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THE LEP2 AND LHC PROJECTS AT CERN

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Abstract

The LEP energy upgrade project (LEP2) which is based on the addition of superconducting cavities will raise the energy of the machine above the W pair production threshold. The planning of the approved phases with the expected energy and luminosity levels as well as the current status of the project are presented.

The Large Hadron Collider (LHC) whose construction has been approved by the CERN Council in December 94, will provide proton-proton collisions with a centre of mass energy of 14 TeV as well as heavy ion collisions with a centre of mass energy in excess of 1000 TeV. An overview of the performance, technological challenges and present status of the project is given.

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1. INTRODUCTION

The long-term scientific strategy [1] of CERN mainly relies on an intense exploitation of the Large Electron Positron Collider (LEP) until the year 2000 when it will be dismounted to allow installation of the Large Hadron Collider (LHC) in the same tunnel.

2. THE LEP ENERGY UPGRADE PROGRAMME (LEP2)

The LEP collider is a 26.6 km circumference e^+e^- storage ring which has a beam energy limited by the copper RF cavities to about 60 GeV. Thus, it was mainly operated for physics around the Z^0 mass of 91.2 GeV with 4 or 8 bunches per beam [2,3]. By the end of 1989, a few months after the first circulating beams, a second phase (LEP2) was launched aiming at an increase of the energy well above the W pair threshold of 160.5 GeV by addition of superconducting (s.c.) cavities. The maximal reachable energy will be close to 200 GeV which would allow the detection of a light Higgs particle, if its mass is near the Z^0 mass, and of new particles with electroweak interactions suggested by the supersymmetric extension of the Standard Model.

2.1 Attainable Beam Energy

The attainable beam energy is determined by the total RF voltage needed to replenish the losses due to synchrotron radiation and by the provision of an "RF bucket" large enough to give a quantum lifetime of at least 15 h. The RF voltage has to increase approximately like the radiation losses, i.e. proportional to the fourth power of the beam energy (Fig. 1).

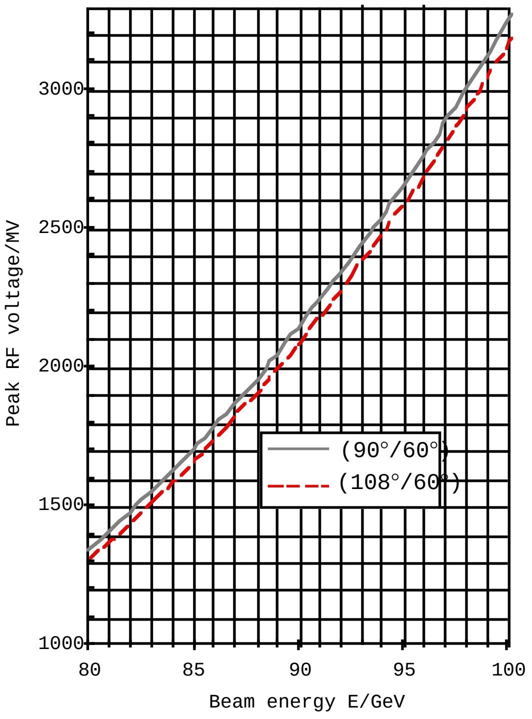


Figure 1 Peak RF voltage required for a quantum lifetime of 15 hours and for different phase advance lattices.

The authorized LEP2 programme foresees the installation of 224 s.c. cavities in addition to the 56 remaining copper cavities. With an operational gradient of 6 MV/m a voltage of more than 2.3 GeV corresponding to a beam energy of 91.5 GeV can be achieved. A further extension to 272 s.c. cavities is under discussion which would raise the beam energy to 96.5 GeV.

2.2 Luminosity Limitations

In order to obtain the maximum luminosity, the betatron amplitudes $\beta^*_{x,y}$ at the interaction point are chosen in order to equalize the beam-beam tune shifts

$$\xi_x = \xi_y \propto \frac{i_b}{\gamma \varepsilon_x} \qquad (1) \qquad \text{with} \qquad \frac{\beta^*_x}{\beta^*_y} = \frac{\varepsilon_x}{\varepsilon_y} \qquad (2)$$

The vertical emittance ε_y is given by the machine imperfections while the horizontal emittance ε_x is dominated by the synchrotron radiation

$$\varepsilon_x \propto \frac{\gamma^2}{J_x Q_x^3} \qquad (3)$$

and the luminosity at the beam-beam limit can be written as follows:

$$L \propto \frac{\gamma\, k_b\, i_b\, \xi_y}{\beta^*_y} \qquad (4)$$

γ is the relative energy, k_b the number of bunches, i_b the current per bunch, J_x the horizontal damping partition number and Q_x the horizontal betatron tune.

