LARGE HADRON COLLIDER IN THE LEP TUNNEL.

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Abstract

With LEP, electron-positron collisions up to 200 GeV will be exploited at CERN in four large experiments in the early nineties. In addition, a second collider (LHC) can be installed in the 27 km LEP tunnel, made of twin superconducting magnets with fields up to ~ 10 T. This collider could provide proton-proton collisions up to ~ 16 TeV and with high luminosity ($\geq 10^{33}$ cm^{-2} s^{-1}), and also electron-proton collisions of ~ 1.5 TeV with a luminosity of 10^{32} cm^{-2} s^{-1}. A final proposal is in preparation.

Introduction

CERN is building LEP, a 27 km ring for electron-positron collisions, initially at 50 GeV per beam to be eventually increased to 100 GeV (Fig. 1).

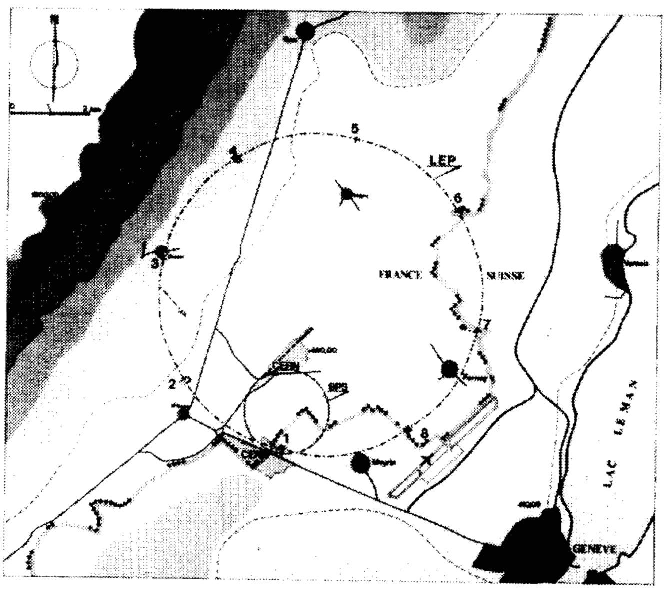

Fig. 1 : LEP in the Geneva area

The same basic infrastructure (tunnel, utilities, injectors, etc.) can be used in the future for the addition of a twin aperture proton ring made of superconducting magnets.

The tunnel circumference was chosen in 1981 as large as possible, compatible with the local geological structure, not only to reach an electron beam energy of ~ 100 GeV under optimal conditions but also the highest possible energy for the proton beams.

In such a case, proton-proton collisions up to 16 TeV in the centre-of-mass would become available in the LEP tunnel at several points around the ring with a luminosity of 10^{33} cm^{-2} s^{-1}. In addition, it would be possible to collide one of the proton beam with the electron beam of LEP at a centre-of-mass energy of 1.5 TeV (five times the one of HERA) with a luminosity of 10^{32} cm^{-2} s^{-1}.

The first feasibility study for the installation of the LEP tunnel of a second collider for hadron physics at high energy was carried out at the ECFA-CERN Workshop "Large Hadron Collider in the LEP Tunnel", held in March 1984[1]. Since then considerably more work has been done in order :

i) to determine the best configuration for the proton-proton option and its advantages with respect to a realistic proton-antiproton option,

ii) to assess the features of collisions between the electron beam of LEP and one proton beam of the LHC,

iii) to design a complete lattice, including insertions,

iv) to make tentative designs of magnets in the field range of 8 to 10 T, and to work out in more detail a European development programme for materials, models and prototypes toward this goal,

v) to outline where and how the various types of collisions could be exploited in the LEP tunnel.

This report gives a summary of the situation to-date.

Proton-Proton Collisions

Counter-rotating proton beams are guided by vertical magnetic fields of opposite polarities, so that one must provide either two different magnet systems or at least two channels (apertures) in a common yoke (Fig. 2).

