contained in magnets with a single iron yoke ("2-in-1" magnets).

To extend the energy frontier as far as possible while taking advantage of the LEP tunnel, the LHC has been designed with the highest magnetic field that can be reliably and economically obtained. With present advanced technology, a relatively low operating temperature of 1.9 Kelvin will be used to push the field to 8.3 Tesla. (This can be compared with the 4 to 5 Tesla fields of the Tevatron and HERA, existing superconducting colliders operating at about 4.3 Kelvin, and the 6.8 Tesla SSC magnets, which were tested at 4.3 Kelvin.) At 1.9 Kelvin, liquid helium is a superfluid, which has highly efficient heat transfer properties and very low viscosity, providing an excellent cooling medium for the LHC magnets.

Maximum use will be made of both physical and organizational infrastructure existing at CERN. In addition to the LEP tunnel and its other underground facilities, surface structures and utilities, the existing chain of accelerators (with some relatively minor modifications) will be used to inject beam into the LHC at 0.45 TeV.

Some of the basic LHC parameters are summarized in Table 2.1. At the design luminosity of 10^{34} cm^{-2} sec^{-1}, each of the two major detectors will observe about six hundred million inelastic interactions per second. This high rate will enable the study of rare, but highly interesting, interactions. Each proton contains a number of quarks and gluons that share the proton energy, and the high luminosity will allow the observation of interactions involving quarks and gluons with an unusually high fraction of the proton energy. In this way, the higher intensity of the LHC will partially offset the factor-of-three energy difference between it and the cancelled SSC. Collisions of these rare, high energy quarks and gluons are expected to create new and very massive particles by converting energy to mass according to $E=Mc^2$.

Table 2.1. Some LHC Parameters at Full Energy.

Proton energy	7	TeV
Bend magnetic field	8.3	Tesla
Luminosity	10^{34}	$cm^{-2}sec^{-1}$
Luminosity lifetime	10	hours
Ring circumference	26.659	km
Revolution frequency	11.246	KHz
RF frequency	400.79	MHz
Number of proton bunches per ring	2835	
Bunch separation	7.48	m
Protons per bunch	1.05×10^{11}	
Transverse normalized rms emittance	3.75	mm • mrad
Transverse rms beam size in arc (β = 183 m)	0.303	mm
Transverse rms beam size at collision point (β = 0.5 m)	0.016	mm
Head-on beam-beam parameter/IP	0.0034	
Longitudinal rms beam size	77	mm
Synchrotron radiation per beam	3.6	kW
Longitudinal damping time	13	hours

The LHC is divided into eight octants, each including a straight section (insertion region), used for the purposes indicated in Figure 2.1. In most of the LHC, the two beams will be located side by side, with a separation of 194 mm. Detectors are foreseen at four of the insertion regions, where the beams cross in a symmetric fashion, such that the two beams go the same distance around the ring.

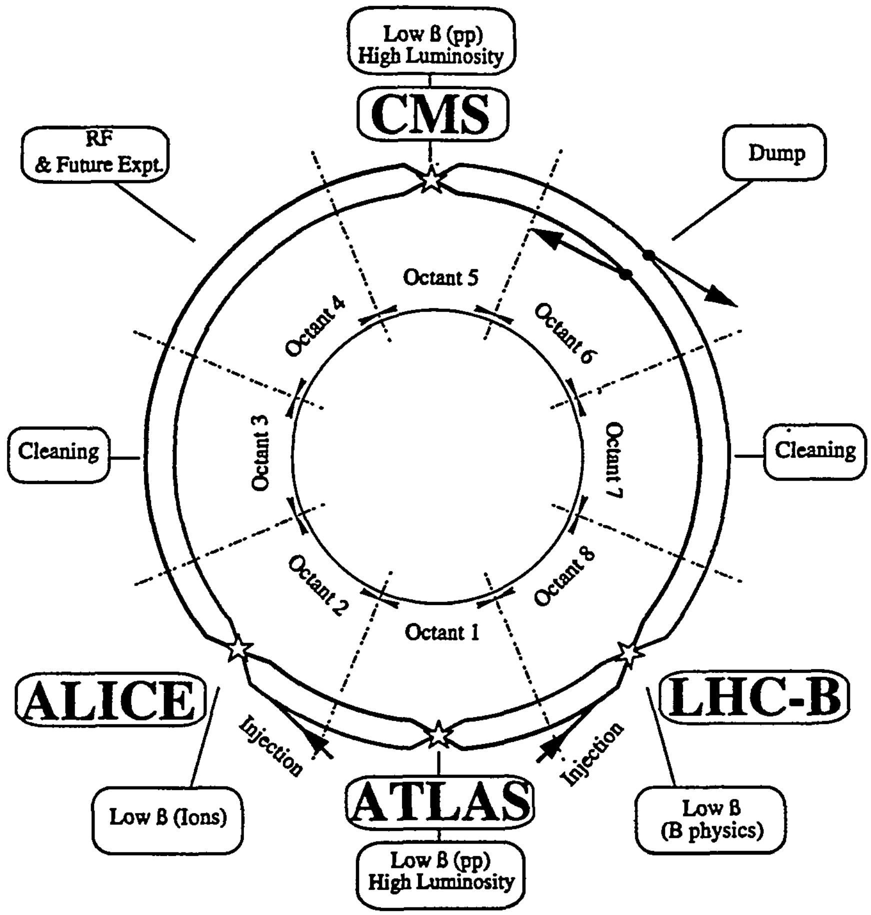

Figure 2.1. Sketch of the LHC layout and the functions of the eight insertion regions. Locations of the four proposed detectors (CMS, LHC-B, ATLAS, and ALICE) are also shown.

Injection of the two beams of protons into the LHC from the existing CERN accelerator complex will take about 7 minutes, followed by acceleration to full energy in about 20 minutes. The beams will then be brought into collision and made to collide for several hours while the detectors record selected interactions. After several hours, enough of the protons in the beams will have been collided and lost to cause the interaction rate to decrease significantly. At that time, remaining protons will be ejected (dumped) and the LHC refilled. Including the time to tune up the injection system, the interruption of data-taking for refilling may take as little as two hours.

The overall feasibility of the project is established by the previous successful operation of colliding beam accelerators at CERN and elsewhere. The experience with superconducting accelerator/colliders at Fermilab and DESY, as well as the further development of superconducting accelerator magnets at CERN, BNL, and other laboratories, provides confidence in the design of the LHC.

2.2 Magnets

A cross section of the main dipole (bend) magnet is shown in Figure 2.2 and some of the important parameters are listed in Table 2.2. Each of the 1,232 dipole magnets bend the beams by about 5 milliradian (0.3 degree). Each beam passes through a magnetic channel formed by sets of superconducting coils that generate the 8.3-Tesla field needed at 7 TeV. These coils are made of two layers of cable held firmly in place by aluminum collars, which in turn are clamped in the iron yoke of the magnet. Significant effort has gone into the design, modeling, and development of these dipole magnets. The dipoles are crucial to proper operation of the LHC, as well as being its most expensive system (34 percent of the cost of the accelerator project).

