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STATUS REPORT ON THE CERN LARGE HADRON COLLIDER (LHC)

The LHC Machine Group
reported by G. Brianti

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ABSTRACT

The LHC is a superconducting collider to be installed in the LEP tunnel for pp (15.4 TeV), Pb ions (1262 TeV) and ep (1.36 TeV) collisions. An overall machine optimization, including a new lattice arrangement, will be presented resulting in an increased energy to field ratio. Recent results from magnet models and a 10 m-long prototype will be given. Some modifications have been introduced in the design of the dipole magnets, which are being realized in new models/prototypes. In total seven 10 m-long prototypes are being constructed by industry. A brief review of the design of all other systems is also given. In December 1991, the CERN Council unanimously adopted a resolution stating that the LHC is the right machine for the future of CERN and requesting a final technical/financial proposal in 1993 in order to move towards a decision.

1 INTRODUCTION

The general design of the collider, which essentially consists of a ring of high-field superconducting magnets to be installed above LEP in the 27 km tunnel, was described in the last HEACC in Tsukuba [1]. A Design Study was published in May, 1991 [2].

The magnets are of the so-called 'two-in-one' structure, namely incorporating two beam channels in the same mechanical structure and cryostat (Fig. 1).

Such a magnetic structure added to LEP can provide three types of collisions, namely proton-proton, heavy ions (Pb-Pb) and electron-proton by colliding the LEP electron beam with one of the proton beams.

The most important parameters of these collisions are given in Table 1.

Emphasis is put on luminosity since the point-like nature of quark-quark interactions implies that the cross sections decrease as the the collision energy E increases. To maintain equally effective physics programmes, the luminosity should increase as E^2, and thus, to explore rare processes such as Higgs $\rightarrow 2Z \rightarrow 4\mu$, the LHC is designed to provide luminosities in excess of 10^{34} cm^{-2} s^{-1}.

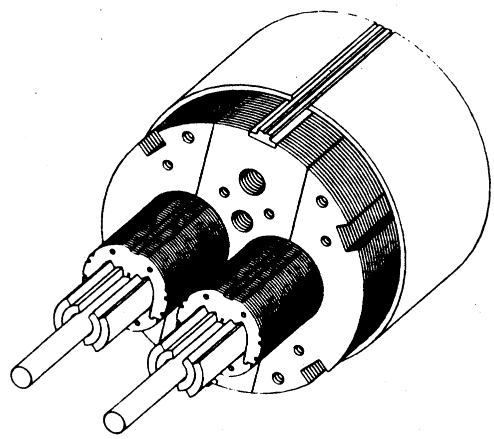

Fig. 1. Perspective view of a 'two-in-one' dipole

In this report, the main design progress and improvements with respect to Ref. 1 are outlined for the main systems together with the results of magnet prototype work and of cryogenic tests.

Table 1 : LHC Main Parameters

	pp	e-p	Pb-ions
Max. cm energy TeV for B=9.5 T	15.4	1.36	1262
Luminosity cm^{-2} s^{-1}	1.6 10^{34}	2.8 10^{32}	1.8 10^{27}
Number of bunches	4725	508	800
Bunch spacing m / ns	4.5 / 15	49.4 / 164.7	31.5 / 105
Particle/bunch p e	10^{11}	3.0 10^{11} 9.2 10^{10}	6.2 10^{7}
Particles/beam p e	4.7 10^{14}	1.5 10^{14} 4.7 10^{13}	5.0 10^{10}
Number of experiments	3	1	2
β at intersect. point m ($\beta_x \beta_y$)	0.5	0.85, 0.26 32.7, 3.05	0.5
r.m.s. radius at intersection point µm (x,y)	15	120 / 37	12.4
r.m.s. collision length cm	5.3	3.8	5.3
Crossing angle µrad	200	0	200

2 INJECTORS

The basic scheme is unchanged (Fig. 2) and makes use of all existing accelerators, namely Linac, Booster, 26 GeV PS and 450 GeV SPS for pp operation with only relatively minor modifications and additions.

