THE LARGE HADRON COLLIDER (LHC) IN THE LEP TUNNEL

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Introduction

The installation of a second collider in the LEP tunnel was envisaged since the very beginning of the project in 1981. In 1984 a feasibility study, successively refined and improved, has shown the possibility of producing proton-proton collisions with an energy of 16 Tev and electron-proton collisions with an energy up to 1.8 Tev in the center of mass.

A ring of superconducting twin aperture magnets can be installed above LEP. The existing CERN chain of accelerators, Linacs, Booster, PS and SPS, which is already the injector of LEP, will also become the injector for LHC. As the SPS has already accelerated ions (Oxygen and Sulphur), collisions between ions can also be envisaged in LHC.

The LHC project has already been described [1], and this paper will mainly deal with the more recent studies and developments :

- a trend towards higher luminosities, up to 10^{34} for proton-proton collisions and up to 10^{32} $cm^{-2}s^{-1}$ for electron-proton collisions.
- the R&D program of superconducting magnets, which has given a promising result with the successful tests of the first magnet model. Collaborations with national institutes and industry have been established for the study and realization of new 10 T dipole models and prototypes.
- The construction work of new experimental areas and the installation of LHC, can be done without long interruption of LEP operation.

Finally it is underlined that the existence of the LEP tunnel and infrastructure and of the injectors makes the project particularly attractive from the economic point of view.

Towards high luminosities

Proton-proton performance

Physicists are expressing a strong interest for high luminosities in LHC, since the effective mass reach of a p-p collider for constituents is about one order of magnitude less than the sum of the proton beam energies and is determined both by the proton energy and the luminosity [2]. Assuming that a non-magnetic detector able to deal with a luminosity up to $5*10^{34}$ $cm^{-2}s^{-1}$ is feasible after a vigourous R&D program, the estimated "discovery limits" are listed in Table I [3] for the nominal luminosity (10^{33}) and a hypothetic high luminosity of $5*10^{34}$.

Possibilities of increasing the nominal LHC luminosity have been studied [4].

The luminosity is given by

$$L = \frac{k N^2 f_0 \gamma}{\pi \varepsilon \beta^*}$$

where k is the number of bunches in each beam, N the number of particles per bunch, f_0 the revolution frequency, γ the relativistic factor, ε the normalized transverse emittance ($\varepsilon = 4\sigma^2 \gamma/\beta$) and β^* the amplitude of the betatron function at the crossing point (round beams assumed). Normally, the total number of particles kN is made of four SPS batches injected into the LHC.

Table I
Discovery limits (TeV/cm^2)

Physics				Luminosity ($cm^{-2}s^{-1}$)	
				10^{33}	5.10^{34}
Higgs	$H \to ZZ$	$\to$	$\mu^+\mu^-\mu^+\mu^-$	-	0.7
		$\to$	$l^+l^-l^+l^-$	0.3	0.8
		$\to$	$l^+l^-\nu\bar{\nu}$	0.6	0.6
	$H \to WW$	$\to$	$l\nu jj + qq\text{tag}$	0.8	X
SUSY		$\tilde{g} \to q\bar{q}\tilde{\gamma}$		1	2
		$\tilde{q} \to q\tilde{\gamma}$		1	2
Superstring Z'		$\to$	$\mu^+\mu^-, e^+e^-$	4	6

The number of bunches can be increased by reducing the bunch spacing from 25 ns to 5 ns by step of 5 ns, due to the SPS 200 MHz RF. Since the maximum number of particles which can be accelerated in the SPS is $4*10^{13}$ p, very small bunch spacings would require the injection into the LHC of an increased number of SPS batches, with some loss of efficiency due to the gaps between batches needed to accomodate the kicker rise-time. A bunch spacing of 15 ns appears as a good compromise.

Due to limitation in the low energy injectors, the total number of particles kN cannot be increased without increasing at the same time the transverse emittance, which partly counterbalances the gain in luminosity.

An upper limit for N is given by the beam-beam tune shift, defined for round beams at crossing point by $\Delta Q = N r_p/\varepsilon$, where r_p the classical proton radius. One may have to reduce the number of crossing points from 4 to 2 during the high luminosity runs, in order to maintain the total beam-beam tune shift below the tolerable limit of ΔQ=0.01.