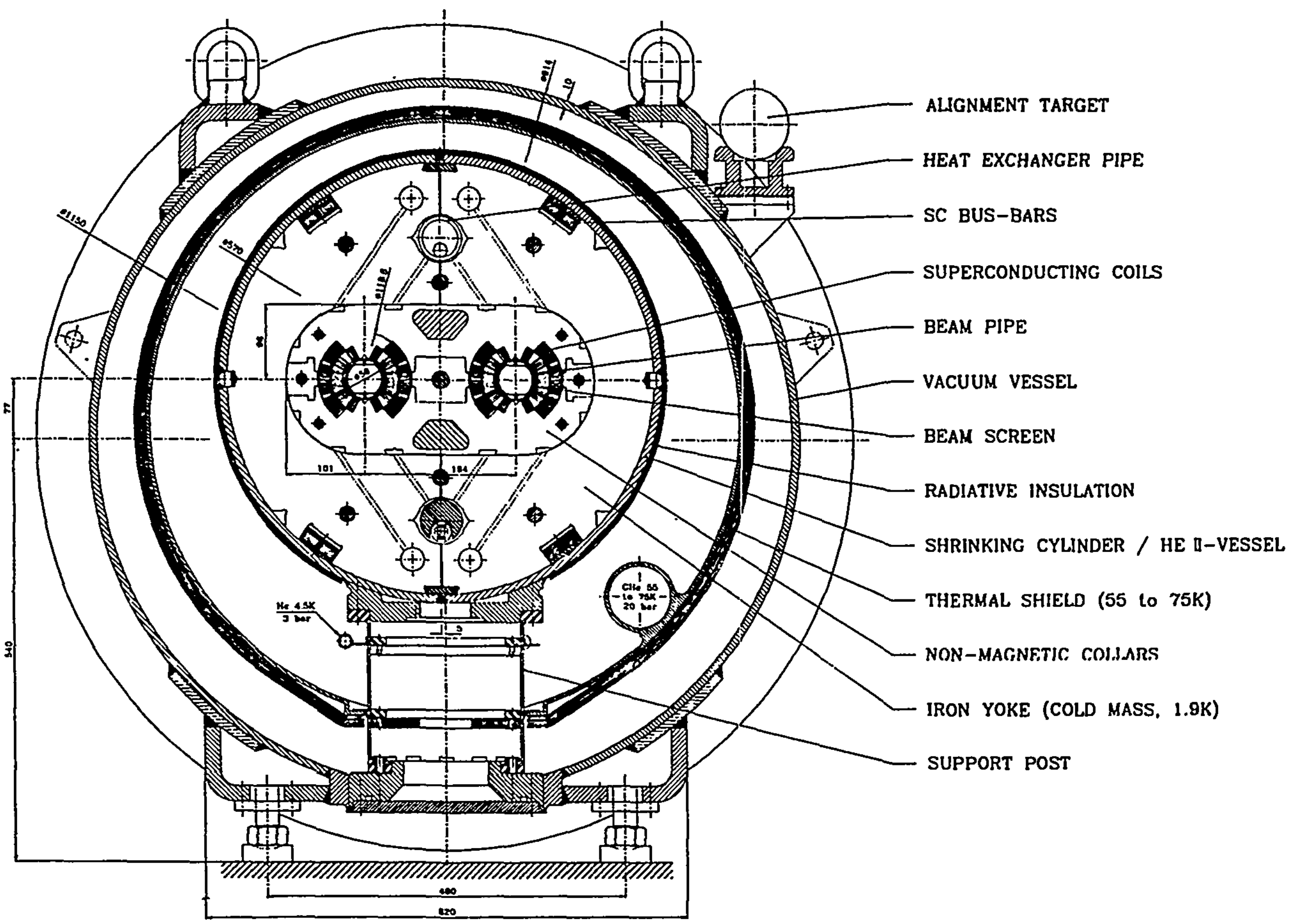

Figure 2.2. Cross section of the "2-in-1" dipole magnet.

Table 2.2. Main Superconducting Magnets.

Bending Magnets (Dipoles)		
Number of "2-in-1" magnets	1,232	
Injection field (0.45 TeV)	0.58	Tesla
Fractional persistent current sextupole field at injection	-3.6	10^{-4} at 1 cm
Operational field (7 TeV)	8.3	Tesla
Coil aperture	56	mm
Separation of beam centers	194	mm
Magnetic length	14.3	m
Operating current	11.5	kA
Operating temperature	1.9	Kelvin
Temperature margin	1.4	Kelvin
Stored energy (both channels)	7.1	MJ
Total mass per "2-in-1" magnet	~27.5	tons
Inner coil		
turns per beam channel	30	
number of strands in cable	28	
copper to superconductor ratio	1.6	
Outer coil		
turns per beam channel	52	
number of strands in cable	36	
copper to superconductor ratio	1.9	
Focusing Magnets (Quadrupoles)		
Number of "2-in-1" arc (dispersion suppressor) magnets	386 (112)	
Magnetic length	3.10 (3.25)	m
Operating gradient	223	Tesla/m
Peak field in conductor	6.87	Tesla
Coil aperture	56	mm

Over most of the circumference of the LHC, focusing magnets (quadrupoles) are inserted after every third bending magnet. This fundamental unit of three bends and a focusing magnet, the half cell, is 53.46 meters long and is repeated over and over again in each of the eight arcs. These half cells also include correction magnets and beam position monitors to aid in controlling the beams. In addition, special focusing and corrector magnets are used in the insertion regions to manipulate and focus the beams. Overall, magnets account for 62 percent of the cost of the accelerator project.

2.3 Cryogenics

The magnets will be cooled by eight large helium refrigerators, each with a nominal rating of 18 kW at 4.5 Kelvin. This will be the largest cryogenic system in the world, not just the largest with superfluid helium. The design of this system is based on past experience with accelerators, as well as the Tore Supra tokamak.

The refrigerators will be located in pairs at the even-numbered insertion regions so that the best use can be made of existing LEP utilities and technical buildings. Each refrigerator will nominally feed a sector (one-eighth) of the accelerator, with partial redundancy afforded by a cryoplant interconnection box. Cold compressor boxes will be installed underground to drop the temperature to the required 1.8 Kelvin. A total inventory of about 750,000 liters (nearly 100 tons) of liquid helium will be needed.

2.4 Vacuum

A very high vacuum is needed because collisions of beam particles with gas molecules remaining in the beam tubes would reduce the beam lifetime. This must be accomplished in spite of the effect of the synchrotron radiation emitted by the protons—this radiation strikes the walls and desorbs gas molecules, which must be given a means of migrating to an area shielded from the radiation.

This function is provided by the beam screen, a perforated tube centered within each magnet beam tube. The perforations allow the desorbed molecules to pass through the screen to the cold bore of the magnets, where they firmly adhere to the lower-temperature surface. By running at a higher temperature than the magnets (5 to 20 Kelvin, compared to 1.9 Kelvin) this screen also allows more efficient operation of the helium refrigerator system.

Other vacuum systems will provide the insulating vacuum required for the superconducting magnets, as well as the beam-tube vacuum in the warm straight sections of the accelerator.

2.5 Magnet Power

A large number of power supplies are needed to provide current to the various magnets that guide and control the beams. The largest of these are eight current-source power converters located in pairs at the even-numbered insertion regions. Each of these converters powers a sector of bending magnets connected in series. A ramp rate of 10 amperes per second while accelerating the beam requires 185 volts. At 7 TeV, about 10 volts will be needed to maintain the operating current of 11,500 amperes. These eight converters must track one another precisely. This will be done with the help of reference magnets, each powered in series with a sector of LHC magnets.

The main focusing and defocusing quadrupole magnets will be separately powered. Many of the insertion magnets and correction magnets will be powered in series as families of magnets, but some must be powered separately. In total, about 1,550 power converters are needed, supplying a total current of about 1,750 kA. They will require a steady-state input power of about 19 MW, with a peak of 41 MW.

2.6 Other Technical Systems

A 400-MHz radio frequency (RF) system with superconducting cavities will be used to accelerate the beams, to replace the energy lost through synchrotron radiation, and to bunch and control the beams. For collision, the beams will be bunched to a rms length of ±7.7 cm, giving a region with rms length of ±5.5 cm over which interactions take place within the detectors.

Transient beam loading dominates the design of the RF system because of the high beam current interspersed with gaps to facilitate injection and extraction. Each beam will have its own RF system with eight cavities. Other RF systems will be used to damp beam oscillations and to control certain beam instabilities.

Other critical systems include beam instrumentation, controls, and cleaning, as well as beam injection, extraction, and dumping. While these are all vital to the successful operation of the LHC and must be carefully engineered, their design is straightforward and the cost of each system is only a small fraction of the total accelerator project.

Two new beam transfer lines will be built to inject beam into the LHC from the Super Proton Synchrotron (SPS), each about 2.7 km long. Since these lines only need to be powered for short periods (that is, when refilling the LHC), conventional magnets will be used; a total of 352 6.3-meter long dipoles and 158 1.25-meter long quadrupoles.

The existing CERN proton accelerators, with some modifications, will be used to accelerate protons to 0.45 TeV for injection into the LHC. This includes the 50-MeV proton linac (Linac 2), the 1-GeV Proton Synchrotron Booster (PSB) modified to run at 1.4 GeV, the 26-GeV Proton

Synchrotron (PS), and finally the SPS. The modifications, which will allow formation of high-intensity LHC bunches with the desired spacing, are being carried out as part of the ongoing CERN program and are not included in the accelerator project. Some testing has already taken place. Additional modifications are planned to form the bunches of lead ions needed for heavy ion collisions.

2.7 Civil Engineering

By making optimal use of the existing LEP facilities, including underground enclosures vacated by LEP equipment, the amount of LHC civil engineering is relatively small. The LEP/LHC underground enclosures are sketched in Figure 2.3. Tunnels and shafts must be excavated for the new transfer lines; additional underground space must be excavated for the beam dumping system and for power supplies and cryogenics equipment; and some new surface buildings for technical equipment, as well as modifications to utility services, must be provided. The cost of modifications required for the experimental areas is not included in the committee's cost assessment.