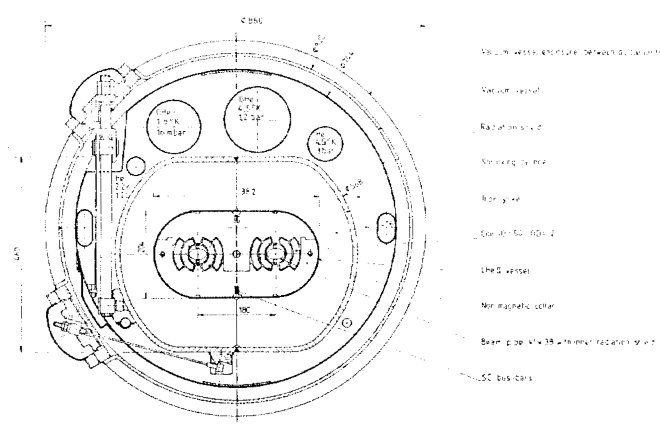

Fig. 2 : LHC, 10 T, twin-aperture dipole. Cross-section

We have tentatively chosen the latter solution for two reasons :

1) it leads to the most compact structure, which makes it possible to reach a field of ~ 10 T in the dipoles, within the dimensional constraints imposed by the existing tunnel,
2) it certainly represents the most economic solution (practically the same amount of materials and workmanship as for one aperture, except for the superconducting coils).

The magnets and their development programme are discussed in Section 3.

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The most important parameters for pp collisions in an experiment are :

Centre-of-mass energy $\sqrt{s}$ = 16 TeV (for 10 T dipole field)
Luminosity $L \approx 10^{33}$ cm^{-2} s^{-1}

The optimisation of the cell length in terms of maximum reachable energy and dynamic aperture was studied in detail. Different cell lengths were considered between 79 m (the present LEP cell length) and 158 m. The cells retained for the comparison were based on the following preliminary choices. Firstly a simple structure of periodicity 8, i.e. with 8 identical arcs, was considered in order to avoid that the two rings be different.This implies an odd number of half-celles in every standard arc, the length of which is equal to 2449 m. The arcs are joined by a 886 m length sector which include dispersion suppressors at either end, straight sections, beam separation dipoles, and the low-β insertion proper. Secondly, two values of phase advance per cell were singled out, i.e. 60° amd 90°, since the first one allows to build achromats in the absence of random multipoles in dipoles and the other one favours longer cells (higher maximum energy). Consequently, we studied 60° and 90° cells with a length of 80.3, 99.96, 119.46 and 158 m. Depending on the number of dipoles per half-cell and of the quadrupole length needed, the maximum energy reachable with these structures ranges approximately between 0.8 and 0.9 TeV per Tesla of the dipole field.

The choice between these lattices was based on criteria concerning the stability of the betatron motion. Since the persistent current effects appear at low energy, the injection conditions were considered (insertion β's increased by a factor 4) assuming the fractional part of the tunes equal to 0.25 and the chromaticity corrected with 2 sextupole families. Three different criteria have been used. The first one based on SPS experience deals with the tune shifts which should not bring the working point on strong resonances. This implies that at injection, the sum of the tune shift with amplitude for 4 r.m.s. beam size and of the tune spread for momentum deviation between ± 1.5 ^{0}/oo must remain smaller than 0.045. The second criterion concerns the smear of the betatron amplitudes : the r.m.s. relative variation of the sum of the transverse invariants must be kept below 3.5%. The last criterion states that the dynamic aperture must be at least equal to 4 times the r.m.s. beam size at injection; the dynamic aperture is defined here as the largest stable amplitude calculated for a restricted aperture given by the physical aperture (0 ± 40 mm) reduced by the closed orbit (3 mm) and the momentum dispersion ($\Delta p/p$ = 1.5 ^{0}/oo). Numerical tracking was used to calculate the relevant quantities. All three criteria agreed in demonstrating that the cell length should not exceed about 100 m and 120 m for a phase advance of 60° and 90° respectively. The 90° phase was retained since it allows longer cells and there is no obvious advantage to use achromats in a ring with strong random multipoles. The final value of the cell length was then chosen to be ~ 100 m assuming that there are 4 dipoles per half-cell of a length smaller than 11 m.

Beam stability and satisfactory behaviour are based on the tolerances, which can be maintained in the magnet system with well controlled production processes.

If wanted, proton-proton collisions can be made to occur at the centre of any of the eight LEP straight-sections, with the exception of the one devoted to the beam disposal system.

The complete parameter list is given in Table 1.