Due to the variation as γ^{-3} of $\xi_{x,y}$ (eqs (1) and (3)), it is very unlikely that LEP2 at 90 GeV be strongly beam-beam limited as it is the case for LEP1 and the luminosity can be written as follows:

$$L \propto \frac{J_x\, Q_x^3\, k_b\, i_b^2}{\gamma^2 \beta^*_y} = \frac{J_x\, Q_x^3\, i_{tot}^2}{\gamma^2\ k_b \beta^*_y} \qquad (5)$$

This equation shows the strategy to adopt for maximizing the luminosity.

The total current i_{tot} is limited by the RF power delivered by the klystrons ($P_{rf} = 2P_{beam} \propto 2 i_{tot}\, E^4$) i.e. about 30 MW with 224 s.c. cavities which allows 8 mA of beam current at 90 GeV. This current shall be stored in a minimum of bunches with a limitation for the current per bunch at injection energy which cannot exceed the Transverse Mode Coupling threshold [4]:

$$i_b^{\max} \propto \frac{Q_s\, E_b^{inj}}{\sum \beta_i\, k_{\perp i}(\sigma_s)} \tag{6}$$

It is foreseen to increase the injection energy from 20 to 22 GeV (two new s.c. bimodules in the SPS) and to reduce the transverse impedance factor $\Sigma\beta_i\, k_{\perp i}(\sigma_s)$ by replacing copper cavities (47% of the present total impedance) by s.c. cavities. A "high Q_s scheme" [5] in which a large synchrotron tune Q_s is chosen at injection and progressively decreased during ramping has been also successfully tested. All these improvements should allow bunch currents of 0.8 mA. With 8 bunches per beam (4 trains of 2 bunches) a peak luminosity of ≈ 7 10^{31} cm^{-2} s^{-1} and an integrated luminosity of 170 pb^{-1} per year will be obtained (assuming an overall efficiency of 0.18 and 150 days of physics runs as in the present LEP).

Looking at the other parameters in eq. (5), it turns out that a further reduction of β_y^* below 5 cm can hardly be considered because of its effect on the aperture limitation in the insertion quadrupoles and on the dynamic aperture. However, a further optimization may be achieved by using a lattice with a higher horizontal phase advance (increase of Q_x). Encouraging results have already been obtained [6] by tuning the lattice to 108°/60° (*H/V*) instead of the present value of 90°/60°. If operation with such an optics is possible, it is conceivable that a luminosity of 10^{32} cm^{-2} s^{-1} be obtained with LEP2.

2.3 Superconducting Cavities

The cavity production, the main couplers and the higher order mode (HOM) couplers which were identified as the most critical aspects of the system are now well mastered.

Thanks to a better control of the fabrication procedures – mainly the sputtering of the cavities and the clean room assembly of the modules – the acceptance rates have largely increased during the last year [7]. The success rate of cavities with a first coating is now 70% compared to 32% one year ago and the recently achieved performances are well above the specified requirements (Fig. 2). Today 77% of the bare cavities and 68% of the modules have been accepted. The end of the delivery of the modules is expected between May and September 1996 for the three firms involved.

An intense R & D effort has been devoted to improve the performance of the main couplers [8]. The multipacting effects in the coaxial part which caused strong pressure rises and required a reprocessing of the coupler after each high power running have been considerably reduced by diminishing the antenna diameter (75 Ω impedance instead of 50 Ω) and by coming back to a fix coupler design (suppression of the inner $\lambda/4$ choke - see Fig. 3). The reduction of the resistance contacts of the ceramic window and the better surface quality of the outer conductor (suppression of welds and better copper coating) also helped in reducing multipacting. Finally the application of a DC bias voltage of 2.5 kV to the antenna completely suppressed multipacting modes in the working range of the couplers which are now capable of passing 125 kW to the beams.

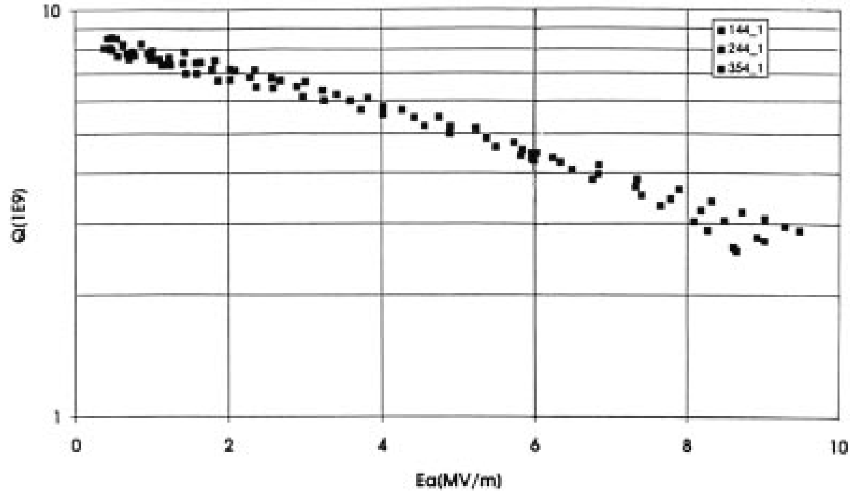


Figure 2 Performance of cavities from industry (4.5 K)