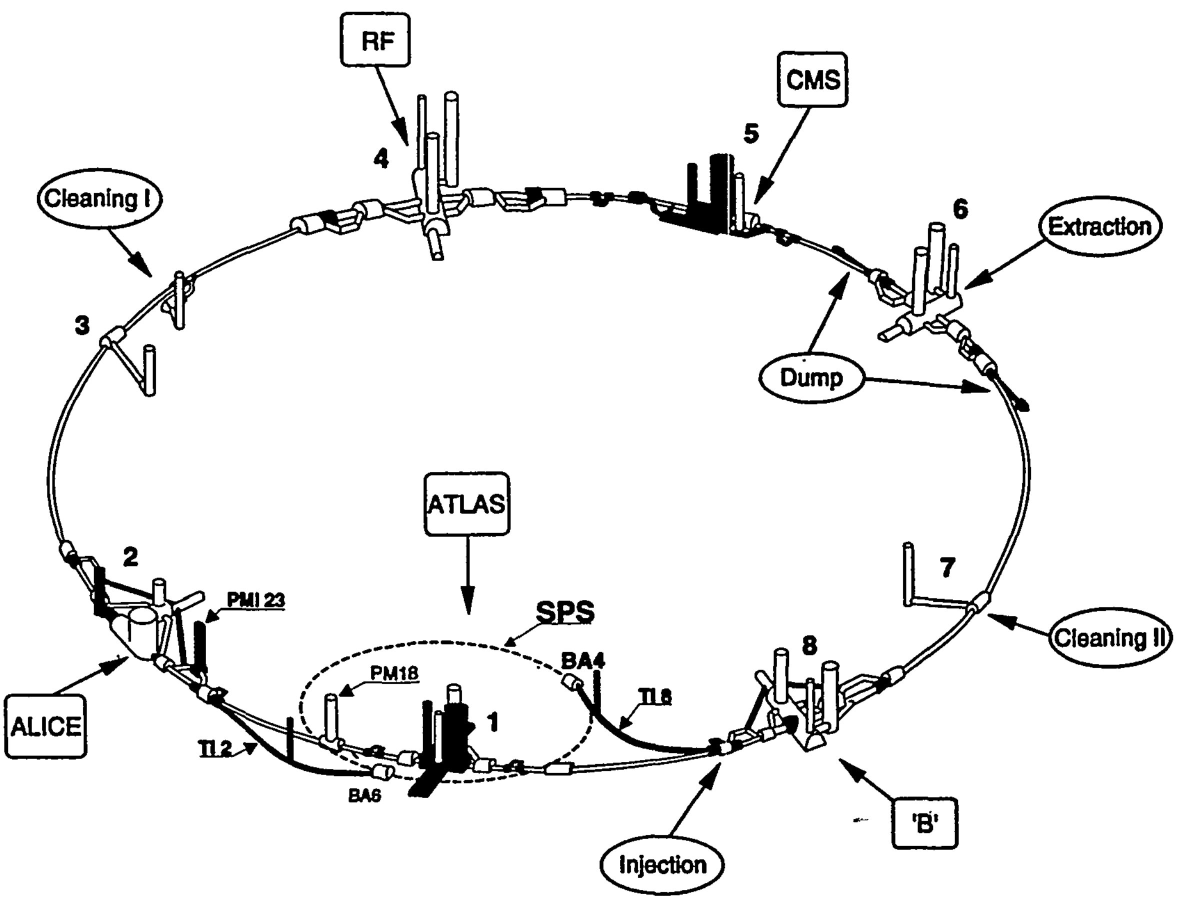

Figure 2.3. Sketch of the underground civil construction. Unshaded regions were constructed for LEP, while the shaded regions will be built for the LHC accelerator and experimental areas.

3. TECHNICAL SYSTEMS – SUMMARY EVALUATIONS

3.1 Magnet Systems

3.1.1 Summary

The magnet systems include all the superconducting magnets for LHC, comprising 62 percent of the estimated accelerator project cost, 2,300 million Swiss francs (MCHF). Research and development on magnet systems has progressed sufficiently to enable a comprehensive cost estimate. Estimating was accomplished using sound methods based on actual costs paid in the LHC R&D program, on scaling from other well-documented projects, and on detailed time and materials costs (that is, a "bottoms up" approach). The committee concluded that the CERN estimate of 1,426 MCHF for the magnet systems is adequate. The magnet schedule can be met with a concentrated effort on the magnet development program. It could be improved substantially if additional resources became available and a relaxation of procurement rules were possible so that the fabrication and testing of long prototype magnets could continue without interruption.

3.1.2 Technical Scope

The LHC is a hadron collider based on superconducting magnets. It is the latest and largest in a series of superconducting colliders that began with the Tevatron in the United States, was followed by HERA in Germany, and which will soon be joined by RHIC at BNL. The art of designing and building magnets for these big superconducting synchrotrons was further advanced with R&D carried out at LBNL, BNL, CERN, DESY, KEK, Fermilab, and the SSC Laboratory. The LHC, therefore, builds on proven technology.

The inventory of superconducting magnets in the LHC will include 1,232 "two-in-one" dipoles, 498 "two-in-one" quadrupoles, and about 7,000 special-purpose and small correction magnets. Almost all of these devices will be operated in superfluid helium at 1.9 Kelvin. The nominal magnetic field is 8.3 Tesla for the dipoles, and the gradient is 223 Tesla/meter for the quadrupoles. The designs have margin for collider operation.

A wide variety of corrector magnets has been included in the design. The decision to power the quadrupoles as four separate systems allows for substantial machine flexibility and eliminates the need for an additional set of correctors.

Appropriate R&D has been underway at CERN and other institutions for more than a decade, in cooperation with qualified potential vendors in many CERN-member countries. No major technology transfer obstacles remain. The most significant technical issue remaining, controlling the strand-to-strand resistance within the superconducting cable, is being appropriately addressed through a comprehensive R&D program. Sufficient options are available to resolve this challenge in a timely, cost-effective manner. The committee identified no areas of significant technical risk.

The CERN-LHC magnet group is also participating in the development of the 12-kA high-temperature superconducting power leads discussed in the cryogenics section.

3.1.3 Cost

The LHC staff has estimated the cost of magnet systems to be 1,426 MCHF. Several methods were employed to generate this estimate for the main magnets, including bottoms-up (time and materials), scaling estimates of other recent projects (HERA, RHIC, and the SSC), and comparison with recent purchases made during the R&D phase. All three methods were utilized and cross-checked where possible. Using similar methods, the committee verified the CERN estimate.

A parametric cost calculation was made by the LHC staff for the various types of corrector magnets. The method and resulting estimates were found to be reasonable and adequate.

All of the CERN magnet personnel who met with the committee understood the scope of their portion of the project and estimated its cost appropriately. All questions were answered satisfactorily.

The main magnet designs are based on more than a decade of development at CERN and other institutions, in cooperation with qualified potential vendors in many of the CERN-member countries. This has resulted in the development and acquisition of a considerable amount of tooling needed for the production of these magnets. As a result, both CERN and the potential vendors have a good understanding of the cost basis involved in the final commercial production of these components. The use of more than one vendor during production is planned. No major obstacles in technology transfer remain.

CERN has chosen to use niobium titanium (NbTi) superconducting cable, with the magnets operating at less than 2 Kelvin in order to reach the required operating field. The committee is comfortable with this choice since it builds on over two decades of superconducting magnet design and construction experience at CERN and other laboratories. The cable cost used in the CERN cost estimates is consistent with prices recently paid by BNL and with cost estimating models developed for the SSC project.

The major sources of the NbTi alloy are U.S. companies. Although NbTi prices have remained constant in real dollars since 1990, there appears to be some instability in the market for the raw material. A $1 per kilogram increase in the cost of alloy would generate nearly a $0.50 per kilogram rise in the cost of the superconducting cable. The United States has a much greater capacity than Europe, and a very mature technology for producing finished cable as a result of DOE-sponsored development during the past 15 years or so. It appears likely that the finished cable can be purchased more economically from U.S. manufacturers.

The estimated cost of other magnet parts compared well to the price of fabricated steel and aluminum parts in the United States after correcting for the differences in labor costs. The values used are reasonable.

Manufacturing labor was estimated on a bottoms-up basis by CERN and the committee. Scaling from RHIC labor experience and SSC labor models and estimates was also used by both. All scaled estimates were below the CERN bottoms-up estimate, but well within the uncertainties.

Tentative engineering, design, inspection, and administration (EDIA) manpower allocations for the LHC program were presented. In addition to CERN manpower (not included in the accelerator project cost estimate), resources will be provided by external design and supervision contractors, contract labor, and collaborating institutions from CERN-member and non-member countries. The committee compared the total EDIA manpower available to historical data from the United States, Germany, and CERN and concluded that it is appropriate.

Adequate provision is made for administration and oversight of production contracts. Inspection costs are included principally in the warm and cold testing estimates. These allocations are sufficient to test all corrector magnets, all of the preproduction magnets, and about 30 percent of the production main dipoles and quadrupoles. In the unlikely event that a larger fraction of magnets must be tested, more labor can be applied from contingency.

Contingency in the DOE sense is built into the estimates rather than drawn out separately. CERN has identified cost reductions in the project design and designated an amount corresponding to 7 percent of the 1,426 MCHF estimate for the magnet systems as contingency. It is expected that further cost reductions will be found sufficient to cover omissions that may occur (the committee found none) and problems that will arise. Contingency in the U.S. sense is adequate, though not accounted for in the same manner.

3.1.4 Schedule

It appears that the superconducting magnets are on the critical path of the project, which is scheduled for completion in 2005. The magnet schedule can be met with focused effort on the R&D program and could be improved substantially if additional resources and a relaxation of procurement rules were possible. Key milestones are:

MAGNET MILESTONES

Test four 10-m magnets of present aperture design	1997
Test two 14-m magnets of present aperture design	4th Q 1997 - 1st Q 1998
String Test 2 (half cell: 3 dipoles and 1 quad)	3rd Q 1998 - 4th Q 1999
Preproduction delivery begins	3rd Q 1999
Preproduction delivery ends	4th Q 2000
Production delivery begins	3rd Q 2001
Magnet delivery ends	1st Q 2005

The present schedule has two substantial delays which could be used for the resolution of problems. First, there are 1-1/2 years between the end of testing two prototype 14-m magnets (1st Q 1998) and the delivery of the first preproduction magnets (3rd Q 1999). Second, after the preproduction magnets are delivered in 2000, there is a year for testing and problem resolution until production magnet delivery begins late in 2001. The first interval seems driven by CERN procurement rules which have a ceiling of 0.2 MCHF for noncompetitive procurements. An increase of the approval ceiling on procurements would allow another magnet design iteration during this period while the large production contracts are being pursued in the normal way. It would also allow additional accelerator system development via a full-cell magnet string test (the present half-cell is too short to study some phenomena). CERN management is aware of this 1-1/2-year interval and is taking steps to exploit it. Many benefits would also be gained from continued production in industry of full-length prototypes while the magnet production procurement is in process. The second schedule delay allows for final problem resolution, and might prove unnecessary if more long prototypes are manufactured and tested during the first 1-1/2-year interval. Once production is underway, annual magnet production rates are reasonable.

