THE LHC MAGNET PROGRAMME: FROM ACCELERATOR PHYSICS REQUIREMENTS TO PRODUCTION IN INDUSTRY

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Abstract

The LHC is designed to provide, at a beam energy of 7 TeV, a nominal peak luminosity of 10^{34} $cm^{-2}s^{-1}$ with simultaneous collisions at two high-luminosity insertions. This objective is being achieved by pushing the technology of superconducting accelerator magnets and cryogenics to its state-of-the-art limits, and by upgrading the existing CERN accelerators and infrastructures.

In this paper, the parameters of the main dipole (1232 units) and quadrupole (392 units) magnets stemming from the LHC design considerations are presented and discussed. Subsequently, the R & D program undertaken at CERN and with industry, to experimentally validate magnet design assumptions, to assess the merits of design variants and to procure and commission the heavy tooling necessary for series manufacture, is described and its main difficulties and results highlighted. Finally a report is given about the procurement strategy, and the progress in manufacturing.

1 INTRODUCTION

The LHC [1] high luminosity at a beam energy of 7 TeV, allowing a world-class physics programme, and the affordable project cost have played a capital role in the project approval in 1994 by the scientific Institutes and the financial authorities of the CERN Member States. The design of the LHC main magnets, worth an estimated 40 % of the total project cost, is the result of an optimisation process which evolved over nearly ten years of R & D work in superconducting (SC) magnets and He II cryogenics. During this time, beam optics studies defined with increasing confidence the necessary LHC dynamic aperture (D.A.) [2], limited at injection energy by the field imperfections of the main dipole and quadrupole magnets, and at high energy by the imperfections of the low-β triplets, enhanced by the crossing angle.

2 DESIGN CONSIDERATIONS, MODELS AND PROTOTYPES

2.1 Initial Design Studies (1988 – 1992)

Since LHC will be installed in the existing LEP tunnel, the peak energy is dictated by the maximum of the bending magnetic field. A field as high as 10 T is chosen as an initial goal, allowing proton beams to be stored at an energy of 7.7 TeV per beam.

Niobium-titanium SC cables operated below 2 K in superfluid helium are the only economic and reliable conductors which can be mass-produced to achieve this unprecedented high field (HERA operates at about 6 T, while the SSC foresaw 6.6 T, both at 4.2 K).

As there is hardly room for two separated rings of magnets, the concept of the twin-bore magnet is adopted. It consists of two sets of coils and beam channels within the same magnetic and mechanical structure and cryostat. In this way, a cost saving of 30 % can be made with respect to two separated structures.

In the initial design studies [3], the lattice of the LHC, was designed to lie in a beam plane 1.21 m above that of LEP. As LEP, LHC consisted of eight 2.45-km-long arcs, and eight 545-m-long straight sections. The initial design foresaw 25, 97.96-m-long lattice cells per machine arc. Each cell contained eight dipoles with a magnetic length of 9 m (about the length of the HERA dipoles) and two quadrupole with a magnetic length of 3.05 m, respectively. Including the dispersion suppressor lattice cells, the initial LHC design required a total of 1792 dipole and 392 quadrupole twin-aperture arc magnets.

The evaluation of the LHC D.A. at injection energy showed that the multipolar components of the main dipoles are the limiting factor. These imperfections stem from the approximation of the ideal SC coil geometry by discrete conductor “blocks” and from the effect of the persistent currents in the filaments of the SC cable strands. The strength of the geometric multipolar components depends on the design and size of the coils, while that of the persistent currents depends mainly on the SC filament diameter. In the dipole case, keeping the field constant on the inner coil surface and enlarging the coil diameter reduces the multipolar component of order n by the enlargement factor to the power $n-1$.