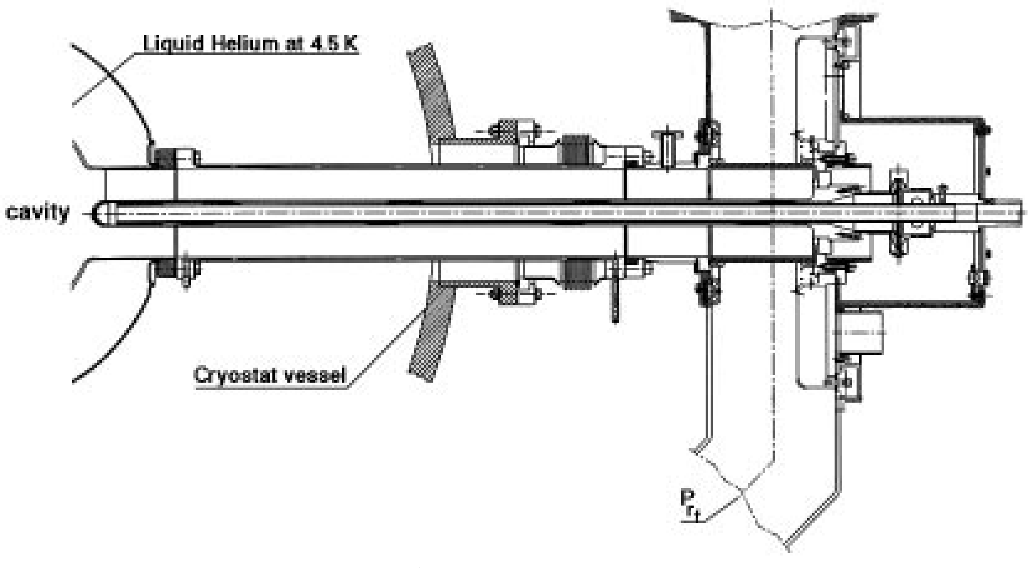


Figure 3 Main coupler

The current limitation and the erratic quenches shown with the initial design of the Higher Order Mode (HOM) couplers have been removed by improving the thermal conductivity of the niobium (*RRR* = 300), the liquid helium cooling (injector in a larger inlet tube) and by replacing the output cables by a rigid low-loss coaxial line. These couplers can now remove 1700 W of HOM power per cavity which provides a safe engineering margin.

At present there are 12 s.c. modules (48 cavities) operational in LEP (4 modules at Point 2 and 8 at Point 6). The modules which have been installed before or during the last winter shutdown have been extensively tested with beam and one of them has been operated for more than 70 hours at its design gradient of 6 MV/m. These tests also allowed to define the operating procedures. It was found that due to their very narrow bandwidth, vibrations and other "microphonic" effects may induce large RF voltage and phase variations around the mechanical frequency of the cavities. Hence, operation at the peak of the resonance curve is favoured over operation on the slope of the resonance curve as it is done for warm cavities.

2.4 Cryogenics

The four 12 kW cryoplants with their transfer lines are operational [9] at the even points and are ready for connection to the cavities and low-beta insertion quadrupoles. The capacity of the cryoplants (11.4 kW guaranteed at 4.5 K, i.e. 5% below nominal) shall cover the static losses (s.c. cavities, transfer lines, s.c. insertion quads) and the dynamic load in the cavities which is proportional to E^2/Q where E is the accelerating field and Q the average quality factor. This fixes a "cryogenic limit" to the number of cavities per point and thus to the energy attainable with LEP2: with the operational values of $Q = 3.2\ 10^9$ and $E = 6$ MV/m, a maximum of 72 cavities can be connected per point.

2.5 Other LEP2 Hardware

The other hardware modifications needed for LEP2 are either already terminated (new klystrons galleries, quadrupole rearrangement in the RF sections, power converters) or will be terminated during the next winter shutdown (installation of the last two s.c. quads and of the enlarged vacuum chambers for experiments).

2.6 Installation planning of the s.c. cavities

Figure 4 shows this planning together with the beam energy calculated with a gradient of 6 MV/m, a 108°/60° lattice, and a quantum lifetime of 15 h. An operational reserve of 160 MV (equivalent of 4 modules) has been kept to cope with faulty modules and to allow the global voltage control to work in case of temporary breakdowns of modules.

