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LHC Project Report 71

Status of the Large Hadron Collider and Magnet Program

N. Siegel for the LHC Magnet Team

Abstract

The Large Hadron Collider (LHC), approved by the CERN Council in December 1994, is a 7 +7 TeV proton accelerator-collider to be installed in the existing 27 km long LEP tunnel. It will represent a unique research facility for particle physics allowing proton-proton collisions with a luminosity of 10^{34} $cm^{-2}s^{-1}$ and capable of providing also heavy ion (Pb-Pb) collisions with a luminosity of 10^{27} $cm^{-2}s^{-1}$, using the existing CERN heavy ion source. The main technological challenges of the machine are the superconducting magnet system, in total more than 8'000 magnet units immersed in superfluid helium, with the lattice dipoles operating at 8.4 T, and the very large cryogenic system, which maintains the entire string of cryomagnets at its working temperature below 2 K. The paper discusses briefly the main issues which have led to the present layout of the LHC, gives an overview of the different machine components and characteristics and describes in more detail the recent development work and results of the LHC magnet program.

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I. Introduction

The LHC is the next frontier research tool for high energy particle physics being built at CERN which will enable proton-proton and heavy ion collisions at unparalleled energies and luminosities. This accelerator-collider machine is essentially composed of a ring of superconducting magnets providing two horizontally spaced magnetic channels which deflect and focus the two countercirculating particle beams. The present status of the LHC, including the machine and experimental areas program, have been reported in recent conference papers [1], [2]. Further, the conceptual design of the LHC has been considerably refined and is described in detail in the so-called "Yellow Book", issued end of 1995 [3].

The main parameters of the LHC for proton-proton collisions are given in Table 1 below.

TABLE 1
Main LHC Parameters For Proton-Proton Operation

Centre-of-mass collision energy	14 TeV
Luminosity	10^{34} $cm^{-2}s^{-1}$
Injection energy	0.45 TeV
Circulating current per beam	0.54 A
Particles per beam	2.8 x 10^{14}
Stored energy per beam	334 MJ
Synchrotron radiation	3.6 kW

Important economical assets are that the machine will be installed in the existing 27 km long tunnel which houses at present the Large Electron Positron collider (LEP), and that the injector chain is composed of the presently existing rapid cycling classical accelerators of CERN, needing only a few additional installations. This will allow the filling of the LHC in a relatively short time of 7 min, reducing injection time during which beams are more sensitive to perturbations like those coming from persistent currents.

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Since the circumference of the machine is given by the existing tunnel a bending field of nearly 8.4 T is required to reach the design energy. To achieve these very high fields, superconductor technology based on the well-developed NbTi alloy, operating in a static bath of pressurised superfluid helium, will be used. For reasons of economy and space limitations imposed by the LEP tunnel cross-section, a compact so-called "two-in-one" structure has been adopted for the main magnetic elements, incorporating the two beam channels in the same yoke and cryostat [4]. Benefits of operating in superfluid helium are its large thermal conductivity, heat capacity and low viscosity which allow it to permeate and cool the magnet conductors.

The LHC cryogenic system will have to maintain some 25 km of bending and focusing magnets at their operating temperature of 1.9 K. The cold masses of the LHC magnets will be subject to heat loads of different kinds: a) synchrotron radiation, resistive losses due to image currents and particle losses coming from the intense beam currents needed to reach the very high luminosities, b) ramping and resistive losses in the magnet excitation circuit, c) heat inleaks from ambient temperature. These constraints impose that the cryogenic system will have to produce an unprecedented total refrigeration capacity of about 20 kW at 1.8 K, in eight cryogenic plants distributed around the machine circumference.

II. Machine Layout And Main Systems

The basic layout of the LHC follows closely that of LEP, with eight arcs separated by straight sections each 528 m long which will house experiments and machine utilities. For optimum use of existing LEP infrastructure, the surface equipment servicing the machine has been concentrated in the even points. This has become known as the "four feed point" version.