By choosing for the dipoles a 6-block coil design, an inner coil diameter of 50 mm and SC filaments diameters of 5 μm, the resulting systematic field imperfections were consistent with the then minimum D.A. requirements of 6 σ of the injected beam size. Similar considerations lead for the main quadrupole to a 4-block coil design, a coil inner diameter of 56 mm, allowing a 12-pole correction coil and the same SC filament diameter as for the dipoles.

The initial dipole cross-section featured two coils, separated by 180 mm; each coil was formed of two layers with a graded current density, supported by high-strength non-magnetic aluminium alloy (AA) collars. AA was preferred to austenitic steel (AS) because its thermal contraction coefficient is closer to that of the coils (thus limiting the loss of coil prestress during cooldown) and its lower cost.

Because of the difference in thermal contraction of the AA collars and yoke low-carbon steel yoke, respectively, the vertically split yoke featured a gap of some 0.5 mm at room temperature (RT), after the welding of the shrinking cylinder. The size of this gap is given by the maximum stress that can be imparted at RT by the welded shrinking cylinder to the coils and their electrical insulation system.

A magnetic insert was placed between collars and yoke, to optimise field quality. The main dipole and quadrupole parameters are given in Tables 1 and 2.

Table 1 Dipole parameters (1991)

Energy per beam	7.7	Tev
B max at 2 K	10	T
Magn. length	9	m
Current	15060	A
Coil inner / outer diam.	50/120.2	mm
Dist. between apertures	180 mm	
Yoke outer diameter	560	mm

Table 2 Quadrupole parameters (1991)

Max. gradient at 2 K	250	T/m
Magn. length	3.05	m
Current	15060	A
Coil inner / outer diam.	56/110.6	mm
Dist. between apertures	180 mm	
Yoke outer diameter	440	mm

The design characteristics of the SC cables for the inner and outer layers of the dipole coil and for the two quadrupole coil layers, wound with a same cable, are given in Table 3.

Table 3 Characteristics (1991) of the keystoned SC cables for the dipoles (MB) and quadrupoles (MQ).

	MB inn. layer	MB out. layer	MQ
I_c (A), at 2 K	≥14800 at 11 T	≥17100 at 9 T	≥15600 at 9 T
Cross-section (mm^2)	2.02/2.48 x 17.00	1.30/1.65 x 17.00	1.70/2.16 x 13.05
Strand numb.	26	40	24
Strand ∅ (mm)	1.29	0.84	1.09
Fil. diam.(μm)	5	5	5
Cu/SC ratio	1.6	1.8	1.8

The cable insulation consisted of two half-overlapped layers of polyimide tape, both 25 μm thick, plus a third layer of 120 μm thick glass-fibre tape, impregnated with B-stage epoxy resin and spaced by 2.5 mm between successive turns. The latter spacing provided channels for the superfluid helium to penetrate the polyimide wrapping and wet the strands.

2.2 Initial R & D with Industry (1990-1994)

To assess practical feasibility and foster at the same time the interest of industry for the possible construction of the LHC, three single- and four double-aperture 1.3 m-long models were procured from five different European firms, following competitive call for tenders. One single- and one double-aperture short model were also assembled at KEK within the framework of a collaboration agreement. Seven 10-m-long double-aperture prototype cold masses were then ordered from four European firms. All these magnets featured a 50 mm internal coil diameter, and SC cables as per Table 1.All the double-aperture ones had combined AA collars, but one short model and one prototype which had separated AA collars for each aperture, and one prototype with separated AS collars. The detailed results of this models and prototypes can be found in [4]. The main conclusions from this R&D work were that:

1. the He II cooling of magnets in long horizontal cryostats is feasible and well controllable;
2. double-aperture magnets can behave satisfactorily in terms of quench and training performance;
3. the required field quality can be achieved.