The milestones are:

- Physics at 45 GeV per beam with s.c. cavities only, in September 95.
- Physics at 70 GeV per beam at the end of 1995.

- Run at 80.5 GeV per beam in the first part of 1996 to reach the W pair production threshold.
- Data taking above the W pair production threshold as from autumn 1996.
- Maximum energy of 9l.5 GeV per beam as from autumn 1997 with the 224 s.c. cavities installed and the remaining 56 copper cavities.

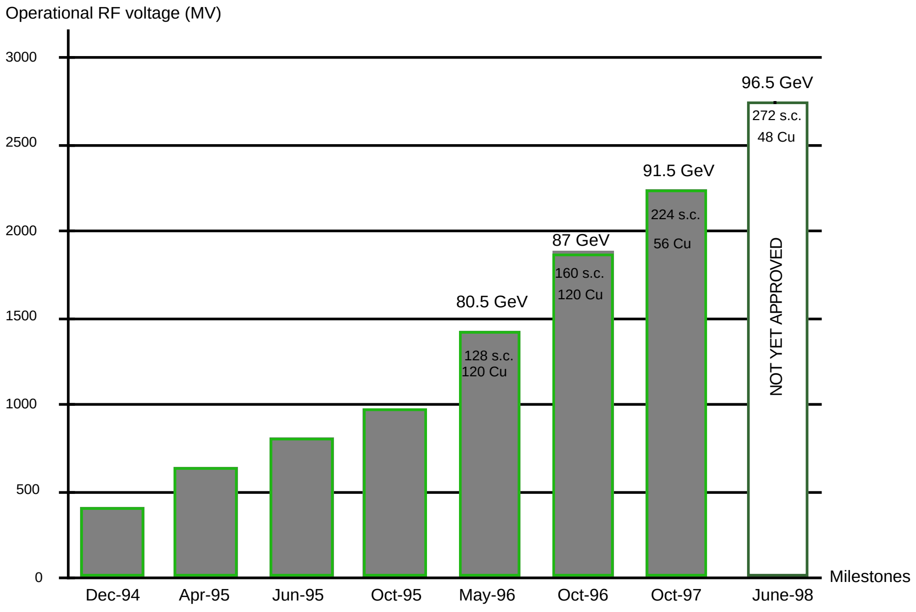


Figure 4 LEP2 Planning

An ultimate step has recently been strongly recommended by the LEP physicists and is waiting for a decision in September: it implies an additional set of 32 cavities to be installed in the tunnel together with the 16 spare cavities. With a total of 272 s.c. cavities and 48 remaining copper cavities, the beam energy would raise 96.5 GeV in June 1998 and the cryogenic limit would be reached at Points 4 and 8 with 72 cavities installed.

Beyond this limit any further extension would require the upgrade of the cryoplants and ultimately the reshuffling of the quadrupoles in the straight sections at Point 2 and 6. The cost which would exceed 20 MCHF per GeV gained in beam energy appears today not commensurable with the physics prospects.

3. THE LARGE HADRON COLLIDER (LHC)

The Large Hadron Collider [10,11] will provide proton-proton collisions with a centre of mass energy of 14 TeV and heavy ion (Pb-Pb) collisions of 1148 TeV in the centre of mass. It will be installed on the floor of the 26.6 km circumference LEP tunnel after removal of the LEP ring. The space kept free above LHC will allow the future installation of an electron machine using LEP components optimized for e-p collisions. (Figure 5).

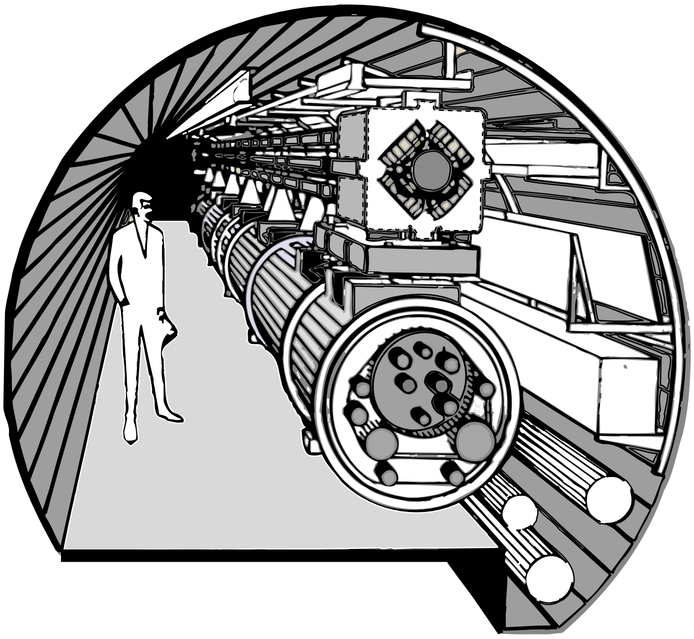


Figure 5 LHC with an electron machine on top

3.1 Layout

The basic layout of LHC mirrors that of LEP with eight 540 m long straight sections available for experimental insertions or utilities (Fig. 6). The two high luminosity proton-proton experiments are located at diametrically opposite points 1 (ATLAS) and 5 (CMS). Two more experimental insertions combined with the injection systems are located at Point 2 (ALICE, Pb ions) and Point 8 (Possible Beauty experiment LHC-B).