Table 1 : Parameters for pp Collisions

LHC PERFORMANCE

Number of bunches		3564
Bunch spacing		25 ns
Number of crossing points		8
β value at crossing points		1 m
Normalized emittance $4\pi\gamma\sigma^2/\beta$		5π μm
RMS beam radius		11.76 μm
Full bunch length ($4\sigma_s$)		0.31 m
Full crossing angle		96 μr
Maximum energy		~ 8 TeV
Circulating current	87.3	164.3 mA
Particles/bunch	1.36×10^{10}	2.56×10^{10}
Beam-beam tune shift	1.3×10^{-3}	2.5×10^{-3}
Stored beam energy	62.10	116.88 MJ
Luminosity	4.02×10^{32}	1.42×10^{33} cm^{-2} s^{-1}
Luminosity/collision	1.00×10^{25}	3.55×10^{25} cm^{-2}
<n> at Σ = 100 mb	1.00	3.55

MAGNETS

Maximum dipole field	10 T
Maximum quadrupole gradient	250 T/m
Eff. gap between dipoles	1.15 m
Eff. gap between dipoles and quads	1.09 m
Horizontal dipole corrector strength	1.5 Tm
Vertical dipole corrector strength	1.5 Tm
Maximum SF sextupole strength	1000 T/m
Maximum SD sextupole strength	4000 T/m
Ramping time	20 min
Vacuum chamber inner diameter	41 mm
Vacuum chamber height	38 mm
Coil inner diameter	50 mm
Horizontal separation between orbits	180 mm

PARAMETERS OF THE RF SYSTEM

Harmonic number	35640
Frequency	400.8 MHz
Momentum compaction	3.035×10^{-4}
<u>At injection energy</u>	450 GeV
Bunch area	1.0 eVs
Bucket area	1.79 eVs
Circumferential voltage	11.85 MV
Synchrotron tune	6.68×10^{-3}
Synchrotron frequency	75.181Hz
Bucket half height	1.25×10^{-3}
<u>At operating energy</u>	8.000 TeV
Bunch area	2.5 eVs
Bucket area	7.5 eVs
Circumferential voltage	11.85 MV
Synchrotron tune	1.60×10^{-3}
Synchrotron frequency	18.0 Hz
Bucket half height	2.95×10^{-4}

TYPICAL LHC PERIODS

Cell length	99.9592 m
Bending angle	28.612 mr
Phase advance	π/2
Number of quadrupoles	2
Effective quadrupole length	3.08 m
Number of dipoles	8
Effective dipole length	9.54 m
Maximum β value	169.4 m
Minimum β value	29.5 m
Maximum dispersion	1.933 m
Minimum dispersion	0.932 m
Bending radius	2668.5 m
Normalized emittance $4\pi\gamma\sigma^2/\beta$	5π μm

TYPICAL LHC PERIODS (Cont'd)

At injection energy	450 GeV
Vertical beam radius (4σ)	2.66 mm
Horiz. beam radius ($4\sigma + D\delta_d$)	5.08 mm
At maximum energy	8.000 TeV
Vertical beam radius (4σ)	0.63 mm
Horiz. beam radius ($4\sigma + D\delta_d$)	1.20 mm

Electron-Proton Collisions

With two machine structures in the same tunnel, it would be possible to collide the electrons of LEP with the protons circulating in one of the apertures of the superconducting magnets.

In the most promising configuration the electron beam is deviated upward and made to collide head-on with the proton beam which is located at 0.86 m above the present LEP beam level.

A feature of these collisions is that with a fixed maximum proton beam energy, the considerable radio-frequency power installed in LEP can be used either to maintain the electron beam at its highest energy and hence obtain the highest centre-of-mass energy, or to increase the electron beam current at lower energy, sacrifying therefore the centre of mass energy ($\sqrt{s}\ \alpha\ E_e^{1/2}$), but increasing considerably the luminosity (Fig. 3).