A. General Layout

The engineering layout of the LHC has been optimized to save on costs but also to increase performance margins. One example is the symmetric location of the two high luminosity experiments which combined with the increased bunch spacing of 25 ns should ease the limitations caused by the so-called "beam-beam effects". Another increase in safety margin comes from the redesign of the magnet lattice in the arcs, consisting now of 23 regular cells, instead of 25, which increases the total arc dipole length, thus reducing the required field level. The regular lattice half-cell of the LHC is 53.5 m long and contains 3 dipoles and a short straight section incorporating the main quadrupole, correction elements, a beam position monitor and a cryogenic connection unit.

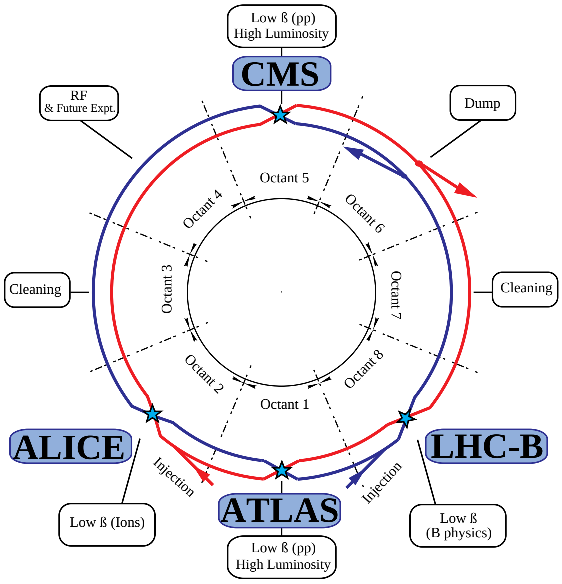

Fig. 1 Schematic layout of the LHC.

The number of crossing points where the beam passes from one ring to the other has been reduced from eight to four as shown on Fig. 1. The two high luminosity proton-proton experiments are located opposite to each other in new underground areas at Point 1 for ATLAS and Point 5 for CMS. Two more experimental insertions are foreseen at Point 2 (ALICE Pb-ions) and Point 8 (B-physics). The remaining four long straight sections have no beam crossings and are used for machine utilities, the layout in point 4 however has been designed to allow the installation of an experiment at a future time.

Points 3 and 7 are identical and used for “beam-cleaning”. Their role is to safely remove and absorb particles of the beam halo with an efficiency of 99.9% in order to minimize the background in the experimental detectors and the beam loss in the cryogenic parts of the machine, which could cause unwanted quenching of the superconducting magnets. These insertions contain only classical magnets, robust against the inevitable beam losses on the primary collimators. Point 4 contains the radio-frequency acceleration system, designed on the basis of separate superconducting cavities for each of the two beams, which requires that the 194 mm beam separation in the arcs is increased to 420 mm to provide sufficient transverse space. Finally, Point 6 contains the beam abort system. Its role is to safely and reliably extract the LHC beams, which will have total energies up to 334 MJ, and dump them in massive absorbers placed in special caverns some 700 m downstream from where the beam is extracted from the machine.

B. Magnets

The novel design features incorporated in the LHC dipole magnets, - i.e. operating in superfluid helium, "two in one" design, high forces (horizontal bursting force of 340 t/m) retained by aluminium alloy collars common to both apertures, two layer coil with graded conductor, vertically split yoke - were confirmed by the results of the first R&D magnets and have been maintained. The main differences with respect to the earlier machine design is the increased aperture from Ø 50 mm to Ø 56 mm, an increase in length to 14.2 m, a new cable width of 15 mm instead of 17 mm to take advantage of lower field requirements, and the increase of the inter-beam separation from 180 to 194 mm.

The main parameters of the dipole magnet are listed in Table 2 and the cross-section is shown in Fig. 2.