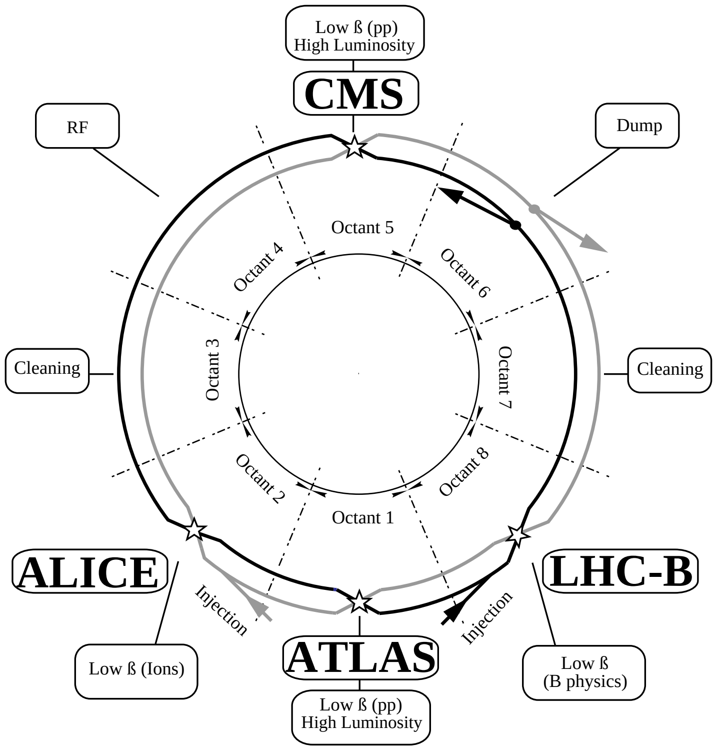


Figure 6 Schematic layout of LHC

The remaining four straight sections do not have beam crossing. Straight sections 3 and 7 contain two beam collimation systems using warm magnets to cope with the inevitable beam loss from the collimators. Straight section 4 contains the RF systems which have now been separated for the two beams. Finally straight section 6 locates the beam dump insertion which allows the vertical extraction of the beams from the machine and their safe abort 750 m away in a dump block.

3.2 Performance for proton-proton physics

The main parameters for proton-proton operation are given in the first column of Table 1. In order to reach very high luminosities, the two counter rotating beams contain a large number (k_b = 2835) of intense ($N = 10^{11}$ protons) and closely spaced (τ_b = 25 ns) bunches with a low transverse normalised emittance (ε_n = 3.7 μm). The bunches are equally spaced by 10 RF wave lengths with some holes which are imposed by the injection scheme and by the LHC beam dump system to allow for the rise time of the kickers.

Table 1 LHC performance for proton-proton and lead ion collisions

Parameters		**p-p**	**$^{208}Pb^{82+}$**	
Beam energy	TeV/charge	7	7	
Center of mass energy	TeV	14	1148	
Injection energy	GeV/charge	450	450	
Dipole field	T	8.4	8.4	
Coil aperture	mm	56	56	
Bunch spacing	ns	25	124.75	
Number of bunches per ring		2835	608	
Normalised transverse emittance	μm	3.75	1.5	
R.m.s. bunch length	m	0.075	0.075	
Beta values at IP	m	0.5	0.5	
Full crossing angle	μrad	200	200	
Particles per bunch		1×10^{11}	$6.3\ 10^{7}$	$9.4\ 10^{7}$
Intensity per beam	mA	530	5.2	7.8
Initial luminosity	$cm^{-2}s^{-1}$	1×10^{34}	$0.85\ 10^{27}$	$1.95\ 10^{27}$
Luminosity lifetime	h	10	10	6.7

The layout of a high luminosity insertion is shown in Fig. 7 together with the optical functions during collision (β^* = 0.5 m at the crossing point). The insertion is antisymmetric and consists of a matching section (outer quadrupole triplet) and an inner triplet focusing the beams to the crossing point. Between the two triplets, a pair of recombination dipoles brings the beams into a common channel with a small crossing angle of ± 100 μrad. This angle is sufficient to prevent parasitic bunch collisions in the interaction region and has a marginal effect on the luminosity (0.9 reduction factor with respect to head on collisions) and on the required aperture

(Ø 70 mm) of the inner quadrupole triplet. The free space available for the experiments between the inner triplets is ± 23 m in the high luminosity insertions (Points 1 and 5) and ± 21 m for the other two experimental insertions (Points 2 and 8) to allow more room for injection.