The focusing at the crossing point can also be increased. It has already been shown [6] that a β^* of 0.5 m can be achieved while maintaining a free space of $\pm$ 20 m for the detectors and by using quadrupoles with gradient not exceeding 250 T/m and a coil internal diameter of 50 mm, as in the design report [1]. While studies are continuing, reducing the free space to $\pm$ 10 m, should allow a β^* of 0.25m in the high luminosity insertions. This reduced free space is compatible with a more compact detector used in this case.

Table II summarizes the main LHC performances in the nominal case [1] and in two high luminosity cases where the SPS intensity reaches its maximum with respectively 4 and 8 SPS batches injected into LHC.

Table II
Possible LHC Performance

	NOM.	HIGH LUMIN.	
No.SPS Batches	4	4	8
LUM. (10E34 cm-2s-1)	0.14	0.82	2.3
BEAM ENERGY (MJ)	117	208	416
SYN.RAD.POWER (kW)	4	7	14
SYN.R./unit length (W/m)	0.24	0.42	0.83
EMITTANCE (π 10-6 m)	5	7	11
No. protons/bunch (10E11)	0.26	0.3	0.64
BEAM-BEAM PAR.(10E-3)	2.5	2.2	2.9
No. protons in PS (10E13)	0.21	0.4	0.9
BUNCH SPACING (ns)	25	15	15
ß* at X.ING (m)	1	0.25	0.25
No. of bunches	3564	5940	5940

The increased transverse emittance remains below the value needed for the e-p option, and the intensity stays below the threshold expected for collective phenomena.

Nevertheless severe limitations may arise at high intensities :

- the amount of particle losses which can be tolerated in superconducting magnets is extremely small [5] and a sophisticated but safe system of restricting aperture collimators has to be designed.

- the power emitted through synchrotron radiation has to be absorbed by the cryogenic system, which increases the operational costs.

Electron-Proton Performance

With two machines in the same tunnel , it will be possible to collide the electrons of LEP with the protons of one of the LHC ring . The electron beam is deviated upward and made to collide head-on with the proton beam of 8 Tev.

Adequate RF power is available from the LEP RF system to compensate the synchrotron radiation losses for an average circulating current of 5 mA at 100 Gev . This corresponds to the highest centre-of-mass energy of 1.8 Tev . Assuming that the electron beam current scales as E-4 , a current of 80 mA would be possible at 50 Gev with the centre-of-mass energy reduced only to 1.3 Tev (E1/2 scaling).

The smallest bunch spacing must be a multiple of the LEP and the SPS RF wavelengths . This is possible with a maximum of 540 bunches in both beams where the bunch spacing becomes 164.8 ns (49.4 m). Assuming three interaction regions, the beam-beam tune-shift limit is not reached for a number of electrons per bunch $N = 8.2*10^{10}$ and a number of protons per bunch $N = 3.0*10^{11}$ with an increased normalized proton emittance ε = 20 mm.mrad. In those conditions with a proton energy of 8 Tev and an electron energy of 50 Gev, the nominal luminosity is $2.7*10^{32}/(cm^2*s)$

Lattice

LHC being in the same tunnel as LEP will also have eight arcs and eight long straight sections. The two protons beams, horizontally separated by 180 mm in the arcs, alternate from the outside to the inside in the middle of each ot the 8 long straight sections, where in principle they can interact.

The LHC lattice [6] of FODO type is constituted by :

- 8 arcs, each of them containing 49 half cells

- 8 insertions, each of them containing one long straight section and two dispersion suppressors of a type that allows to have trajectories of identical length for the hadrons in LHC and for the leptons in LEP.

For each ring an antisymmetric design is adopted, in which corresponding quadrupoles have equal and opposite strength on either side of an interaction point (Fig 1).

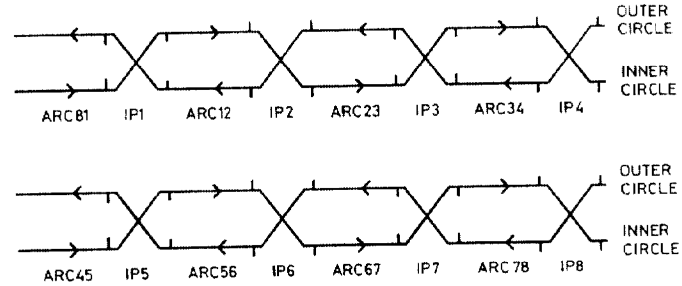

Fig. 1 Crossing geometry and quadrupoles polarities in the LHC insertions

The present design considers three intersections with low-β configuration for p-p or e-p experiments, one for beam dumping, the four others with high-β configuration corresponding to straight-sections where present LEP experiments are installed. The injection devices are housed in one of the experimental insertions.