TABLE 2
MAIN DIPOLE PARAMETERS

Operational field	8.36 T
Coil aperture	56 mm
Magnetic length	14.2 m
Operating current	11500 A
Operating temperature	1.9 K
Coil turns per aperture: inner/outer shells	30 / 52
Distance between aperture axes	194 mm
Outer diameter of cold mass	570 mm
Overall length of cold mass	15140 mm
Outer diameter of cryostat	980 mm
Overall mass of cryostat	31 t
Stored energy for both channels	7.4 MJ
Self-inductance for both channels	119 mH
Quantity	1232

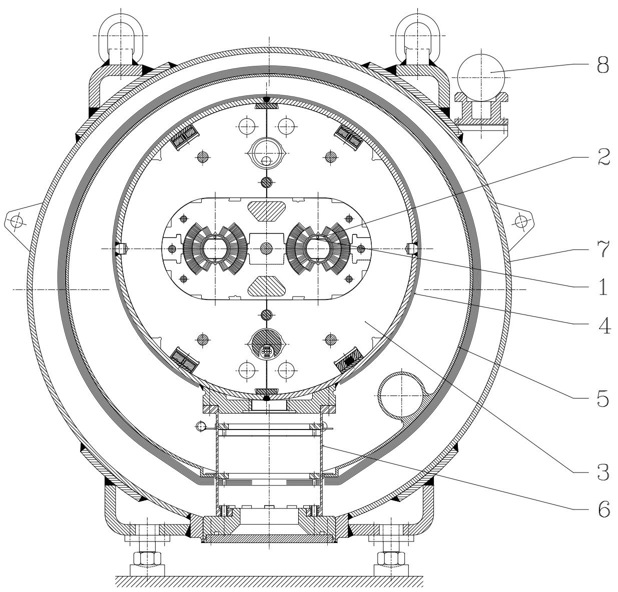

Fig. 2 Cross section of the dipole magnet and cryostat.
1. Beam screen, 2. Cold bore, 3. Cold mass at 1.9 K, 4. Radiative insulation, 5. Thermal shield (55 to 75 K), 6. Support post, 7. Vacuum vessel, 8. Alignment target.

The cable insulation is all in polyimide and composed typically of two half-overlapping wraps made of 25 µm thick tapes and a third wrap of adhesive coated tape, applied with 2 mm space between turns to leave channels for helium penetration. A grooved glass-epoxy spacer is placed between the inner and outer coil layers to provide further channels for superfluid helium. The insulation to ground is composed of superposed polyimide films including the quench protection heater strips. The collars are of racetrack shape reducing the yoke parts from the original 4 to 2, making assembly of the structure less sensitive to build up of tolerances. Magnetic steel inserts in the collars, punched from sheets of double the thickness of the collars, correct the field distribution at the different field levels and at the same time firmly lock pairs of collars together. The yoke, vertically split, tightly fits and supports the collars and is held together by an outer welded stainless steel shrinking cylinder. Attached to the ends of each dipole magnet are one small sextupole and one small decapole corrector to compensate in situ the corresponding multipole errors introduced by the main dipoles.

The main parameters of the arc quadrupoles are given in Table 3. The quadrupoles will be powered separately from the dipoles, which makes the operation of the LHC more flexible and reduces the need for tuning quadrupoles. This liberates space which is used to increase the dipole length. The design of the arc quadrupoles is based on using the same cable as for the dipole outer layer. Their main constructional features are: two layer coils made from a single stretch of cable, austenitic steel collars sustaining the full electromagnetic forces and a "two in one" yoke structure held by an outside stiffening cylinder. This tube also serves as helium vessel.

TABLE 3
ARC QUADRUPOLE PARAMETERS

Operational gradient	223 T/m
Coil aperture	56 mm
Magnetic length	3.1 m
Operating current	11750 A
Operating temperature	1.9 K
Coil turns per aperture	96
Stored energy for both apertures	786 kJ
Self inductance for both channels	11 mH
Quantity	386

The standard short straight section of the regular arcs houses the main quadrupole, two combined sextupole-dipole correctors and an octupole or a tuning quadrupole.

The dispersion suppressors, situated between the regular arcs and the insertion regions use standard arc dipoles and standard arc quadrupoles supplemented by small trim quadrupoles. Special dipoles recombine the two beams into a common channel close to the crossing points.

The final focusing triplet in the experimental insertions are built up from single bore 5.5 m long quadrupoles (32 units) of a novel design based on a graded coil with an aperture of 70 mm wound from NbTi cable and an operating gradient of up to 235 T/m.