3.2 Cryogenic System

3.2.1 Summary

The cryogenic system is a low-risk design that has been verified and optimized over the last six years. CERN is capable of completing it on cost (337 MCHF) and on schedule (December 2004).

3.2.2 Technical Scope

The scope consists of two refrigerators (each with a rating of 18 kW at 4.5 Kelvin) at each of the four even-numbered interaction points, a cryogenic transfer line to distribute the refrigeration around the accelerator, connection boxes, and magnet current-feed boxes. The system has been well optimized to the boundary conditions of magnet constraints and civil engineering costs.

The basic magnet cooling system has undergone extensive R&D, starting with heat exchanger testing and continuing through the present string test. The baseline refrigeration system is based on the CEBAF system which is currently operating with an availability of over 98 percent. The refrigeration system contains an overall safety margin of 1.5, plus another factor of 1.25 on the static low-temperature loads and lead flows. Based on the detailed measurements made to date, this is appropriate.

The only remaining technical risk is developing the 12-kA high-temperature superconducting power leads; 600-ampere leads for the correctors have already been developed. The backup option is to add a central helium liquefier to provide liquefaction flow for 12-kA conventional leads.

3.2.3 Cost

The cost of the Cryogenic System (337 MCHF), as broken out by CERN, is as follows:

28	MCHF	Cryogenics at Odd Points,
170	MCHF	Cryogenics at Even Points,
108	MCHF	Arc Cryoline,
31	MCHF	Contingency.

A more meaningful breakdown by task and cost is as follows:

40 percent	Refrigeration Equipment,
40 percent	Helium Transfer Lines,
10 percent	Interface Boxes,
10 percent	Contingency.

The refrigeration equipment costs are based primarily on previous LEP contracts including options for upgrades. The cold compressor coldbox cost is based on CEBAF costs. The refrigeration costs are firm numbers, subject only to market fluctuations (the current state of the cryogenic market is depressed).

The material costs for the helium transfer lines are based on detailed part costs and quantity discounts. The transfer line labor costs, markups, and profit are very sensitive to procurement style. The LHC arc transfer line costs per meter are the same as the HERA line (which is half the cross sectional area). In order to reduce costs, the conceptual design is split into a high-tech 3-m module and a low-tech 50-m pipe. The LHC straight section transfer lines are estimated at twice the cost per meter as those in the arcs, due to their custom nature.

The transfer line costs are clearly possible if CERN assumes the role of a prime contractor; whether these costs are possible to achieve with cryogenic contractors as primes remains to be seen. Pricing scaled from the HERA procurement method would require an additional 40 MCHF of contingency beyond what is presently allotted.

The estimated costs for the interface boxes are ample and require no contingency.

It must be noted that considerable resources are supplied from outside of the project scope. The first element is the LEP–II refrigeration system. The second is the assumed CERN manpower, which in total is very healthy but late and slow in its ramp-up (light in the 1996 to 1998 period). A third resource is the central helium storage facility.

In summary, the contingency of 31 MCHF is adequate provided CERN is flexible in its management of the transfer line procurement.

3.2.4 Schedule

While the majority of the cryogenics tasks are not on the critical path, two items are: the cryogenic distribution line and the first 18-kW refrigerator.

The cryogenic distribution line (CDL) must be installed and leak-checked prior to the start of dipole installation. The acceptance testing must be completed prior to quadrupole installation. The timeline for this is very aggressive, with vendor qualification and prototype ordering being done this year and prototype delivery scheduled before the end of 1997. The prototype lines will be used initially for evaluation and later to support String Test 2. This would lead to a call for final bids in 1999 and placing contracts in 2000. The critical milestone would be in August 2002, for the completion of first sector CDL leak check and the start of magnet installation. There is no time to spare in the prototype timeline, and only about six months extra in the timeline for the production run.

The first 18-kW refrigerator will be used for: 1) commissioning, starting procedures, and off-design and reduced-capacity operation of the cold compressors (2000-2002); 2) testing of components other than the dipoles (2001-2003); and 3) cooling the first sector (2003). The timeline for this requires final decisions to be made on the capacity and cycle by March 1997, and placement of the order by year's end. The goal is to have the first 18-kW refrigerator operational by December 1999. There is no spare time in this schedule.

Although these two timelines are aggressive, they are totally feasible.

3.3. Beam Transfer Lines, Beam Injection, and Beam Dumping Systems

3.3.1. Summary

These systems include two 450-GeV beam transport systems, two 450-GeV LHC injection systems, and the beam abort systems that must be able to eject beam from the two LHC rings over the range 450 GeV to 7 TeV. The plans for each of these systems are based on existing technology used at CERN and other accelerator laboratories. The costs are based on component prices that are similar or identical to items regularly purchased at CERN. There are no items of appreciable risk and the cost estimates are reliable.

3.3.2. Technical Scope

This area consists of the beam systems that transport the 450-GeV beam from the SPS to the LHC, inject the transported beams into the LHC, and cause the beams to be quickly dumped or aborted from the LHC in case of malfunction. For each of these three functions, there are two such systems, one each for the clockwise and counterclockwise rings of the LHC. Since each of these three systems is different in functionality, components, and other aspects in need of discussion, they are treated sequentially below.

3.3.2.1 Technical Scope – Beam Transfer Lines

The two beam lines that transport the 450-GeV beam from the SPS to the LHC include all the magnets, power supply systems, vacuum systems, beam diagnostic devices, stoppers, safety systems, cooling water systems, and associated installation costs. Extraction devices from the SPS are presumed to be existing parts of the SPS; injection devices into the LHC are covered in the next subsection. Costs for the civil engineering for the two transport lines are discussed in Section 3.7.

These two transport lines use only iron-and-copper (normal-conducting) magnets. They were chosen over superconducting solutions for cost reasons. Normal-conducting magnets can be used because the required magnet bore is small (the beam is transported at high energy and very low emittance in a single pass, so relatively inexpensive and simple magnets are usable) and because the magnets are used in normal operation only a few times a day and can be quickly turned on when needed. This choice obviates the need for a large cryogenic capacity; and furthermore, existing LEP power supplies can be used.

Transport lines such as these are common, and there are no items which require significant R&D or have uncertain cost estimates.

3.3.2.2 Technical Scope – Injection Systems

The systems used to inject the transported beams into the LHC rings involve the kicker magnets, the septum magnets, the beam stopper, vacuum systems, and beam diagnostics; installation also figures into the cost and schedule. Each of these systems includes power supplies and the interfaces to the control system.

While the kicker systems can be simple copies of existing devices, it is reasonable to expend some R&D effort to take advantage of new technology that would improve parameters such as ripple, stability, reliability, and cost. The cost estimates for these systems are conservative and based on older technology. Improved parameters are expected to be possible once the first R&D prototype is completed next year.

3.3.2.3 Technical Scope – Beam Dump Systems

The technical scope of the beam dump systems is conceptually much like that of the injection systems. However, while the names of the subsystems are the same, they are much different in performance requirements and execution. For example, the injection system kickers operate at 450 GeV with fast risetime and tight flat-top ripple requirements, while the beam dump systems kickers must track the LHC energy and quickly extract the beams at any energy from 450 GeV to 7 TeV. In addition, the beam dump systems include the beam dumps themselves, the dilution kicker systems that spread the beam across the faces of the dumps, and the logic systems for beam abort control.

3.3.3 Cost

The beam transfer lines are estimated to total 53 MCHF, injection systems are 11 MCHF, and beam dump systems are 37 MCHF. The costs for the civil engineering associated with these systems are not included in these numbers (see Section 3.7).

The 352 6.3-meter long dipoles and 158 1.2-meter long quadrupoles, together, amount to more than half the cost of the beam transfer lines. The budget for the dipoles is adequate to build magnets of the field quality needed for these single-pass beam transport systems. The magnets have been identified as possible contributions from Russia. Many rebuilt LEP magnets and power supplies are part of the transport lines, and costs for their refurbishment have been included in the estimates. The other components of the beam transport lines are similar to those regularly purchased at CERN and their costs are well known.

The costs for the injection and beam dump systems are dominated by the kicker magnets and their pulse-forming networks. These devices have often been problems for past accelerators, requiring significant R&D. However, the state-of-the-art is now such that the largest uncertainty will be the cost reductions available by using the most modern components.

The cost estimates for these systems are conservative and include no items of appreciable risk.

3.3.4 Schedule

None of these systems are critical path items. In fact, none of them should take more than three years from start to finish at the budgeted cost. The designs of most of the components are well underway, with prototypes already under construction. Therefore, the schedule for these systems is very relaxed, adding a degree of flexibility to the LHC project.

3.4 Radio Frequency System

3.4.1 Summary

The RF system for the LHC has 16 superconducting cavities. In addition, there are two transverse damping systems and one longitudinal damping system in each ring. These systems are based on existing technology with little technical risk. The cost of 26 MCHF for these systems is reasonable, with little risk. The schedule for these systems has a two-year leeway and little risk.