Magnets and cryogenics

The LHC magnet system

Since the circumference of the LHC orbit is fixed by the LEP tunnel, a magnetic field as high as possible must be obtained in the guiding dipoles. In order to reach the top energy of 8 Tev per beam, a nominal field of 10 T is needed.

The superconducting coils providing equal but opposite magnetic fields have a common iron yoke and force-retaining structure (Fig 2), the whole being housed in one cryostat. This "two-in-one" solution allows the highest possible field in the restricted space above LEP [7], and has not only the advantage of compactness but also of lower cost, compared with that of two independent rings with separate cryostats. The required current density and magnetic field of 8 to 10 T can be reached either by a NbTi conductor operating at 2 K and cooled by superfluid He or by a Nb_3Sn conductor operating at 4.2 K , both technologies beeing applicable and economically feasible provided the R&D programme already undertaken is vigourously pursued.

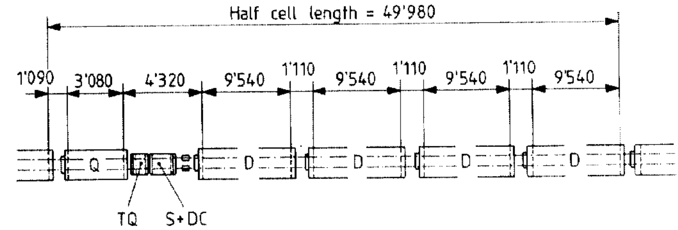

Fig. 2 Standard half-cell

One half of a regular cell (Fig 3) consists of four, ~ 10m long, dipoles (D), a focusing (or defocusing) quadrupole (Q), a tuning quadrupole (TQ), a combined sextupole/dipole corrector (S+DC) and a beam observation station. All these magnets are superconducting. Their approximate number and main characteristics are given in Table 3.

Table III
General characteristics and number of magnets
(for 8 TeV beam energy)

		Magn. Length (m)	Number of magnets
Dipoles	B_0 = 10 T	9.54	2 x 1760
Quadrupoles	G' = 250 T/m	3.08	2 x 552
Tun. quads.	G = 120 T/m	0.72	800
Sextupoles	B'' = 3640 T/m^2	1.1	800
H Corr. dipoles	B_0 = 1.36 T	1.1	400
V Corr. dipoles	B_0 = 1.36 T	1.1	400

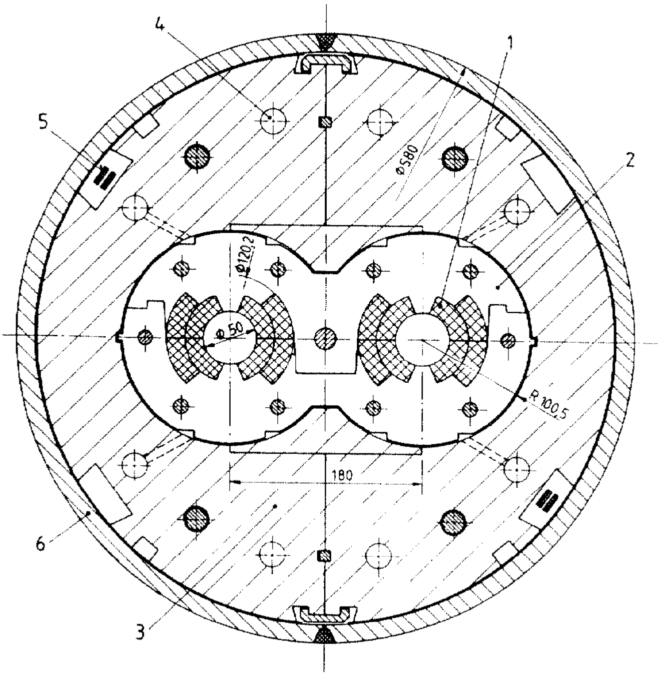

Fig. 3 Cross-section of a dipole model
1) coils, 2) collars, 3) iron yoke
4) Helium duct 5) bus-bars
6) shrinking cylinder