The luminosity is given by

$$L \propto \frac{N^2 k_b \gamma}{\varepsilon_n \beta^*} F \tag{7}$$

where N is the number of protons per bunch, k_b the number of bunches, γ the relativistic factor, ε_n the normalised transverse emittance, β^* the beta values at the crossing point and F the reduction factor due to the crossing angle. The luminosity is limited by the beam-beam tune shift due to head on collisions ($\xi \propto N/\varepsilon_n$) and to the long range interaction. With two experiments operating simultaneously and a beam-beam tune shift reasonably limited at 0.01, the luminosity will reach the unprecedented value of 1 x 10^{34} $cm^{-2}s^{-1}$.

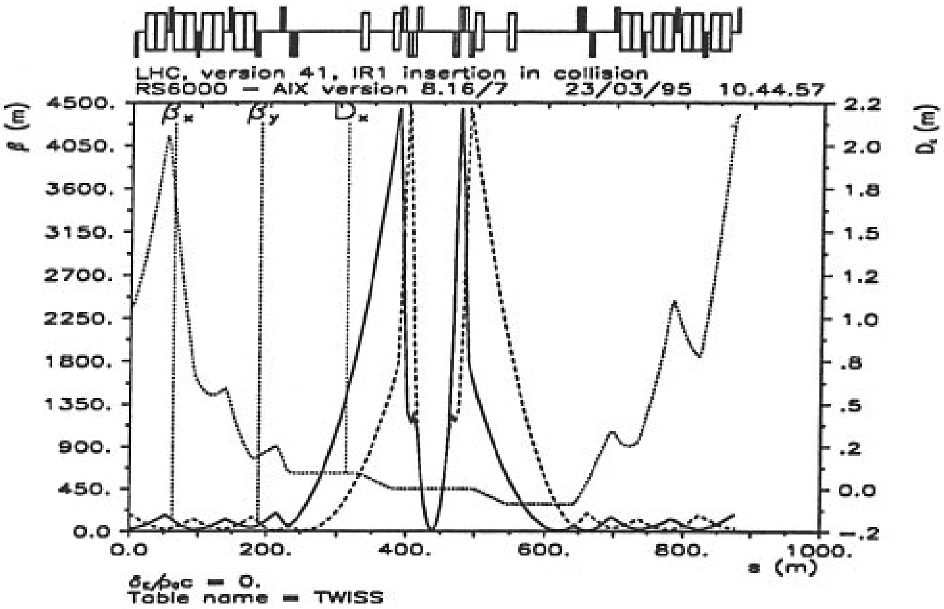


Figure 7 High luminosity insertion

During injection and acceleration, the insertion is "detuned" bringing the maximum beta value in the inner triplet down from its collision value of about 4500 m to below 400 m.

At the design luminosity of 10^{34} $cm^{-2}s^{-1}$ the initial decay time of beam current due to beam-beam collisions is 40 hours. Taking into account all other losses (beam-gas and mainly machine imperfections), the beam lifetime is reduced to 22 hours which gives a luminosity lifetime of 10 hours.

However, learning how to operate the LHC at these high beam current of about 0.5 A will take time and the initial commissioning will be done with beams of much smaller intensities. In order to avoid a dramatic reduction of luminosity, the emittance will be reduced accordingly and it is expected that a luminosity of $10^{33}cm^{-2}s^{-1}$ could be achieved after one year of commissioning with a beam current of 0.1 A.

3.3 Performance as a lead-ion collider

The performance of the LHC as a lead-ion collider with one interaction point is given in the second column of Table 1. At the nominal field of 8.4 T, an energy of 1148 TeV in the centre of mass is obtained. The luminosity lifetime is governed by the intrabeam scattering and dominantly by the electromagnetic effects in the collision points (electromagnetic dissociation and electron capture after a pair production) causing loss of ions from the beam. Hence it depends on the beam density. Two sets of operational values of beam densities and corresponding luminosities are given in Table 1.

Injection of lead ions in LHC will require an upgrading of the present CERN Heavy Ion Injector and the transformation of LEAR with its powerful electron cooling system into a lead ion storage ring to accumulate 20 linac batches during one PS cycle.