C. Cryogenics

Although the basic features as well as the main technical choices for the LHC cryogenic system remain unchanged, the detailed layout has considerably evolved from further design work and experimental results from models and prototypes [5].

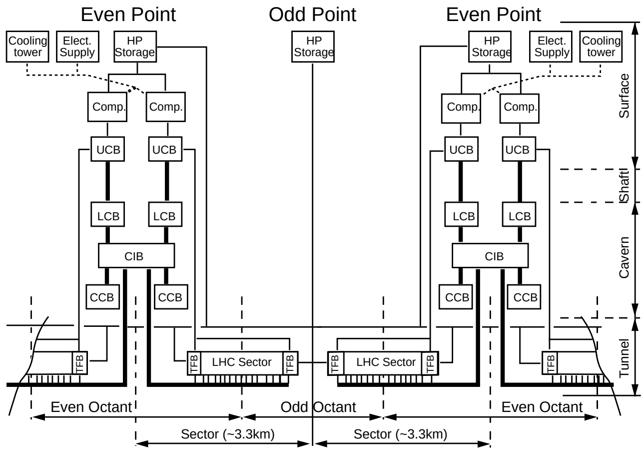

Fig. 3 General architecture of the LHC cryogenic scheme.

The general architecture is based on grouping all the active cryogenic equipment at the four even points, already developed and equipped with LEP infrastructure and to transport the refrigeration power over a full octant length, i.e. 3.3 km, instead of the previous 1.7 km half-octant. The four LEP cryogenic plants of 12 kW capacity at 4.5 K existing at these points will need to be upgraded for LHC to 18 kW and supplemented by a further four 18 kW plants. This results in the four point cryogenic feed scheme shown in Fig. 3 with two split-coldbox helium refrigerators of the LEP type serving adjacent sectors installed in each even point. The upper cold box (UCB) located on the surface cools helium gas to 20 K and the lower cold box (LCB) located in underground caverns, cools it to 4.5 K. Some redundancy is built in by using a cryoplant interconnection box (CIB) allowing distribution of cryogenic power of each sector to either or both plants. Refrigeration at 1.8 K is provided by two cold compressor boxes installed at tunnel level, consisting each of 4 to 5 stages of centrifugal compressors in series fed from the 4.5 K refrigerators through the CIB. Prototype monostages of centrifugal compressors have already been supplied by industry and successfully tested. They are now under investigation for completing their development. No infrastructure is required at the odd points, except storage tanks for recovery of gaseous helium after a full sector quench.

The cryogenic flow scheme of an LHC half cell is shown in Fig. 4. The magnets are immersed in a static bath of superfluid helium at 1 bar and cooled through a linear heat exchanger tube. The tube extends over each half cell and absorbs the heat quasi-isothermally by gradual vaporization of flowing two-phase liquid helium which is supplied by

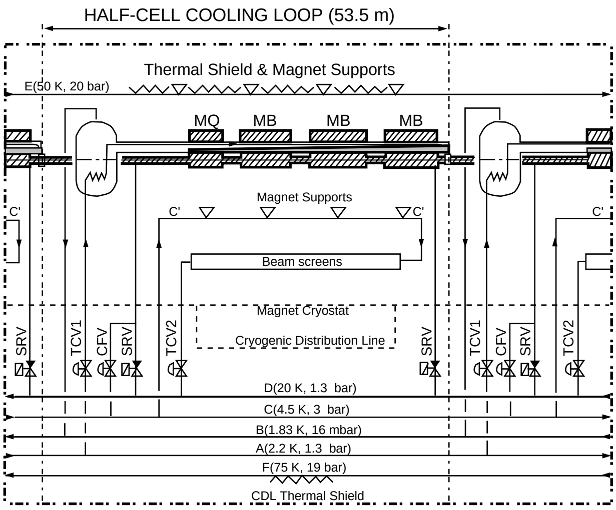

Fig. 4 Cryogenic flow-scheme of an LHC half-cell.

line A through the expansion valve TCV1. The low saturation pressure of 16 mbar is maintained on the flowing two-phase helium by pumping the vapour through line B. Line C supplies cooling at 4.5 K for heat interception on the magnet supports and on the beam screen placed in the aperture. Lines E and F provide cooling to intercept primary heat loads on magnet supports and the cryostat thermal shields at temperatures between 50 and 75 K.