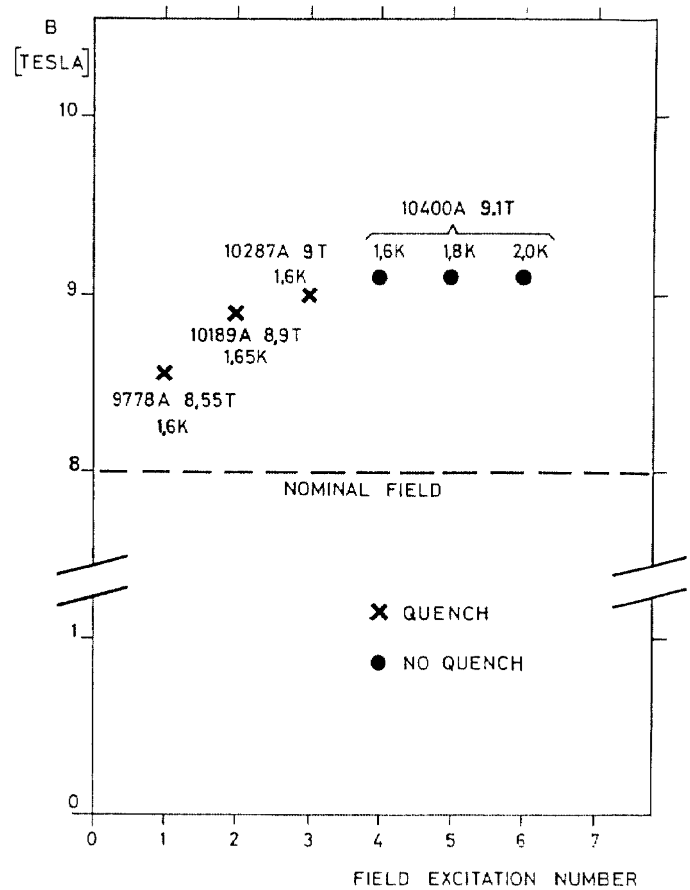

Fig. 4 History of the 8 T model

R & D programme for superconducting magnets

The first step in the experimental R & D programme [7] has been reached last April with the successful tests at CERN of the 8 Tesla, 1.35 m long, single aperture (50 mm) dipole model [8]. Designed and built as a joint project between CERN and the Italian firm ANSALDO, it passed its 8 T nominal induction without quench, the first three quenches occuring at central fields of 8.55, 8.9 and 9.0 T, respectively (Fig 4). At 9.1 T (= 10400 A), it was possible to increase progressively without quench the Helium temperature from 1.6 K to 2.0 K. Field rise time and intensity discharge time corresponding to LHC nominal values have also been achieved without quench [9].

An other single aperture model with Nb_3Sn conductor is being built in collaboration with the Austrian firm ELIN.

To reach an operational field of 10 T in 10 m long "two in one" dipoles, several other steps are being implemented. A large collaboration with national institutes (INFN-Italy, CEA-France and RAL-U.K) and European industries is under way. It concerns :

- the conductor and cable activity, both in NbTi and in Nb_3Sn.
- the construction of several 10 T, 1 m long, twin aperture dipole models. The specifications already launched have found a great interest for a joint development between CERN and European companies. Orders will be placed by end of June.
- the construction of full length prototypes. A 7.5 T, 9m long, twin aperture dipole, using the HERA-type windings (internal diameter = 75 mm) has been designed at CERN and ordered to industry (BBC,Germany). It will allow to test the "two in one" concept with superfluid helium cooling. The full-size 10 m long cryostat has also been ordered. Following the tests of the 1 m models, prototypes of 10 T, 10 m long, dipoles will be ordered.
- the design of the regular lattice quadrupole in collaboration with CEA, of the sextupole/dipole corrector with RAL and a British firm (TESLA).
- the design and tests of other important components such as correction dipoles, current leads, high current diodes.

- the elaboration of a model of superfluid helium heat transfer both in steady state and in transient behaviour in collaboration with CEA and the design of a set of collimators to trap the particles with excessive radial, vertical or momentum amplitudes.

Cryogenics

The power to be dissipated in the superconducting coils during transient periods (Beam acceleration and intensity discharge of the "sane" magnets following a quench detection) is now better known, as well as the risk of beam losses in dipoles; these beam losses could be concentrated on a few dipoles but the regions of the machine where they may occur can not be predicted. It substantially increases the volume of superfluid helium and the cryogenic power needed to cool the magnets. Therefore a solution with circulation of superfluid helium is now envisaged, instead of the static helium cooling, originally foreseen. The design is in progress.