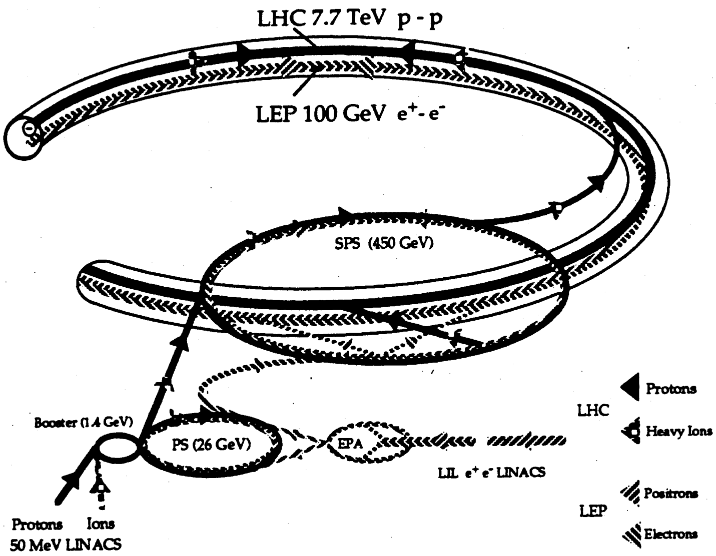

Fig. 2. The LHC injection complex

The nominal high luminosity operation requires two Booster cycles to fill the PS circumference, with the injected beam first accelerated by the existing RF system on h = 8, debunched and recaptured by a new 66.8 MHz RF system to form a bunch train with 15 ns bunch spacing. Three such bunch trains are captured in the SPS and compressed to fit into the standard 200 MHz buckets by a new 66.8 MHz system, accelerated to 450 GeV and finally transferred to the LHC. The whole operation is repeated 12 times to fill the entire LHC circumference via two new transfer lines.

The new developments are :

i) in the Linac/Booster complex, beams of almost nominal parameters have already been obtained even before the installation of the new RFQ in front of the Linac,

ii) tests are under way in the SPS to form tightly spaced bunches (10 ns) as reported in this Conference [3],

iii) it may be possible to merge in the SPS the 15 ns-spaced bunches into 30 ns-spaced bunches, either to better suit the electronics of the experiments or to further increase the luminosity, still maintaining the same total circulating current.

3 LATTICE

The FODO lattice is now constituted by :

- 8 arcs, each of them containing 48 half-cells,
- 8 insertions, each of the them containing one long straight section, which incorporates two beam recombination sections to provide quasi head-on collisions, and two dispersion suppressors.

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

One half of a regular cell (Fig. 3) consists now of three ~ 13.5 m long dipoles (MB) and one main quadrupole (MQ).

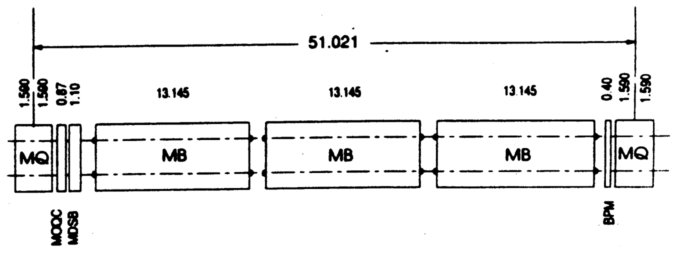

Fig. 3. The new LHC half-cell with three long dipoles

Near each main quadrupole and for each ring there are two sets of combined corrector magnets, namely one MOQC, a combined octupole/quadrupole corrector and one MDSB, a combined decapole/sextupole/dipole corrector. MOQC serves to change the working point (over two integer) since MQ's are in series with MB's, while the other correctors compensate the systematic multipolar errors and provide chromaticity and orbit corrections. All correctors are single and not twin units, so that each counter-rotating beam can be separately adjusted. With this new half-cell layout, an important improvement was obtained in the relation between beam energy and dipole field. Indeed the maximum beam energy of 7.7 TeV is now obtained with a dipole field of 9.5 T instead of 10 T (Fig. 4).

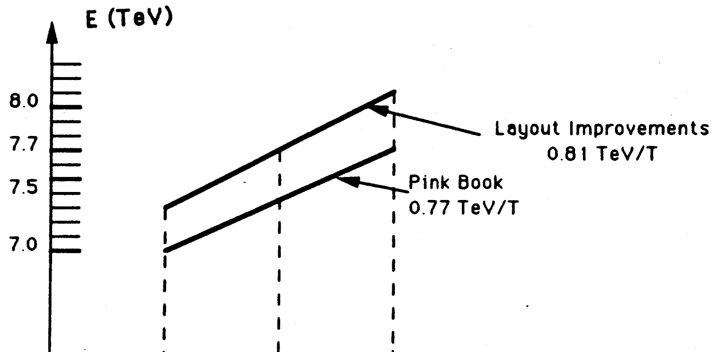

Fig. 4. LHC beam energy versus field

4 MAGNETS

The detailed results of the R&D programme obtained so far are summarized here for completeness.