Concentrating the refrigerators at the even points modified substantially the cryogenic distribution: larger diameter pipes are required for distributing the cryogenic fluids over a full sector, notably increasing the diameter of the cold pumping line B to 257 mm making impractical the previous integrated design incorporating in a common cryostat magnet and cryogenic lines. As a consequence, a separate cryogenic distribution line (CDL) running alongside the magnet cryostat carries most of the piping and connects to the short straight sections every 53.5 m.

D. Vacuum

The LHC vacuum system must cope with a number of particular problems. Synchrotron radiation from the primary beam and resistive wall losses from circulating image currents would be an excessive heat load at the 1.9 K level. Therefore a liner, or so-called beam screen, cooled by tubes carrying high pressure gas, is inserted into the cold bore of the machine to intercept this power.

Further, synchrotron radiation impinging on the liner will desorb gas molecules from the near surface which will then be cryopumped onto the same surface. The effect of hydrogen is particularly undesirable: once a monolayer of H_2 builds up the pressure will rise to the vapour pressure of hydrogen at the temperature of the liner which is two orders of magnitude higher than compatible with the required beam life time. To limit this effect, the beam screen will be perforated over a few percent of its surface to allow pumping by the cold bore surface at 1.9 K.

The present design of the screen is based on a 1 mm thick stainless steel tube with a round cross-section and a flattened top and bottom. This shape optimizes aperture requirements and is less sensitive to alignment errors. The cooling pipes are fixed to both flats and maintain the screen temperature between 5 and 20 K. The inside will be coated with 50 µm of copper to minimize the beam coupling impedance.

E. Magnet Powering and Protection

As for the cryogenic system, the powering of the machine elements [6] is concentrated in the even points where the existing ac supplies and cooling towers of LEP can be re-used. From these points, all main lattice magnets, including a good number of insertion magnets, are fed using superconducting bus-bars running through the machine cryostats and magnet cold masses, so segmenting the machine into eight galvanically separate sectors. Since the large RF galleries of LEP will no longer be needed, they can house the high current lattice power converters very close to the current feedthroughs. The advantage of the segmentation is a reduction in the total quenching voltage, rapid discharge of only 1/8 of the machine in case of a magnet quench, no risk of a complete machine avalanche quench, better static and dynamic control of the machine since one sector will contain magnets of the same manufacturer (Fig. 5).

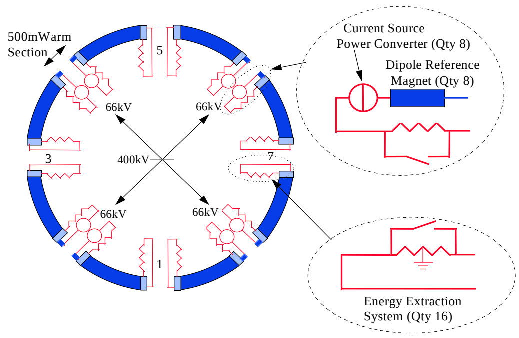

Fig. 5 Segmentation of main dipole powering circuit.

The quench protection of the LHC is based on the so-called "cold diode" concept. In a string of series connected magnets, the quench of one unit would induce the discharge of the stored energy of all other units in the quenching magnet, destroying it. This is avoided by by-passing the quenching magnet and rapidly de-exciting the rest. It is foreseen to use silicon diodes, two connected in series for each dipole magnet, located in an appendice of the cold mass at 1.9 K, allowing accessibility without dismounting the cold mass.

These diodes will be exposed to ionizing radiation. In the case of the dipoles a relatively well shielded place has been provided, so diffusion diodes can be used, but for the quadrupoles it will be necessary to use the more resistant epitaxial diodes. Occasional annealing to room temperature may be necessary to extend their life time. Thin epitaxial diodes, mounted between Cu heat sinks, which can absorb 1.5 MJ of energy have been tested in an accelerator environment at LN_2 temperature and appear sufficiently radiation resistant.