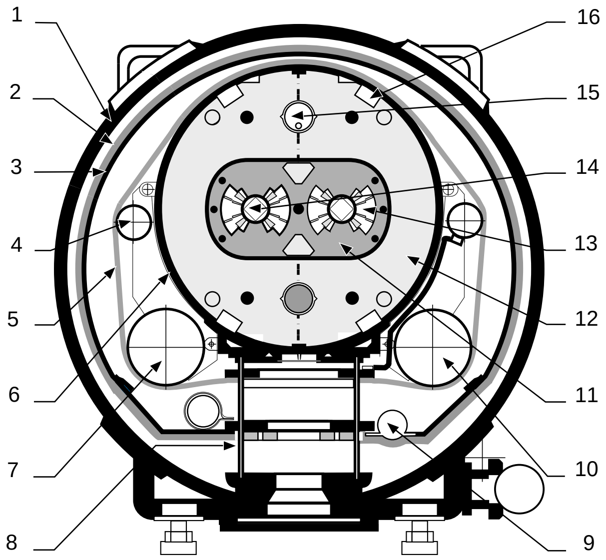
The use of LHC for collisions of lighter ions has also been recently investigated. The electromagnetic effects are drastically reduced and hence much higher beam densities and luminosities can be obtained. Measurements with Kr and Ar will be done in 1996 in order to provide more quantitative figures.

3.4 Status of machine hardware

A considerable effort is going on to finalise the design and reduce the cost of all the main LHC systems. The aim is to be able to tender for large series production by the end of 1997.

S.c. magnets – In order to reduce the space lost in the junctions, the magnet layout [12] is based on 53.45 m long half cells containing only 3 dipoles of 14.2 m magnetic length and one 3 m long quadrupole. The regular lattice and dispersion suppressors will require 1232 dipoles and 368 quadrupoles which both have a two-in-one design where the two beam channels are incorporated into a single iron yoke and cryostat. In the dipoles (Fig. 8), the coils are clamped by combined aluminium collars rather than separate stainless steel collars in order to minimise the prestress at room temperature and to ensure a better parallelism of the fields in the two channels. More than a dozen short models of a 1 m length have been constructed and tested. All of them have exceeded 9 T with the best reaching 10.5 T. Seven 10 m long prototypes have been ordered in industry and four of them have been tested so far. They all have exceeded 9 T [13] after a few quenches which mainly occur in the coil ends. This training should be further reduced in the new 10 m and 14.2 m long prototypes which have been recently ordered in industry with an improved design of the coil ends.

Two full size quadrupoles have also been constructed under a CERN-CEA Saclay collaboration agreement and have reached their design gradient of 250 $\mathrm{Tm^{-1}}$ with very little training.



1. Vacuum vessel
2. Radiative insulation
3. Thermal shield (55 to 75 K)
4. 2.2 K GHe pipe
5. Radiative insulation
6. Shrinking cylinder / HeII vessel
7. 1.8 K GHe pipe
8. Support post
9. 50 to 75 K GHe pipe
10. 20 K GHe pipe
11. Aluminium collars
12. Iron yoke
13. Superconducting coils
14. Beam pipes
15. Heat exchanger pipe
16. Sc. bus-bars

Figure 8 Cross section of the dipole magnet

Cryogenics – The magnets are immersed in a static superfluid helium bath which is pressurised at 1 bar and cooled by heat exchange with saturating superfluid helium flowing through a tube running through the magnet chain of each half cell (see Fig. 9). The sub-cooled helium at 2.2 K supplied by line A is expanded to saturation through the Joule Thomson valve LCV and sent to the end of the half cell from where it returns gradually vaporising from heat exchange with the static bath. The loop is maintained at the saturation pressure of about 16 mbar by the pumping tube B. By exploiting the latent heat of vaporisation the temperature of each magnet is well controlled (< 1.95 K) and independent of its distance from the cryoplant.

A key technology for the LHC cryogenic system is the development of cold sub-atmospheric and large flow helium compressors [14] to pump on line B. Based on the pioneer work done for the Tore Supra Tokamak and at CEBAF, CERN has launched a comprehensive development programme with CEA Grenoble and ordered two prototypes in industry which will be tested at CERN during this summer.

The helium refrigeration capacity will be provided by eight 18 kW cryoplants located at the even LEP pits where most of the infrastructure already exist. Half of them are the four existing LEP cryoplants which will be boosted from 12 to 18 kW.