- A 10 m-long twin dipole, in which two sets of HERA coils are incorporated into an LHC two-aperture structure, was tested at CEA-Saclay both at 4.5 K and at 1.9 K. (Fig. 5).

At 4.5 K it behaved exactly as good HERA single magnets, while at 1.9 K it reached the short sample field of 8.3 T in five quenches.

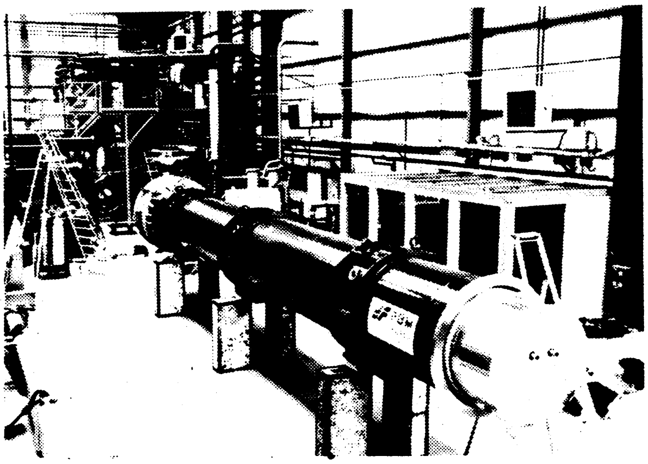

Fig. 4 Twin Aperture Prototype

- A few 1 m-long models of full cross-section reached their short-sample field of ~ 8 T in two to three quenches at 4.2 K; they also reached the short-sample field of 9.8 to 10 T but after a long training above 9 T.

  The great majority of the quenches are located in the ends. In particular only three quenches occur in the central part before the short sample field is reached. A single aperture magnet built by KEK - Japan, with different cables, collars and steel structure on the basis of their own design, gave very similar results [4].
- In all magnets there is no sign of any negative influence of the 'two-in-one' structure.

These results give confidence that final magnets operating satisfactorily close to the maximum field of 9.5 T could be built.

Seven 10 m-long prototypes [5], all with the same set of coils but with three different mechanical structures are being built in industry. They will start to be delivered to CERN at the beginning of 1993.

After an individual test, four of them will be mounted, together with a lattice quadrupole, to form a half-cell for extensive cryogenic tests.

At CERN new models are being built to optimize the coil design (especially ends) and mechanical structure.

The lattice quadrupole has been designed by CEA-Saclay and two full-scale units are being built.

Prototypes of various correctors have also been built and some of them satisfactorily passed first tests.

5 CRYOGENICS

The block diagram of the cryogenic refrigeration system which corresponds to a half-cell (~ 51 m) is shown in Fig. 6.

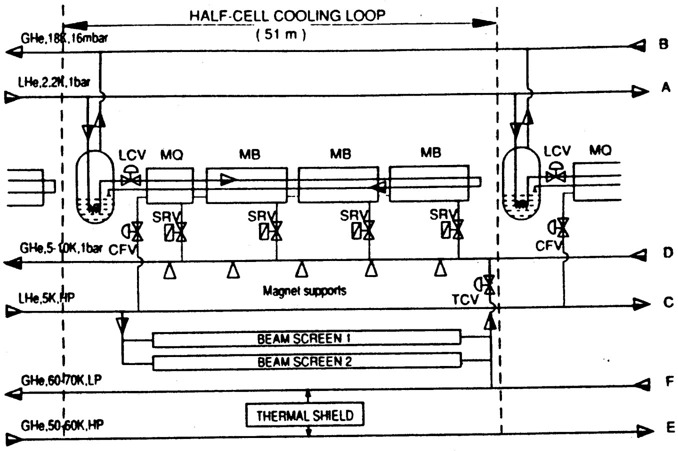

Fig. 6 Flow-scheme of LHC cryogenic loop

The magnets are immersed in static pressurized superfluid He at 1.9 K and cooled by heat exchange with saturated superfluid He flowing in a tube passing through the magnets and running all along the length of the half-cell. In this way the cooling loop is hydraulically isolated from the He contained in the magnets, which can be polluted by solid impurities. Subcooled liquid He arrives at each half-cell loop through line A and expands in the Joule-Thompson valve LCV.