The very large energy density in the magnets and the relatively low natural quench propagation require fast detection of any incipient quench to trigger strip heaters which will spread the quench rapidly over a sufficiently large volume of the magnet.

III. MAGNET PROGRAM

A considerable amount of development work has been done on the main dipole and quadrupole magnets, which has resulted in the successful testing of 10 m dipoles and 3 m quadrupoles of the first generation which are now operating routinely in the magnet string test facility up to fields of 9 T. Short and long dipoles of the new design are in an advanced stage of completion and should be tested soon. A cross section of the cold mass is shown in Fig 6. A large effort is also deployed to refine the design and complete the prototyping of the numerous other magnet types for insertions and machine correction.

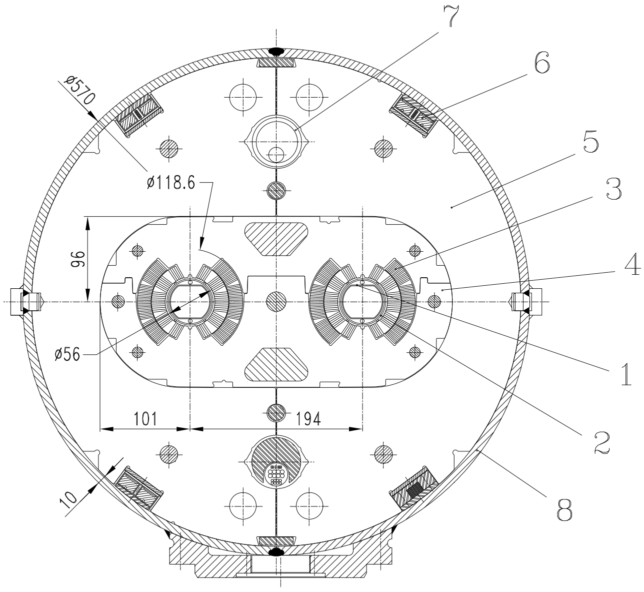

Fig. 6 Cross section of dipole cold mass.
1. Beam screen, 2. Cold bore tube, 3. Superconducting coils, 4. Aluminium alloy collars, 5. Iron yoke, 6. Superconducting bus-bars, 7. Heat exchanger pipe, 8. Austenitic steel shrinking cylinder and helium vessel.

A. Superconducting Cables

The considerable experience gained during the manufacture of 17 mm wide cables for the 10 m dipoles for the R&D phase, in total 66 km of cable representing more than 14 t of material, has been the basis for specifying the present 15 mm wide cable. The critical current densities were set at the 3 σ limit of the average obtained previously and the cable thickness tolerance was set to ±6 μm. The main strand and cable characteristics are shown in Table 4.

TABLE 4

DIPOLE STRAND AND CABLE CHARACTERISTICS

	Inner layer	Outer layer
Strand:		
Diameter (mm)	1.065	0.825
Cu/Sc ratio	1.6	1.9
Filament size (μm)	7	6
Twist pitch (mm)	25	25
Critical current (A)		
at 10 T, 1.9 K	≥515	
at 9 T, 1.9 K		≥380
Cable:		
Number of strands	28	36
Cable dimensions		
width (mm)	15	15
thin/ thick edge (mm)	1.72/2.06	1.34/1.60
Transposition pitch	115	100
Critical current (A)		
at 10 T, 1.9 K	≥13750	
at 9 T, 1.9 K		≥12960

More than 10 t of this cable have already been produced to specification and are being used in the manufacture of short and long magnets. In preparation of mass production, an intense program of cable tests and measurements is in progress with collaboration of European and US Laboratories, addressing also questions of stability [7] and inter-strand resistance [8], [9], an important issue for field distortions during ramping, the goal being to achieve a range of 10 to 20 μΩ.

B. Main Dipoles and Quadrupoles

CERN is now finishing measurements of the seven 10 m long magnets of 50 mm aperture using 17 mm wide cable [10]. The first five (with aluminium collars common to both apertures) have all well exceeded 9 T with some training. The magnets have been thoroughly measured and the field harmonics are as expected [4]. Detailed studies are in progress to understand and quantify effects related to the magnetization of the superconductor, to time dependent effects at injection field levels and behaviour during acceleration. Results will be reported at this conference [11]. The last two magnets of the seven mentioned above have a variant structure with separate collars and are now being tested.