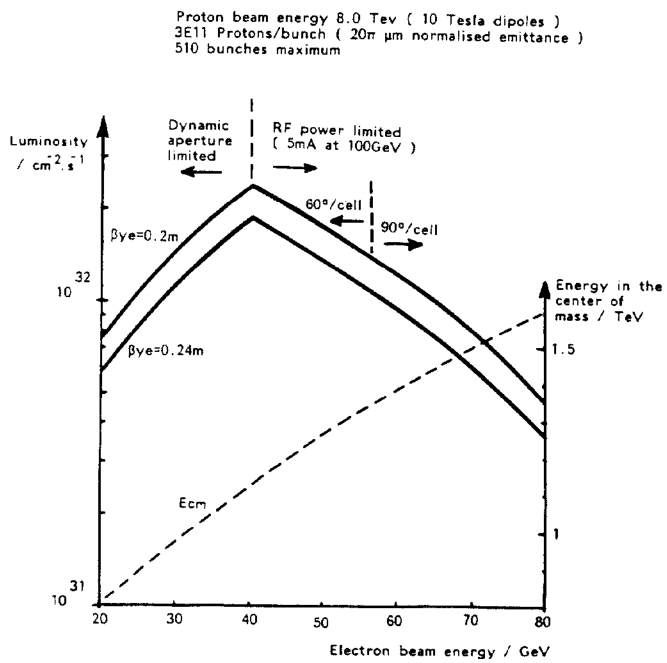

Fig. 3 : Luminosity in e-p collisions between LEP and LHC

In summary the most important parameters of ep collisions in an experiment are :

Centre-of-mass energy $\sqrt{s}$ = 1.4 to 1.8 TeV
Luminosity L = 10^{32} to 10^{31} cm^{-2} s^{-1}

where the highest luminosity if associated to the smallest energy and vice-versa.

The parameters of the ep collisions are given in Table 2 (for a max. number of 3 experiments).

Table 2 : General Parameters for the ep Option

Proton beam	
Number of particles per bunch	3×10^{11}
Number of bunches	510
Bunch spacing (ns)	164.8
Normalized emittance (μm)	20 π
Vertical β.value at crossing point (m)	2.8
Horiz. β-value at crossing point (m)	91
Particle energy (TeV)	8.0
Beam-beam tune shift parameter	≤ 0.003
Electron beam	
Number of particles per bunch	8.6×10^{10}
Number of bunches	510
Bunch spacing (ns)	164.8
Horizontal emittance (nm)	49.5
Vertical emittance (nm)	3.6
Vertical β-value at crossing point (m)	0.24
Horiz. β-value at crossing point (m)	1.37
Particle energy (GeV)	50
Beam-beam tune shift parameter	0.03
Performance at these energies	
Luminosity (cm^{-2} s^{-1})	1.37×10^{32}

Magnet System

Design studies and calculations carried out to-date are based on the following :

i) field range 8 to 10 T,

ii) use of NbTi conductor at 2 K, or of Nb_3Sn (or other A-15 compound) at 4.5 K,

iii) two-shell coils, surrounded by Al. collars and (split) cold iron to form the so-called "hybrid" structure,

iv) "two-in-one" configuration for pp collisions,

v) inner coil diameter d_0 = 50 mm.

The most demanding case in terms of mechanical and cryogenic design and space is a "two-in-one" 10 T dipole of ~ 10 m physical length, cooled by He II at ~ 2 K. A preliminary design was made for the current cross-section, the suspensions, the ends and their junction.

Such dipoles could be fitted in the available space in the LEP tunnel, above LEP. (Fig. 4)

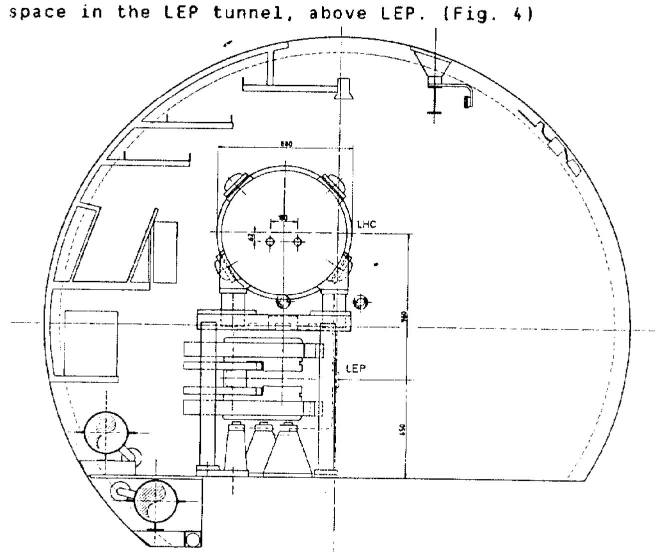

Fig. 4 : Regular LEP tunnel cross-section with LHC dipole

Tentative specifications of the superconducting wire are :

Wire diameter	0.7 to 1.2 mm
Critical current density at 11 T, 4.2 K (over the whole wire cross-section and at $\rho = 10^{-14}$ Ωm)	650 A/mm^2
Percentage of stabilizer copper in the wire cross-section	≥ 50%
Copper resistivity ratio (RRR)	≥ 100
Effective filament diameter (as deducted from magnetization measurements)	≤ 10 μm and possibly ~ 5 μm
Twist pitch	20 to 30 mm

The present design of the windings features a two-layer coil with graded current densities. The conductors of the two layers are different in cross-section and shape, though carrying the same current. The ratio between the current density in the outer layer and the current density in the inner layer is about 1.7. Trial productions of such high current, high aspect ratio (width to thickness) cables have been made in industry.