3.4.2 Technical Scope

The RF system consists of eight superconducting cavities in each ring. They will be built at CERN using the facility developed for the LEP–II cavities. A 500-kW klystron drives each pair of cavities. Therefore, eight klystrons and their associated power supplies are required. The klystrons will be bought from industry and the power supplies will be recycled from LEP. The controls front-end and local processing are included in the technical scope and associated cost and schedule. This scope is complete and adequate. The system is based on existing systems.

The RF coupler is of a new design and entails some risk. Prototypes will be available by the end of the year and will be tested with a 500-kW klystron from SLAC. This design should be resolved well before the beginning of construction. A prototype cavity has been installed in the SPS for testing.

Two transverse and one longitudinal damping systems are required for each ring. The transverse systems in each ring must have the capability of damping the transverse oscillations introduced by injection errors. The power supplies for the dampers will be recycled from the SPS electron-positron RF systems. The controls for the damping systems are included and the scope is well understood and adequate.

Installation of the damping systems and the RF system is included in the estimates.

3.4.3 Cost

The RF cavity costs are based on recent experience with the LEP–II cavities. The LHC requires eight 500-kW klystrons, and the estimated cost per klystron is based on a recent PEP–II purchase of 1.2-MW klystrons. This should be conservative. The rest of the cost is based on existing technology and has little risk. The damping systems costs are based on existing systems and have little technical risk.

Adequate engineering talent exists at CERN to design and implement these systems. There is little technical risk from that standpoint.

3.4.4 Schedule

The construction of the RF cavities cannot begin until approximately two years from now, when the LEP–II cavities are complete. Nevertheless, the construction of 16 single-cell cavities can be readily completed before they are needed. The rest of the systems cannot be constructed until components from LEP are available in 2000. These will also be ready well before needed. There is adequate manpower to design these systems prior to the beginning of construction.

3.5 Vacuum System

3.5.1 Summary

The vacuum system includes three main parts: the beam vacuum in the cold bore tubes of the arc magnets, the warm vacuum systems in the straight sections, and the insulating vacuum system for the cryogenic magnets. The total cost for all vacuum systems is estimated at 79 MCHF. The cost estimates for each of the subsystems were reviewed and discussed in detail and each is considered adequate to meet the requirements. There should be little cost risk for the conventional insulating vacuum and warm vacuum systems since they are based on standard components. The cold beam vacuum system, comprising over half of the total cost, is based on a beam screen system that is presently under development and test. The manufacturing plans and costs for producing the screens and related items in quantity are considered reasonable and appropriate.

3.5.2 Technical Scope

The three primary vacuum systems required for the LHC consist of cold beam vacuum, cryostat insulating vacuum, and warm straight section vacuum. The largest and most challenging of these is the cold beam vacuum system. Although the cold bore tube provides great cryopumping capability, the synchrotron radiation power emitted by the beams and the resistive wall power loss of the beam tube could create a significant heat load for the 1.9 Kelvin cryogenic system. Therefore, an intermediate beam screen—a perforated copper-lined tube centered within each magnet cold bore tube—is provided to intercept this power at a higher temperature; the screen is maintained at a temperature between 5 Kelvin and 20 Kelvin by gaseous helium flow. Careful analysis of the beam screen system has been carried out to ensure the vacuum properties and mechanical properties can be maintained in a way that is consistent with the large-scale manufacturing capabilities necessary for producing approximately 45 km of cold beam tube and screen. Testing of full-length screen prototypes in the magnet string test facility is planned for the near future.

For the insulating vacuum and warm vacuum systems, both the scope of work and the selection of the components are more straightforward. Both of these systems, although very large in scale, are based on extending designs similar to those now in use both at LEP and other accelerator systems throughout CERN, and those accelerators have also made the scope of the procurements qualitatively familiar.

3.5.3 Cost

The beam screen and cold bore tube cost estimate was developed by examining the material costs and processing costs now envisioned for producing these elements in large quantities. Although the final design and manufacturing choices have not been optimized and finalized, the costs projected appear to be adequate to cover some flexibility in the design choices.

For the insulating vacuum and warm vacuum systems, the selection of components and unit pricing used in the estimate have been reviewed and are considered adequate to cover the requirements. Costs are also included in the estimate for cabling and controls, as well as design, installation, and testing. Estimates in these areas also appear to be reasonable and adequate for the required work scope.

In summary, the cost estimate of 79 MCHF is considered to be adequate.

3.5.4 Schedule

The overall schedule for meeting the vacuum system milestones is realistic and achievable. The insulating vacuum and the warm vacuum systems consist of standard components and present little or no schedule risk. The cold bore system requires final design development of the screen and support structure followed by test demonstration and verification. The vacuum group plans to install full-length prototypes in the magnet string test by the end of this year; satisfactory completion of these tests should ensure high confidence levels in meeting the overall milestones for the cold bore systems.

3.6 Beam Cleaning, Beam Observation, Controls, and Other Systems

3.6.1 Summary

The systems discussed here include the collimation systems used to remove unwanted beam, the global and local beam observation systems, the control system, and assorted systems used for hardware protection and personnel access. The total costs are estimated at 69 MCHF. Component designs are similar to existing equipment on other accelerators at CERN. The scope is relatively well defined and cost estimates appear reasonable.

3.6.2 Technical Scope

3.6.2.1 Technical Scope – Beam Cleaning

The beam cleaning system is required to remove the inevitable beam losses arising during normal operation. These losses can arise from protons being outside the RF acceptance region at injection and from diffusion mechanisms at high energy. Significant beam impinging on the superconducting magnets could cause the magnets to quench, stopping machine operation. It is estimated that if no cleaning were done, unwanted beam halo could exceed the quench threshold by three orders of magnitude. Beam halo can also cause unwanted backgrounds in the detectors. The beam cleaning systems required to solve these problems are comprised of primary and secondary collimators together with room temperature magnetic sweeping systems located in Intersections Three and Seven (see Figure 2.3). Retuning the dispersion suppressor for Insertion Seven to produce a residual dispersion wave is necessary for momentum collimation. The scheme to do this has not been finalized. Present understanding indicates that additional protection for the superconducting magnets immediately downstream of this region is not necessary.

3.6.2.2 Technical Scope – Beam Observation

The beam observation system consists of the global beam position and loss monitors (about 1,000 elements each) together with the stand-alone systems for beam-current, profile, and tune measurements. Beam position is measured in both planes at each quadrupole location to facilitate lattice function measurements. Provision has been made to provide small amounts of modulation of individual quadrupole magnet currents for beam-based measurement of the center of the beam position monitor relative to the magnetic center of the quadrupole. The loss monitor system provides the primary protection against magnet quenches from beam losses. These systems are similar in technical scope to hardware used in both the SPS and the LEP colliders. Costs for beam instrumentation for the injection lines and straight sections are included explicitly in the estimates for these systems.

3.6.2.3 Technical Scope – Controls

The control system includes the tunnel network and machine equipment interfaces needed to connect the subsystems to the machine network, together with software to implement the system. While the application software tends to be accelerator-specific, the system specifications are similar to those of the existing LEP network. A significant utilization of the existing networks, which continue to evolve under the ongoing operational program, is planned. The LHC control room will evolve from the present LEP facility.

3.6.2.4 Technical Scope – Other Systems

Personnel access will take place primarily in the existing LEP tunnel penetrations. Like other superconducting accelerators, the LHC will produce very low levels of systematic radioactivity outside of the interaction points, so extensive radiation monitoring will not be necessary.

3.6.3 Costs

The total costs for these systems are estimated at 69 MCHF, split as follows: beam cleaning system (7 MCHF), the beam observation system (28 MCHF), control systems (20 MCHF), access and radiation monitoring systems (8 MCHF), and contingency (6 MCHF). Since essentially all these systems are based on existing CERN designs, the unit costs are well understood. These costs compare quite closely to those obtained from analysis of U.S. facilities and, if anything, tend to be slightly conservative. The scope of the systems is, in general, well understood and appears to leave little risk of subsequent cost changes. The committee finds no reason to modify the cost estimate as presented.

3.6.4 Schedule

Few of these systems are needed before the end of LEP operation and the major activity in the next several years involves prototyping. The existing CERN system groups are adequate to implement these systems over the eight-year period available. The potential schedule impact arising from technical risk is low.

3.7 Civil Engineering

3.7.1 Summary

The civil engineering work for LHC is well defined for a project in the preliminary engineering design phase. Cost estimates are well documented and reflect anticipated final construction costs. The total cost of civil engineering for the LHC accelerator project is estimated at 144 MCHF. The civil engineering schedule supports the overall project schedule.

3.7.2 Technical Scope

The civil engineering scope included in the LHC accelerator cost estimate is comprised of the following:

- beam transfer lines between SPS and LHC (TI2 and TI8, both 3-meter diameter tunnels)
- beam dump systems (3-meter diameter tunnels and 9-meter diameter underground halls)
- underground work for powering, cryogenics, and installation
- surface buildings
- additional shielding.

The LEP/LHC underground enclosures are shown in Figure 2.3. Note that the LHC cost estimate for the accelerator project excludes civil engineering related specifically to experiments.

The scope of work is defined by the conceptual design documentation developed for the environmental impact study and for construction package planning. Review of this documentation by the committee concluded that the proposed scope is complete and adequate for this stage of the project. There were no high risk areas identified.