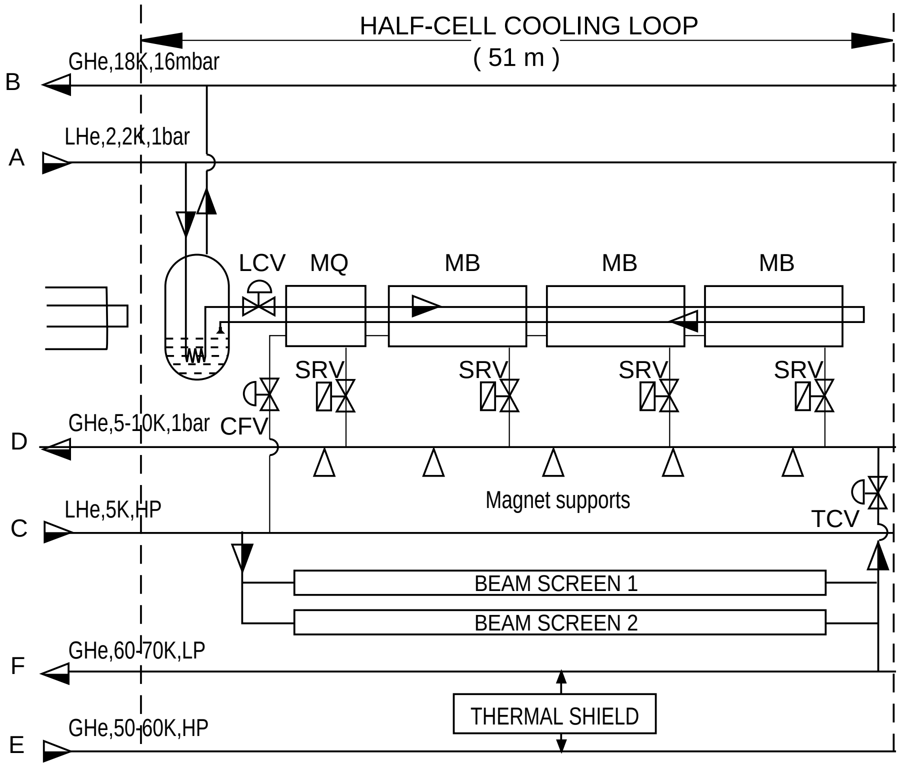


Figure 9 The magnet cooling scheme

String test – In order to test the actual operation of the cryogenic, powering and quench protection systems of the magnets, two 10 m long dipoles and one short straight section (which itself includes the quadrupole, correctors, beam position monitor and cryogenic unit) have been assembled in a string [15] simulating the basic half cell. The tests performed since the end of 1994 at the nominal LHC field have confirmed the soundness of the technical choices and opened the way to further savings. They have shown that two relief valves SRV (one on each side of the SSS) are sufficient to evacuate the boiling He in case of quench. On that basis, it is envisaged to replace the integrated cryostats with their many functions by simplified cryostats tapped at every 53 m to a separate cryoline.

Other hardware – Among the other major hardware developments, it is worthwhile to recall the RF and the vacuum systems. The 16 MV per beam needed at 400.8 MHz will be provided by sixteen (eight per ring) superconducting cavities. A prototype cavity has been built and installed in the SPS for tests.

The LHC beam vacuum poses particular problems [16] due to the synchrotron radiation emitted by the protons (about 4 kW per ring at 7 TeV). A copper cladded stainless steel liner cooled to around 20 K will therefore be installed inside the cold bore. An adequate number of slots allow cryopumping of the desorbed gas on the cold bore and not on the liner itself where it could be easily desorbed with very detrimental effects to the average pressure and beam lifetime. Tests performed in the $e^{\pm}$ accumulator ring (EPA) ring at CERN and at VEPP2M at INP Novosibirsk have confirmed the validity of the design.

3.5 LHC experiments

The main goal of the two large general purpose experiments (ATLAS [17] and CMS [18]) is the search for the Higgs and for supersymmetric particles. They are both concentrating on precise measurements in the central region at the highest achievable luminosities. CMS is using a large central solenoid whereas ATLAS consists of a central and two forward toroids.

The Heavy-Ion experiment ALICE [19] has to cope with much larger (~ 1000 times) particle densities in Pb-Pb collisions but at a reduced luminosity of $L \cong 10^{27}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$. The hope is to find evidence for a quark-gluon plasma which may be formed at these high energy densities of about 10 GeV/fm^3.

A specialized experiment (LHC-B) on CP-violation in beauty physics at moderate luminosities of $L \cong 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ is presently under discussion. Further thoughts are also given to an experiment which would explore the particle production in the very forward region, also including diffraction and elastic scattering.

3.6 LHC Planning

The approval of LHC by the CERN member states in December 1994 foresees a staged construction with the following milestones:

- Operation at 9.3 TeV centre of mass energy, from 2004 to 2006 with a missing magnet scheme (2 out of 3 dipoles per half cell).
- Operation at 14 TeV nominal as from 2008 after a one-year shutdown to install the missing magnets.

However, it is very likely that the additional contributions of non-member states which are being negotiated will permit to advance the commissioning date at full energy. A review of the project is foreseen in 1997 to define the final planning.

Acknowledgements

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