Dipoles

Preliminary parameters of the dipole magnets are given in the following table :

Table 3 : Preliminary Parameters of the Dipole Magnets

Nominal field		10 T
Peak field in the windings		< 11 T
Current density (averaged across the coil area)	inner layer	345 A/mm^2
	outer layer	575 A/mm^2
Nominal current		~ 15.5 kA
Stored energy (for the full two-in-one magnet)		~ 670 kJ/m
Ramping time		600 s
Coil inner diameter		50 mm
Distance between gap center lines (intra-beam distance)		180 mm
Transverse size of active part	width	560 mm
	height	460 mm
Outer diameter of cryostat (1.8 K version)	at magnets	820 mm
	at junctions	880 mm
Overall weight		~ 1.85 t/m
Cold mass		~ 1.6 t/m

With this design, it was possible to determine the expected field errors due to various causes, in terms of the multipole components expressed by :

$$B_y + i B_x = B_0 \Sigma (b_n + i a_n)(Z/R_r)^{n-1}$$

where B_0 = magnitude of dipole field in the y (vertical) direction

b_n = normal multipole coefficient

a_n = skew multipole coefficient

b_1 = 1

a_1 = dipole x-component

b_2 =)) quadrupole components
a_2 =)

$Z = x + iy$; R_r = reference radius

The calculated components are given in the two summary tables hereafter, for systematic and random errors respectively.

Table 4

Summary Table for Systematic Multipole Components

(Normalized for R_r = 1 cm, in 10^{-4} units)

B_0 (T)	0.5	1	2	6	8	10
a_2	± 0.6	± 0.6	± 0.6	± 0.6	± 0.6	± 0.6
b_2	± 1.6	± 1.6	± 1.6	-0.2 ±1.6	-0.8 ±1.6	-2.4 ±1.6
a_3	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1
b_3	-3.7 ±1.0	-1.5 ±1.0	-0.5 ±1.0	0.68±1.0	1.2 ±1.0	1.6 ±1.0
a_4	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03
b_4	± 0.05	± 0.05	± 0.05	-0.1 ±0.05	-0.2 ±0.05	-0.4 ±0.05
a_5	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03
b_5	0.45±0.11	0.18±0.11	0.06±0.11	-0.02±0.11	-0.03±0.11	-0.05 ±0.11
a_7	± 0.01	± 0.01	± 0.01	± 0.01	± 0.01	± 0.01
b_7	± 0.15	± 0.15	± 0.15	± 0.15	± 0.15	-0.007±0.15
a_9	± 0.001	± 0.001	± 0.001	± 0.001	± 0.001	± 0.001
b_9	± 0.04	± 0.04	± 0.04	± 0.04	± 0.04	± 0.04

The table corresponds to 5 μm filament diameter.

Table 5

Summary Table of Random Multipole Components

(standard deviation for R_r = 1 cm, in 10^{-4} units, at injection field)

	Main contributions		
	Fabrication tolerances, alignment errors, etc.	Persistent current	Total
a_1	5		5.0
b_1	5.4		5.4
a_2	1.7		1.7
b_2	1.2		1.2
a_3	0.5		0.5
b_3	1.5	0.20	1.6
a_4	0.20		0.20
b_4	0.15		0.15
a_5	0.07		0.07
b_5	0.20	0.022	0.20
a_7	0.04		0.04
b_7	0.02		0.02
a_9	0.002		0.002
b_9	0.005		0.005

The table corresponds to :

- 5 μm filament diameter
- 5% random variation of superconductor magnetization.

The lower-order components, and primarily the sextupole (b_3), was taken into account to determine the maximum allowable cell length, leading to the maximum beam energy for a given field namely 0.85 TeV/T.