3.7.3 Cost

The scope of work was quantified from existing design documents in parametric form (e.g., meters of tunnels or shafts; square meters of buildings). Costing was derived from actual CERN experience with previous similar work (e.g., LEP). Costs reflect final contract values, and therefore, include an allowance for contingencies. Allowances were made for architectural engineering and construction management services.

The committee reviewed the scoping of the project from the existing design documents as well as the methodology used to determine estimated costs. This review concluded that the cost estimate is reasonable and credible. Contingency is adequately included within the unit costs used to develop the estimate.

3.7.4 Schedule

Preliminary engineering design is underway in anticipation of a start of physical construction in the second quarter of 1998. The schedule for civil engineering supports completion of facilities necessary for key milestones, such as the shut down of LEP and the completion of transfer line TI2 (first quarter of 2002, important since it is needed to support first beam testing). Completion of civil engineering is scheduled for the third quarter of 2003.

The committee reviewed the civil engineering schedule in detail and found it to be reasonable and supportive of the overall project schedule.

3.8 Services

3.8.1 Summary

The LHC relies heavily on the infrastructure developed for the LEP machine. The LHC accelerator project covers additions to the power distribution network and reconfiguration of the cooling and ventilating system. The cost of the power distribution network modifications is split between the machine and the experimental areas in proportion to the usage.

There is little cost risk in this estimate, and a reasonable probability that value-engineering efforts will reduce the cost.

3.8.2 Technical Scope

The water cooling system must be reconfigured to make room for additional cryogenic equipment and the reconfiguration of power supplies. The ventilation system must be modified to accommodate the reconfiguration of the buildings and the rearrangement of the technical components.

New high voltage feeders are required in two locations, and general utility power must be reconfigured and expanded to accommodate the new civil engineering.

3.8.3 Cost

The estimated cost of 52 MCHF is based on LEP experience and preliminary designs of the new configurations. There is little risk in the unit costs as these are derived from current experience at CERN. Similar work is undertaken routinely.

The configurations have not been optimized. Work is underway to reduce the cost. For example, adding an extension to the vaults for the cryogenic equipment and leaving the existing utilities essentially as they are may reduce the cost.

3.9 Installation

3.9.1 Summary

The LHC accelerator project cost estimate covers installation of the magnets in the ring. The interconnections and welding between the magnets are included, as is the alignment of the magnets. The estimated cost of 67 MCHF is adequate for the task.

3.9.2 Technical Scope

There are 1,232 14.2-m long dipoles and 498 3-m long quadrupoles to install and interconnect. The interconnection welds must be leak-tight and reliable, as repair is costly. The schedule calls for installing an average of nearly two dipoles per working day, with the remaining elements interleaved with the dipoles. The dipoles will be moved with new magnet movers because of their weight and size. All other components will be moved using the existing monorail system.

There will be a new access shaft at Region Two with which to lower magnets into the tunnel (see Figure 2.3). The plan is to move magnets from there to final positions at night (when there is no work going on in the tunnel) and to carry out the positioning, interconnections, and alignment during the day. After two octants are installed, they will be cooled and tested. This plan is feasible.

3.9.3 Cost

The projected cost for magnet installation is 67 MCHF. This includes the supports of the magnets and the tools and material for the interconnection of the magnets. Sixty trained welders will be required. There is little experience at CERN with such an intensive effort in field welding, but the cost numbers compare favorably with the experience at RHIC, where they are using similar techniques. The LHC staff will be able to take advantage of the RHIC experience by the time they are ready to begin magnet installation.

There is some risk that the interconnections will not go as smoothly as planned, but there are six years in which to work out the details prior to starting installation.

3.9.4 Schedule

The installation schedule is paced by the availability of magnets. The plan is to install the magnets over a three-year period after the LEP components have been removed. With 220 working days per year, the 1,232 dipoles will have to be installed at an average rate of 1,232/660 = 1.87 magnets per day. This is feasible but may require more than one of the special dipole movers.

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4. COST ESTIMATE SUMMARY

4.1 LHC Estimate Methodology

The accelerator cost estimate is based on the latest design report: *The Large Hadron Collider, Conceptual Design*, document CERN/AC/95-05 (LHC), dated October 20, 1995.

Whenever appropriate, the cost estimate was established following previous experience with the construction of CERN accelerators. The costs of systems similar to existing ones were determined analytically (sum of materials and labor costs) and/or synthetically (unit cost of complete components or systems). For the main magnet system, the cost estimate was made analytically, taking into account previous experience with the production of the HERA magnets in Europe and the RHIC and SSC magnets in the United States.

All the prices in the cost estimate are quoted in 1995 Swiss francs. This cost estimate includes all material costs incurred for the components, related tooling, and the additional civil engineering and technical services necessary to complete the LHC in the LEP tunnel. These costs also include, where appropriate, the price of manpower hired for specific jobs during the construction period.

The estimate does not include costs that may be incurred during the R&D phase, value of existing tooling, and environmental, safety, and engineering studies. Also excluded are the decommissioning of the LEP machine, modifications to the existing injector system, the experimental areas, spare parts, and preoperation costs. Following CERN accounting methods, CERN manpower is not directly accounted for in the project cost estimate but is indicated separately as man-years. All these items are included in the normal annual CERN operations budgets of years 1989 to 2009.

4.2 Cost Estimate Conclusions

The summary of the cost estimate presented by CERN is included in Appendix D. The committee reviewed the CERN estimate on the basis of the methodology described above. There were no variances identified. Comments on the LHC cost estimate by the committee are summarized in Appendix D. The committee observed that this estimate has the contingency built into the base estimate, unlike DOE estimates that explicitly identify contingency. The committee concluded that the cost estimate of 2,300 MCHF was adequate and reasonable for the defined scope and CERN estimate methodology.

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5. SCHEDULE

5.1 Overview

In an introductory statement, CERN's Director General C. Llewellyn-Smith noted that the LHC Project had been approved in late 1994 by the CERN Council. However, in order to reduce the construction period, CERN was encouraged to seek additional funding support from CERN non-member countries for constructing the machine. This recommendation is being pursued with promising success, and the LHC is setting a new scale in global scientific collaboration.

5.2 Assumptions

The estimated "cost of the LHC Project" by CERN is 2,300 MCHF. For planning purposes, it is currently assumed that sufficient contributions from CERN non-member countries will be obtained so that the project could be completed in "a single step" by the year 2005.

As part of the LHC project approval, CERN was told by the Council to assume a frozen budget for the three years following approval and, thereafter, a Swiss franc inflation rate of two percent, but a budget indexed at only one percent. The present CERN funding is 938 MCHF per year. Of this, it is expected that during the project about 200 MCHF per year, on average, will be dedicated to completing the LHC accelerator project.

Finally, consistent with the efforts of many CERN-member countries to reduce their numbers of national civil servants, CERN plans to reduce its staff from the present size of about 2,850 to about 2,100 by the year 2005. An estimate of the LHC project manpower requirements peaks at 570 CERN staff per year and sums to about 4,750 person-years over the life of the project.

5.3 Key Milestones

A critical near-term LHC milestone is the presentation of the next CERN Ten-Year Plan to the CERN Council in December 1996. As presently described, this plan will request approval to build the LHC in "a single step" to be completed in 2005. A critical feature in gaining approval of this plan will be success in gaining funding from CERN non-member countries.

A summary schedule is shown in Appendix E. Key project milestones include:

Quarter	Year	MILESTONE
2nd	1993	First 9 Tesla "2-in-1" Superconducting Magnet
4th	1994	Magnet String Test Start
4th	**1994**	**LHC Project Approved by Council**
2nd	1996	Civil Engineering Design Contracts Placed
4th	**1996**	**Ten-Year Plan Approval by Council**
4th	1997	First Cryoplant Under Contract
1st	1998	Superconducting Magnet Fabrication Contracts Placed
3rd	1999	Delivery of Superconducting Preproduction Magnets Begins
4th	1999	First Cryoplant Operational
	1999	Provisional LEP Shut Down
3rd	2001	Delivery of Superconducting Production Magnets Begins
2nd	2003	First Quadrant Magnet/Cryogenics Test
1st	2005	Superconducting Magnet Production Complete
3rd	2005	LHC Commissioning Begins

5.4 Schedule Evaluation

Extensive planning has taken place for a project at this early stage. A "formal scheduling system philosophy" has been developed. This system is based on a long history of successfully building accelerators at CERN. The most recent CERN experience was with an elaborate (but cumbersome and barely useful) formal scheduling system on the LEP project, recent experience in scheduling accelerator projects in the United States, and the widespread availability of user-friendly scheduling software packages.

A scheduling software package has been selected and is being used to develop three types of schedules: master schedules, coordination schedules, and detailed schedules. The LHC management anticipates about five each of the first two types of schedules as follows:

Master Schedules	Coordination Schedules
Main Ring	R&D and Design
Transfer Lines	Procurement
Injector Modifications	Manufacturing
Common Systems	Construction and Installation
Conventional Facilities	Tests and Commissioning

It is expected that there will be many tens of detailed schedules (perhaps even 100) that each group/institute/participating organization will develop to plan its work packages in detail.

A single integrated schedule of the type which evolved for high-level management use on LEP has also been developed for the LHC. Using this schedule, LHC personnel can acquaint interested persons with the entire project plan in 15 to 30 minutes.

The Main Ring Master Schedule and detailed schedules for several systems were presented during the review. Manpower loading iterations have already been made. Workflow continuity considerations also have been taken into account. These schedules, which support the Key Milestones listed above, were judged to be achievable by the committee.