An important advantage of this system is that the working temperature of each magnet does not depend on its distance from the cryoplant located near the LEP/LHC interaction point.

To test this scheme in realistic conditions, a cryoloop model was built in which the magnets are replaced by 10 m-long cryostat modules with an almost full scale heat exchanger tube. The actual magnet heat loads are provided by electrical heaters.

The experimental results are excellent in the sense that the nominal heat load of 0.3 W/m may be exceeded by several factors while still maintaining the temperature difference between the static He baths and the flowing He within a few mK, and that the bath temperature does not depend on the distance from the inlet.

Globally, the LHC will require per octant :

- 1.8 kW isothermal refrigeration at 1.9 K,
- 8.5 kW non-isothermal refrigeration at 4.5-10 K
- 30 g/s liquefaction at 4.5 K
- 30 kW non-isothermal refrigeration at 50-75 K.

The four 12 kW cryoplants at 4.5 K already acquired for LEP 200 (increase of LEP beam energy above 90 GeV) and installed at the even points, suitably boosted to 18 kW by additional compressors, will be used for LHC.

Four additional plants for the odd points and suitable cold boxes for lowering the temperature from 4.5 K to ~ 2 K will have to be installed in order to complete the refrigeration system.

6 BEAM COLLIMATION

Beam losses in superconducting high luminosity proton colliders like the LHC are of concern because, even if the effects of accidental beam losses can be minimized by adequate beam monitoring and fast and reliable beam dumping system, systematic and continuous beam losses will nevertheless occur during steady state operation and may induce quenches in unprotected magnets.

The most prominent of these continuous losses originate from the beam-beam collisions and from non-linear beam diffusion processes. With a nominal luminosity of 1.65 10^{34} cm^{-2} s^{-1} in three collision points, 2 10^9 protons per second will be produced and remain in the periphery of the beam envelope. In addition slow diffusion processes due to machine non-linearities (including the collisions themselves) will add a similar rate to this beam halo.

These halo particles are the first candidates to be lost against aperture limitations and deposit most of their energy as hadronic showers in the surrounding material.

It is imperative that this does not occur in the superconducting magnets, in which a quench may be induced by a steady loss of ~ 10^7 protons per second and per magnet.

With several hundred half-cells all around the machine, in which points of β_{max} and D_{max} will inevitably exist, the risk of quenching one or several magnets at any given time would be too high.

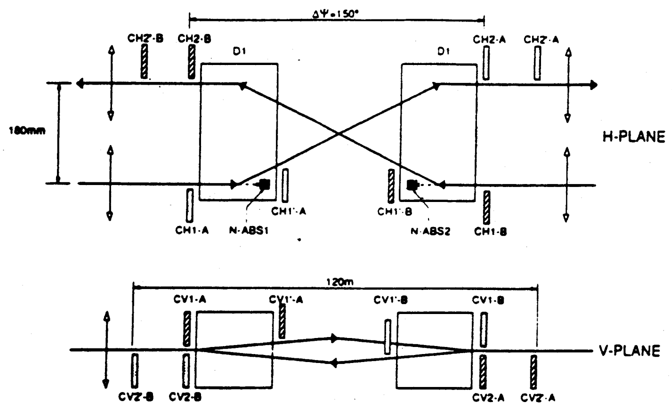

Fig. 7 A schematic view of the collimation insertion, together with the recombination magnets. The vertical separation is exagerated.

For this reason it was decided to devote one full straight section to a two-stage warm collimation system with an aperture restriction in both transverse planes of 6 beam σ at collision energy. Its layout is given in Fig. 7.

Its calculated efficiency is in excess of 99.98%, which is more than adequate for the purpose, but at this stage of the project, important unknown remains like the exact value of the impact parameter on the first collimator and/or of the halo intensity.