Quadrupoles

As the quadrupoles will be excited in series with the dipoles it was necessary to update their design. The main results of a preliminary study are reported in the list of parameters of Table 6. The new design features two layers windings with graded current densities as for the dipoles. The cable, of different cross-section on the two layers, would have the same width (~ 12 mm).

Table 6
Preliminary Parameters of the Quadrupole Magnets

Nominal gradient		250 T/m
Peak field in the windings		≤ 7.5 T
Current density, averaged over the coil cross-section	inner layer	475 A/mm^2
	outer layer	740 A/mm^2
Nominal current		15.5 kA
Stored energy (full "two-in-one" quad.)		180 kJ/m
Coil inner diameter		50 mm
Distance between gap center lines		180 mm
Transverse size of active part	width	430 mm
	height	250 mm
Weight		~ 0.7 t/m

Injection and Beam Transfer

The existing CERN 450 GeV superproton-synchrotron (SPS) will be used as injector of the LHC. It can provide proton bunches containing more than 10^{11} particles and it can cope with a total number of particles of about 3×10^{13} per pulse. Its typical repetition time is about 10 s which makes it easy to provide in about 100 s the 10^{14} particles required for each ring of the Hadron Collider. The same injector can also provide electrons for the ep options as it is the injector of LEP.

There are some possible variants to transfer the beam from the SPS to the LHC. The most interesting ones has the shortest beam transfer lines SPS to LHC and has been chosen.

Since the circumference ratio LHC/SPS is 27/7, the LHC can be filled by four SPS pulses. Each SPS pulse consists of a bunch train which is added behind the preceding one already circulating in the LHC ("box-car" stacking). The bunch train is ejected from the SPS and injected into the LHC using fast deflecting kicker magnets. The bunch-to-bunch distance is too small for the kicker field to rise between two bunches at this energy. It is proposed to leave an azimuthal gap of 0.5 to 1 μs in the SPS beam so that the kicker field (ejection SPS, injection LHC) can rise in this gap without disturbing the preceding bunch and providing full field for the first bunch to be deflected.

The spacing between two bunches collisions T_x can be adjusted in the interesting range between 5 and 35 ns with the sufficiently fine stepsize of 5 ns. Higher values 50, 60, 75, 100 ns etc. are also possible.

Possible experimental Programmes

As seen above, the installation of a second collider structure in the LEP tunnel opens up unequalled possiblities of creating collisions between various types of particles up to very high energies. It is planned to operate LEP up to ~ 4000 hours per year and therefore several months would be available every year for installing in the arcs the new magnet structure which includes the distribution of the cryogenic fluids.

Once the LHC is installed, it is useful to consider a scenario in which the two colliders (LEP and LHC) could be exploited in the same operational year, consisting of two main periods, one devoted to electron-positron and the other to proton-proton (or proton-electron) collisions.

The conditions would be :

i) Initially two to three new experimental areas are opened up for the LHC, each one consisting of a beam enclosure and a garage position,

ii) The experiments would be taking data when their collider is in operation, or in their garages when the other collider is in operation. Of course, the beams pass through unused experimental areas in removable vacuum pipes*.

The evolution with time could be that some or all of the present LEP experiments are transformed for pp collisions and work in their present areas, possibly adapted for this new use.

Conclusions

The simultaneous existence on the CERN sites of powerful high quality injectors with record performance and of the LEP tunnel and the related infrastructure opens up a wide range of possibilities within the same facility with optimal cost effectiveness.

The studies and the preliminary design work carried out to-date indicate that :

i) excellent machine optics exist, which satisfy all requirements of beam stability and ensure a very good performance of the collider for both proton-proton and proton-electron collisions,

ii) reasonable scenarios for the running of LEP and LHC can be established,

iii) suitable superconducting magnet system with a dipole field in the range of 8 to 10 T can be built, but require a vigourous development programme for materials and cryogenics (2° K) and for the construction of magnet prototypes.

* In the case of experiment L3, which cannot be withdrawn as a whole, the central detector should be removed.

Acknowledgement

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The author is indebted to the members of the LHC Sub-panel for their substantial contributions, and to the Long Range Planning Committee and its Chairman for many stimulating discussions.

References

1 Large Hadron Collider in the LEP Tunnel. ECFA-CERN Workshop, Lausanne and Geneva, March 1984 Vol. 1, ECFA 84/85, CERN 84-10, 5 Sept.1984.