Six long dipoles of the final aperture are in fabrication, two having the full 14.2 m magnetic length and four a length of 10 m due to temporary limitations in the tooling. The first 14.2 m prototype, made in collaboration with INFN, Italy, will be delivered to CERN in spring 1997. Of the 10 m dipoles, the first collared coil assembly has been successfully made. All CERN owned tooling in industry is now being modified to full length in preparation of series fabrication. In addition a 15 m long press has been installed in CERN to facilitate the assembly or repair of dipoles. It will be used for the assembly of the first 10 m dipole of the final aperture.

The short model program at CERN [12] is devoted mainly to the fabrication, collaring and testing of coils in single aperture structures to study and optimize coil end designs and difficult areas like the layer jump and splice region. It also provides a facility to check components, cable performance and special design features. Training behaviour of the first four single aperture models are shown in Fig. 7. Common to them is a gradual training at fields above 9 T. A double aperture model, of the same cross-section as the long dipoles, will be tested and measured this autumn.

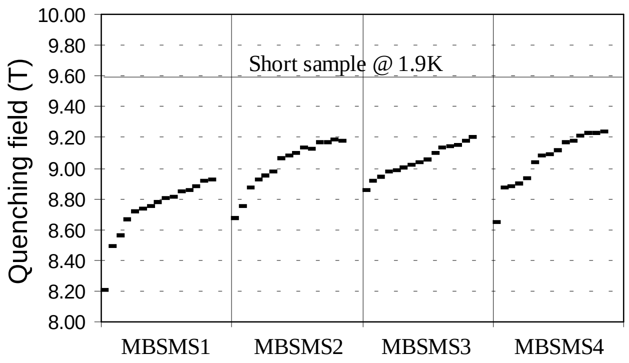

Fig. 7. First 15 training quenches of short dipole models 1 to 4.

Two full size 3 m quadrupoles have been constructed at CEN-Saclay under a CERN/CEA collaboration. Both magnets reached design gradient with only a few quenches [13]. The design and construction of two quadrupoles prototypes at Saclay has now started under the terms of a new collaboration agreement. They will be part of a new short straight section for the next magnet string.

C. Insertion and Corrector Magnets

Recently, a short model of a large aperture insertion quadrupole (70 mm aperture and 235 T/m) featuring a graded four-layer coil design [14] has been successfully tested in industry. CERN is collaborating with FNAL/USA and KEK/Japan to finalize the design of these insertion quadrupoles in view of fabricating full size magnets. The RF insertion layout is based on the use of RHIC bending magnet coils for the twin aperture separation magnets. A 1 m model of a single aperture separation dipole (88 mm aperture, 4.5 T and 4.5 K) for IR's 2 and 8 will be built with industry.

A number of prototypes of corrector and auxiliary magnets have been made and tested recently: a combined dipole/sextupole, an octupole and the small sextupole and decapole spool pieces for correction of dipole error multipoles. Automated fabrication of coils for the spool pieces (nearly 40'000 individual coils) is being developed. Correctors being made this way [15] will then be used in the next 15m dipoles which will be installed in the next magnet string.

IV. MAGNET STRING

A major milestone in the project has been the assembly, commissioning and testing of a magnet string facility, which at present consists of one short straight section and three 10 m dipole magnets connected electrically and cryogenically together on a slope of 1.4%, in simulation of the LHC ring conditions. The string was first tested cold and powered in December 1994, extended from two to three dipoles in 1995 and undergone more than 1500 hrs of operation with more than 50 quench recoveries and three thermal cycles with full success [16]. It is at present being powered with LHC like ramping cycles between injection and 8.4 T field in a routine fashion. In total, 2000 such current cycles are planned for the string, corresponding to more than 10 years of collider operation, to test its components for fatigue phenomena.

V. CONCLUSIONS

The results of the extensive R&D work accomplished over the past years confirm the validity of the fundamental technical choices which have been made for the construction of the LHC. In the key areas the project has now entered the phase of detailed engineering design to be followed by the beginning of the procurement stage.

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