2.3 A New Coil Inner Diameter and Length, the LHC Nominal Energy becomes 7 TeV (1993)

The D.A. studies progressed after the publication of the so-called Pink Book [3] in 1991. They showed that, with the error coefficients assumed for a 50 mm inner diameter of the dipole coils, and taking into consideration all known imperfection sources, including residual closed-orbit deviations and coupling, the long-term D.A. was only 5.5 σ of the injected beam size. This value was considered insufficient, since simulations can never incorporate all the real imperfections of a real collider. Further studies were made with reduced error coefficients corresponding to an inner diameter of the dipole coil of 56 mm. As a result, the D.A. was found to increase to an adequate 6.5 σ. The progress in understanding led to revised main dipole parameters and a new cell layout [4].

The dipole magnetic length was increased to 13.145 m, its nominal field fixed at 8.65 T (a value providing a field safety margin of about 10% of the nominal quench field of the inner layer cable) and the number of cells per arc, each containing 6 dipoles, reduced from 25 to 24. The cables design was reviewed (see Table 4), the lower nominal field allowing a reduction of the cables cross-sections and hence of their cost.

Table 4 Design (1993) characteristics of the keystoned SC cables for the dipoles (MB) and quadrupoles (MQ).

Cable charact.	MB inn. layer	MB out. layer	MQ
I_c (A), at 1.9 K	≥13750 at 10 T	≥12950 at 9 T	≥15600 at 9 T
Cross-section (mm^2)	1.72/2.06 x 15.00	1.34/1.60 x 15.00	1.34/1.60 x 11.60
Strand numb.	28	36	28
Strand ∅ (mm)	1.065	0.825	0.825
Fil. diam.,(μm)	7	6	6
Cu/SC ratio	1.6	1.9	1.9

The choice of a 6 and 7 μm diameter (instead of 5 μm as previously) of the SC filaments stemmed from economical considerations, as these diameters could also be obtained by the single-stacking NbTi billet manufacturing process.

The total number of dipole units became thus 1280 (plus 16 shorter ones in the dispersion suppressor regions) instead of 1792, entailing an important cost reduction.

With the increase of the dipole coil inner diameter from 50 to 56 mm, a simpler 5-block coil cross-section was found to satisfy the smaller error coefficients required to satisfy the 6.5 σ criterion for the D.A..

The 1993 dipole cross-section featured AS separated collars rather then combined AA collars. The yoke diameter of the cold mass was kept at 560 mm as before, the increased inner coil diameter being counterbalanced by the smaller cable width. In this way, the overall dimensions of the LHC magnets stayed within the boundaries required for their installation above LEP. The quadrupole design was revised as well [4].

2.4 The "Yellow Book"(1995)

The LHC project was approved in December 1994. The LHC design continued to progress in the understanding and optimisation of beam optics aspects, while the layout of its various systems was further streamlined towards flexibility and overall cost minimisation. A new conceptual design was published [1]. The LHC would be installed on the tunnel floor, after removal of LEP. This change made the design of the dispersion suppressor regions easier, allowing there the use of dipoles identical to those in the regular cells. The regular lattice period was further stretched by about 4.9 m, reducing the number of full cells per octant from 24 to 23. This period length was found to be the longest one which still yielded a sufficient D.A. (a lattice with 21 cells per arc was evaluated, owing to the larger β and dispersion, its D.A. was lower by 10 %). The number of dipole and quadrupoles was reduced by 48 and 16 units, respectively. The dipole magnetic length was also increased with a consequent reduction in the field needed for 7 TeV, giving an increased quench margin (see Table 5).

The separation between beams was increased for various reasons from 180 to 194 mm, allowing among other things to base the design of the main quadrupoles on the same cable as the outer layer of the dipoles. The dipole cables parameters were the same as in Table 4.

Table 5 Dipole parameters (1995)

Energy per beam	7	Tev
B nom. at 2 K	8.4	T
Magn. length	14.2	m
Current	11500	A
Coil inner / outer diam.	56/120	mm
Dist. between aperture axes	194	mm
Cold mass outer diameter	570	mm

The dipole featured a 5-block coil design and combined AA collars, with an embedded magnetic insert. AA material was chosen to minimise coil pre-stress at RT, and the combined collar geometry to ensure the best possible parallelism between the dipole fields in the two beam channels. The SC cables insulation was changed to a full polyimide system, maximising wetting by He II [5] and heat transfer from the cable strands to the He II cooling the cold mass.