There is an implicit commitment profile that accompanies these schedules. However, this profile was not discussed. LHC personnel are quite aware of the need for a "peaked" rather than "flat" profile for the optimal execution of a project. A method for achieving a peaked commitment profile while receiving a flat funding profile will be presented to the CERN Council for consideration as part of the proposed Ten-Year Plan.

A complete assessment of the proposed LHC project cannot be made until a self-consistent funding profile, commitment profile, and execution schedule are available as part of the CERN LHC Progress Review in 1997, which will be open to DOE.

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6. MANAGEMENT

6.1 Management Team

An experienced, dedicated management team is in place on the LHC project. The LHC Project Director has an enviable record of accelerator successes. The small Project Office plans and coordinates LHC activities, many of which are being accomplished in a "matrix management" mode by several CERN divisions. A management style has evolved over the last 15 months that is already proving to be effective, although it is different from the more dedicated project-staff style in which LEP was designed and built.

This development is particularly appropriate at this time for several reasons. There is a wider international participation in design and construction by an increased number of laboratories and institutes (e.g., quadrupole magnets at Saclay in France). With the planned reduction in CERN staff over the life of the project, even more of the work (including design and assembly) must be accomplished in industry. For these reasons, an effective method of planning and coordinating work by persons whom you do not "hire and fire" is required. Finally, it is viewed by CERN management that the "dedicated project-staff" method of performance is more expensive.

6.2 Management Tools

Appropriate formal management tools to successfully accomplish this increased coordination requirement are being considered and put in place. For example, the need for a widely accessible LHC set of formal baseline documentation is being addressed by putting this information on the World Wide Web. This Internet-based system has protocols for information transfer that are computer-hardware independent and can be used to easily access this information from anywhere on earth. The LHC project is adopting a "standard" set of software programs and versions to further facilitate the uniformity of information developed and viewed by all participants.

Configuration management considerations have been taken into account with the development of formal LHC design documents, including Design Process and Control and Design Standards, that are being applied to the 10,000 or more existing LHC drawings and to new ones.

An appropriate formal Quality Assurance system will be "grown" as LHC moves from the R&D and conceptual design stage into final design and production. Because of the increased sensitivity to limiting costs, the management and engineering staff plan to grow this system very carefully.

In summary, there is an experienced management staff in place, dedicated to a successful LHC, quite sensitive to the need for cost control, with a high probability of successfully delivering the LHC as planned.

Appendix A

DOE F 1325.8 (8-89) EFG (07-90)

United States Government **Department of Energy**

memorandum

DATE: February 27, 1996

REPLY TO ATTN OF: Energy Research

SUBJECT: Assessment of the Large Hadron Collider Project

TO: Daniel R. Lehman, Director
Construction Management Support Division, ER-65

In May 1994, the High Energy Physics Advisory Panel endorsed the subpanel's report on "Vision for the Future of High-Energy Physics," (DOE/ER-0614P). This report recommended to DOE and the National Science Foundation (NSF) significant U.S. participation in the accelerator and detectors of the Large Hadron Collider (LHC) project at CERN. In April 1995 and in August 1995, DOE and NSF officials held discussions with representatives of CERN on the prospects of participation in the LHC project. Negotiations were initiated with CERN officials in January 1996, and a cost assessment was discussed.

DOE is considering contributions of in-kind components and systems to the LHC accelerator portion of the project. University groups supported by both DOE and NSF have proposed taking responsibility for components and complete subsystems that are integral parts of the two large LHC detectors, ATLAS and CMS. The size of the U.S. investment in the LHC project will be determined by negotiations.

Because of the potential size of the U.S. investment in the LHC project, its importance to CERN, its impact on the U.S. High Energy Physics program, and its importance to U.S. participation in future international science projects, the Office of Energy Research will need to be able to substantiate to the Congress, and to elements of the Administration, that its investments in the LHC project are reasonable and able to achieve expected results.

Therefore, I request that you assemble a project team to assess: the cost estimate for the LHC machine, understand the basis for these elements, identify uncertainties, and judge the overall validity of the estimate; and the proposed schedule and related issues. This request supersedes my memorandum to you of October 20, 1995.

It should be noted that the construction schedule and funding profile will depend on the outcome of the negotiations between DOE, NSF and CERN, as well as CERN's discussions with other governments, and will be fixed in CERN's 1997 Review of the LHC Project. As part of, or pursuant to, this 1997 Review, I ask that your project team assess the final schedule and related issues.

By copy of this memorandum, the Office of High Energy and Nuclear Physics of the Office of Energy Research is directed to support you in whatever ways that are required by this endeavor. We encourage you to seek NSF support in areas where they have a significant participation.

Please provide me a written report within two months following the assessment.

James F. Decker
Deputy Director
Office of Energy Research

cc: W. Hess, ER-20
H. Jaffe, ER-20
J. O'Fallon, ER-22
R. Eisenstein, NSF

Appendix B

U.S. Department of Energy
Large Hadron Collider (LHC) Accelerator
Assessment Committee
April 22–26, 1996

Dan Lehman, Chairman (DOE)

Report Coordinator
Robert Diebold (DOE)

Support
Anna Bennington (DOE)

SC 1
Magnet System
WBS 1
* Jay Benesch (CEBAF)
John Carson (FNAL)
Phil Debenham (DOE)
Eugene Kelly (BNL)
Al McInturff (LBNL)
Richard Orr (FNAL-Retired)
Bruce Strauss (Consultant)
Stefan Wipf (DESY)

SC 2
Cryogenic System
WBS 2
* Claus Rode (CEBAF)
[Earle Fowler]

SC 3
Transfer Lines, Beam Injection,
Beam Dumping (WBS 3)
RF System (WBS 4)
Vacuum System (WBS 5)
Beam Cleaning & Observation,
Controls, etc. (WBS 6)
Services (WBS 8)
Installation (WBS 9)
* Lowell Klaisner (SLAC)
Mike Harrison (BNL)
Rolland Johnson (DOE/CEBAF)
Ron Yourd (LBNL)

SC 4
Civil Engineering (WBS 7)
Steve Tkaczyk (DOE)

SC 5
Schedule & Funding
Project Management
* Ed Temple (ANL)
Earle Fowler (DOE)
[Richard Orr]
[Ron Yourd]

SC 6
Cost Estimate Summary
* Steve Tkaczyk (DOE)

Observers
William Chinowsky (NSF)
John O'Fallon (DOE)

Total –	Committee	19
	Observers	2
		21

LEGEND
* Chairperson
SC Subcommittee
WBS Work Breakdown Structure
[ ] Part-time SC member

Appendix C

LHC Conceptual Design Assessment
Agenda
Auditorium Building 30, CERN

<u>Monday, April 22, 1996</u>

8:00 a.m.	*DOE Executive Session (Bldg. 30, Floor 7, Room 012)*	
9:00 a.m.	Welcome Address	C. Llewellyn Smith
9:05 a.m.	Overview of the Conceptual Design Cost and Schedule Management Structure	L. Evans
10:00 a.m.	BREAK	
10:20 a.m.	Cost Estimate Methodology	G. Drouet
10:40 a.m.	Experience from LEP	M. Buhler-Broglin
11:00 a.m.	Magnet O verview Technical Scope Cost Schedule	R. Perin /T. Taylor P. Proudlock/P. Sievers
12:30 p.m.	LUNCH	
1:30 p.m.	For Each of the Following Systems, Present an Overview of the: Technical Scope, Cost, and Schedule	
	Cryogenic System	P. Lebrun
	Transfer and Dumps	E. Weisse
	Radiofrequency	D. Boussard
	Vacuum	A. Mathewson
	Beam Cleaning	J.B. Jenneret
	Beam Observation	C. Bovet
	Controls	R. Lauckner
	Civil Engineering	J.L. Baldy
	Services	G. Drouet
3:15 p.m.	BREAK	
3:35 p.m.	Installation, Planning and Logistics General Schedule Quality Assurance	P. Faugeras
4:20 p.m.	Staffing Levels	M. Buhler-Broglin
6:00 p.m.	*DOE Executive Session (Bldg. 30, Floor 7, Room 012)*	

Tuesday, April 23 and Wednesday, April 24, 1996

Each subcommittee will meet with their LHC counterparts to discuss the details of the scope, cost, schedule, and management of each system. The meetings will be working sessions with the LHC staff taking the lead to present the backup information. Sessions need to be organized for efficient transfer of information. Detailed presentations may not be required depending on the topic. However, hard copies of discussion material will be needed by the assessment committee for use in preparing their report.