7 USE OF STRAIGHT-SECTIONS AND EXPERIMENTAL AREAS

As can be seen in Fig. 8, two of the LHC straight-sections will be used for machine functions, namely the beam collimation system mentioned above in Chapter 6 and the double extraction system for aborting the circulating beams at the end of each run and in case of machine malfunctioning onto external dumps.

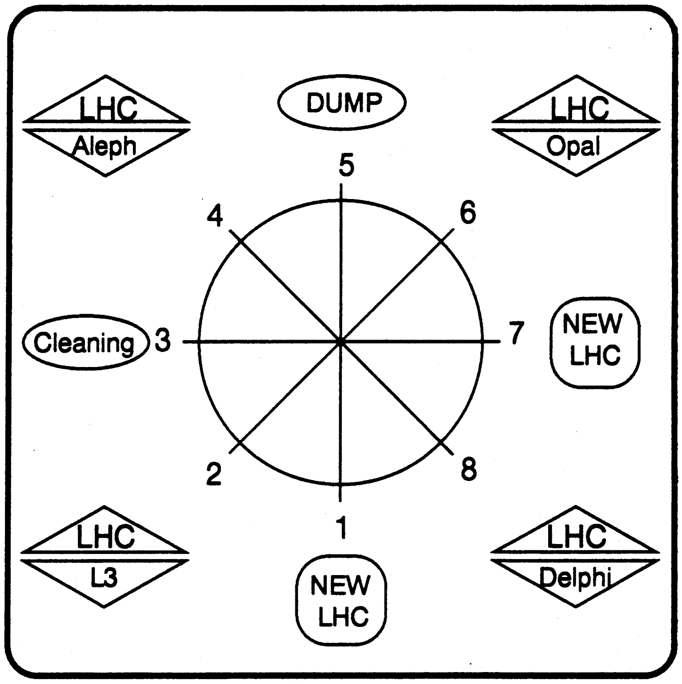

Fig. 8 Utilisation of LEP/LHC points

Of the remaining six straight-sections and interaction points, four are presently occupied by the LEP experiments and two (points 1 and 7) offer excellent geological conditions for the construction of new underground caverns for LHC experiments. These two regions will be used for large general purpose LHC detectors. The use of the existing LEP areas is also possible either when LEP experiments have been completed, or in the case of somewhat smaller LHC experiments on an alternate basis. This is possible because three of the LEP experiments can be rolled out into garage positions.

The design of the two new LHC areas is actively pursued in close collaboration with proponents of experiments.

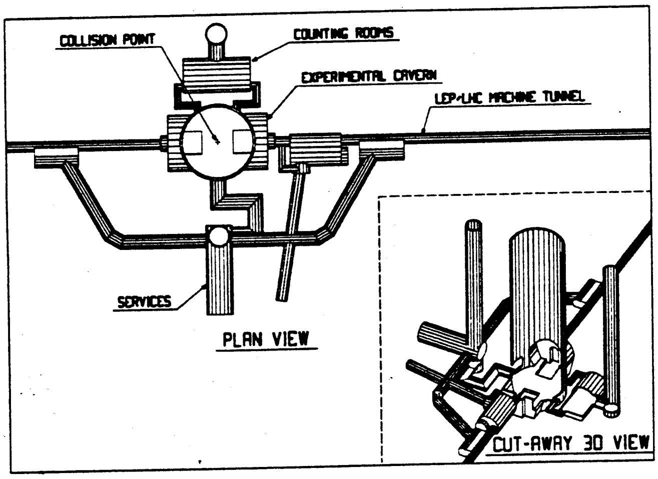

Fig. 9 Example of LHC underground experimental area

LHC experiments will be about twice the size of the LEP detectors and weigh between 10,000 and 30,000 tons. A design study for a suitable underground cavern, based on a 33 m diameter vertical access shaft directly over the collision point is shown in Fig. 9. Relatively modest alcoves are added along the beam-line to allow the forward detectors to slide along the beam pipe and give access to the central region for repair and maintenance. In this way the underground handling of heavy components will be minimised. The counting room for the experiment and machine services are housed in separate caverns.

8 TIME TABLE AND CONCLUSIONS

The considerable amount of design work already carried out and the encouraging results of the magnets and cryogenics models make us confident that we will be ready to start construction in 1994.

Technical studies suggest that with adequate funding, the LHC could be built and installed in about five years, while fully exploiting the physics potentials of existing CERN programmes including LEP 200.

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