Compatibility with the LEP programme

The aim of minimizing the interruption of the LEP exploitation due to work fot the LHC is obviously of great importance. A careful study was undertaken recently to determine the impact of the construction and installation of the most important systems. This can be summarized as follows.

Injection and beam dumping

The injection into LHC uses the CERN complex of existing accelerators : Linacs, Booster, 28 Gev PS, 450 Gev SPS. In p-p mode the LHC bunch spacing is already formed at top energy in the PS by a dedicated RF system. The bunches are then compressed in the PS to fit into the 200 MHz buckets of the SPS. After box-car stacking of PS pulses in the SPS, the beam is accelerated to 450 Gev and transferred to LHC. This is repeated four or eight times for filling one LHC ring. The SPS polarity is reversed for filling the other LHC ring, allowing to eject one beam from LSS5 and the other from LSS1 out of the SPS towards the intersection point 1 of LHC (Fig 5). This layout minimized the length of transfer tunnel.

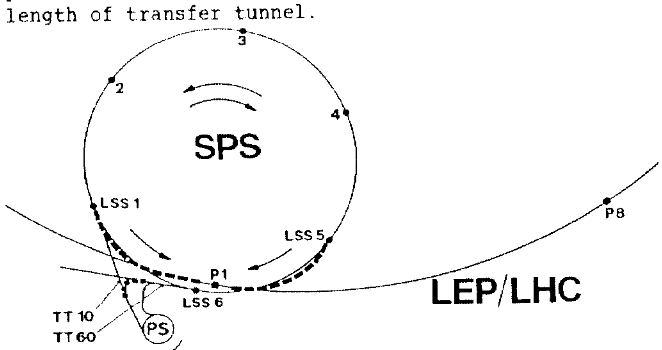

Fig. 5 Beam transfer through the injector chain

Dumping the high power LHC beams requires to locate the absorber blocks in small caverns with enough shielding to protect the environment and to allow a safe access to the LEP tunnel during shut-downs. On both sides of intersection 3, each proton beam will be extracted and sent to a cavern via a transfer channel of small aperture.

The civil engineering concerns the two new transfer lines for injection at 450 Gev between SPS and LEP, and the two transfer channels and caverns for the beam dumps. The junctions between the transfer tunnels and LEP will not require the destruction of parts of the LEP tunnel, but only openings between two adjacent tunnels. The total shut-down will be about 8 months.

Experimental areas

The experimental areas, under active study for the various types of experiments, namely for p-p collisions (high luminosity and general purpose) and for e-p collisions, are all based on the concept that each area includes an "in-beam" position and a garage, to which at least the most important parts of the experiment can be withdrawn when LEP is operating.

The construction of such areas (up to three in LEP points 1,5,7) could start with the garage, so allowing an early first assembly of the experiment in parallel with the continuation of the civil engineering work for the "in-beam" enclosure. With this approach the LEP shut-down required for the construction of the experimental areas will not be longer than 12 months.

Machine Installation

The magnet and cryogenics installation will require a shut-down totalizing 14 to 18 months, which can be subdivided in 2 to 3 periods. All the other machine systems can be installed during the same periods.

Conclusions

In total, the LEP shut-down required for the construction and installation of the LHC will be around 18 months, which could be subdivided , say, in two periods of 6 to 8 and 10 to 12 months. Extended over three years, the LHC installation will then not compromise the LEP operation, which was originally foreseen to be 4000 hrs per year.

The exploitation of LEP and LHC in the same tunnel is not only compatible, but is of considerable interest for collisions between protons and electrons. Furthermore the current CERN experience in accelerating ions allows to envisage collisions between ions in LHC.

The superconducting magnet system with a dipole field of 10 T still requires a vigourous development program for cryogenics (1.8 K) and for the construction of magnet prototypes, but the first result with a model cooled by superfluid helium is very encouraging.

The possibility of increasing the p-p luminosity up to a few 10^{34} $cm^{-2}s^{-1}$ is an other valuable trump card for LHC.

In those conditions, with the availability of the existing injectors and of the general CERN facilities (infrastructure,offices, workshops,general services), and with the know-how of CERN staff, considerable savings can be made in the cost of LHC. A cost estimate for the basic machine structure for the pp mode, which consists essentially of the super conducting magnet system (NbTi, 2 K cooling) and of the cryogenics has been worked out. This cost is ~ 750 M Ecu (for 10 T) and represents as much as 85 % of the new investment. Adding ~15 % of contingency, the total amounts to ~ 860 M Ecu .

References

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