Subcommittees	WBS	Description	Meeting Location Bldg. Floor. Room
1	1	**Magnet System**	**30, 6, 041**
2	2	**Cryogenic System**	**30, 6, 015**
3		**Technical Systems**	**30, 4, 040**
	3	Transfer Lines, Beam Injection, & Beam Dumping	
	4	Radiofrequency System	
	5	Vacuum System	
	6	Beam Cleaning, Beam Observation, Controls and Other Systems	
	8	Services	
	9	Installation	
4	7	**Civil Engineering**	**54, 3, 035**
5	—	**Schedule, Funding & Project Mgmt.**	**30, 6, 017**
Other		Visitors' Office	30, 6, 013
		Visitors' Office	30, 6, 014
		Jill Karson-Forestier (Lyn's Sec.)	30, 6, 029

8:30 a.m. Subcommittee Reviews

12:00 p.m. LUNCH

1:30 p.m. Tour of magnet development and test facilities (Wednesday)

4:30 p.m. DOE Executive Session *30, 7, 012*

Thursday, April 25, 1996

	Subcommittee Report Drafting	
1:30 p.m.	Tour of LEP tunnel and L3 experiment	
4:30 p.m.	*DOE Executive Session*	*30, 7, 012*

Friday, April 26, 1996

	Subcommittee Report Drafting	
11:00 a.m.	*DOE Executive Session*	*30, 7, 012*
2:00 p.m.	DOE Closeout with CERN Management	30, 7, 012
3:15 p.m.	*DOE Executive Session*	*30, 7, 012*

Appendix D

CERN Cost Estimate for the LHC Accelerator Project (MCHF-1995 prices)

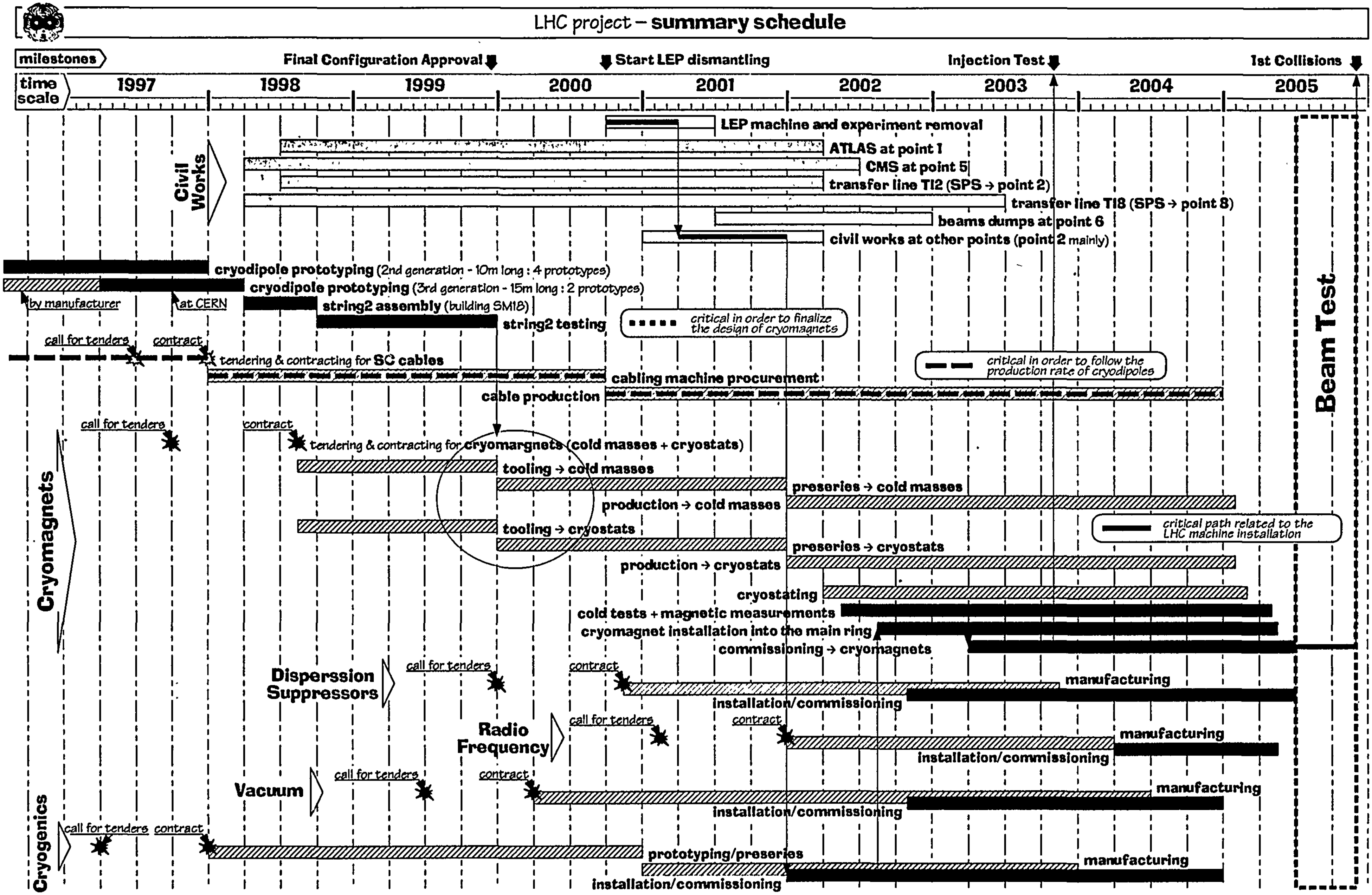
Level		System or Item	Total Cost
1		**Magnet System**	**1426**
	1.1	Magnets of all kinds in the arcs	862
	1.2	Magnets of all kinds in the dispersion suppressors	121
	1.3	Magnets of all kinds in the straight sections	77
	1.4	Powering and quench protection	123
	1.5	Tooling, test station and tests	148
	1.6	Contingency	95
2		**Cryogenic System**	**337**
	2.1-2.3-2.5-2.7	Cryogenics at Points 1-3-5-7	28
	2.2-2.4-2.6-2.8	Cryogenics at Points 2-4-6-8	170
	2.9	Cryoline	108
	2.10	Contingency	31
3		**Transfer Lines, Beam Injection and Beam Dumping**	**101**
	3.1	Transfer lines SPS/LHC	53
	3.2	Injection systems	11
	3.3	Beam dumping systems	37
4		**Radio Frequency System**	**26**
5		**Vacuum System**	**79**
6		**Beam Cleaning, Beam Observation, Controls and Other Systems**	**69**
	6.1	Beam cleaning	7
	6.2	Beam observation	28
	6.3	Controls	20
	6.4	Other systems	8
	6.5	Contingency	6
7		**Civil Engineering**	**144**
	7.1	Underground civil engineering for transfer lines	53
	7.2	Underground civil engineering for beam dumps	16
	7.3-7.4	Underground civil engineering for powering, cryogenics and installation	40
	7.5-7.6	Equipment buildings and shielding modifications	30
	7.7	Contingency	5
8		**Services**	**52**
	8.1	Electricity	12
	8.2	Cooling and ventilation	40
9		**Installation**	**67**
	9.1	Survey	13
	9.2-9.3-9.4	Installation	48
	9.5	Contingency	6
		TOTAL ACCELERATOR	**2300**

Version: November 1995

Committee Comments on the CERN Cost Estimate for the LHC Accelerator Project

Level	System or Item	MCHF 1995 Prices	COMMITTEE COMMENTS
1	Magnet System	1426	Mature technology exploited by competent people.
2	Cryogenic System	337	Based on previous LEP contracts, refrigeration costs are hard numbers subject only to market fluctuations. The estimates of labor costs for transfer lines are soft, but there is reasonable contingency based on sensitivity of costs to style of procurement. The cost estimated for the interface boxes are healthy, and require no contingency.
3	Transfer Lines, Beam Injection, and Beam Dump Systems	101	These systems include conventional accelerator components that are used at CERN and U.S. facilities. The costs presented compare well with existing installations and there is little cost risk.
4	Radio Frequency System	26	Cost based on recent experience with LEP-II superconducting cavities and recent purchases of high power klystrons by SLAC for B-Factory. The costs are conservative with little cost risk.
5	Vacuum	79	Half of the cost is based on recent prices of commercially available vacuum components. The other half is for the cold bore and screen. These components are under development but have little cost risk.
6	Beam Cleaning, Observation, Controls, Other Systems	69	These systems are based on existing CERN designs and the unit costs are well understood. They compare well with costs for similar elements at U.S. facilities.
7	Civil Engineering	144	Civil engineering is well defined and costs are adequate.
8	Services	52	This is conventional utility installation that is carried out routinely at CERN. The costs are based on recent experience at CERN.
9	Installation	67	The installation of cryogenic magnets on this scale is new to CERN. They have some limited experience with the string test. The cost estimate is comparable to that for similar activities at RHIC.
	TOTAL	2300	

Appendix E



LHC Project Summary Schedule

Appendix F

Glossary

BNL	Brookhaven National Laboratory (Upton, NY)
CDL	Cryogenic distribution line
CEBAF	Continuous Electron Beam Accelerator Facility (Newport News, VA)
CERN	European Laboratory for Particle Physics located outside Geneva, Switzerland)
cm	Centimeter
DESY	Deutsches Elektronen-Synchrotron, a high energy physics laboratory in Hamburg, Germany
DOE	U.S. Department of Energy
EDIA	Engineering, design, inspection, and administration
Fermilab	Fermi National Accelerator Laboratory (Batavia, IL)
GeV	Billion electron volts
He	Helium
HEPAP	High Energy Physics Advisory Panel
HERA	Hadron Elektron Ring Anlage, an electron-proton collider at DESY
IP	Interaction point
ISR	Intersecting Storage Rings
K	Kelvin
kA	Kiloamperes
KCHF	Thousand Swiss francs
KEK	High energy physics laboratory located at Tskuba, outside Tokyo, Japan
KHz	Kilohertz
km	Kilometer
kW	Kilowatt
LBNL	Lawrence Berkeley National Laboratory (Berkeley, CA)
LEP	Large Electron-Positron Collider (CERN)