The design of the arc quadrupoles (Table 6) was redone at CEA-Saclay [6], using the cable of the outer dipole layer. Concerning field quality, as the b_6 (normal dodecapole) due to persistent currents contributed to the limitation of the D.A., in the new design b_6 was partly compensated by acting on the coil geometry.

Table 6 Quadrupole parameters (1995)

Nom. Gradient at 2 K	223	T/m
Magn. length	3.10	m
Current	11780	A
Coil inner / outer diam.	56/118.6	mm
Dist. between apertures	194 mm	
Yoke outer diameter	456	mm

The other major design features of the original quadrupole cross-section were maintained.

2.5 Short and Long Dipole Models, First Prototype

The manufacture at CERN of a series 1-m single aperture models and of four 10-m long model collared coils to be delivered by industry was launched to assess the performance of the Yellow Book (YB) dipole design.

The short model programme, started in October 1995, allows the assembly and test of more than one model magnet (or its variants) per month. In this way a larger number of important design issues can be studied and assessed with sufficient data within a short time.

The 10-m model programme aimed at maintaining the know-how in industry in coil winding and collaring, while the cold mass assembly was carried out at the newly created CERN Magnet Assembly Facility.

Among other important results, this model programme showed that the 5-block coil design had a tendency to mechanical instabilities in the coil straight sections, at field levels close to the nominal field. The assembly of long cold masses with an open yoke gap at RT proved to be difficult and time consuming to be controlled. This because of the needed tight tolerances, measurements and adjustments of components and pre-assemblies.

These aspects were also observed in a full-length dipole prototype, completely assembled in industry within the framework of a CERN-INFN agreement [7].

2.6 Dipole Design for Series Production

As from the beginning of 1997 the dipole design was reconsidered in the light of the acquired experience, with a view to optimise it for series manufacture in industry. This entailed to give weight to robustness with regard to mechanical tolerances in view of a simple, fast and reliable cold mass assembly, relative independence of assembly steps, a sufficient range for fine-tuning of field quality without major tooling modifications.

A 6-block coil cross-section, was eventually chosen [8], [9]. Following the important experimental results obtained on the short model programme [10], a coil pre-stress at RT lower then originally assumed turned out to provide good training performances, allowing thus to reconsider the use of AS material for the collars. Three alternative designs (two featuring combined AA and AS collars, respectively, one with separated AS collars) were analysed with respect to admissible component tolerances and structural stability, field level, field quality, number and weight of parts [11]. AS was chosen as collar material because: a) it allows to achieve the required structural behaviour with realistic component tolerances [12]; b) the yoke halves can be made to mate (no gap) after assembly at RT, avoiding thus accidental coil over-stressing during assembly and simplifying the overall assembly procedure.

The insert between collars and yoke has inclined mating surfaces as for the MFISC [13] short model magnet. The combined collar design was maintained in view of the experience made so far and of the conspicuous tooling already available in industry. Changes to the existing drawings and tooling, and hence delays, were minimised by adopting strong AS collars, having about the same cross-section as that of the AA collars used for the 10-m models. In this way also the coupling between collared coils and cold mass assembly is minimised, making field quality and cold mass behaviour only weakly dependent on assembly history, which is a positive feature for a large series production.

With respect to Table 5, the magnetic length could be slightly increased to 14.3 m, the nominal field reduced to 8.3 T, and the nominal current had to be increased to 11800 A because the chosen 6-block coil has one turn less than the previous 5-block one. The cable main parameters are as given in Table 4, but for their thin edge thickness and width, increased by 0.02 mm and 0.1 mm, respectively, to improve the thin edge cooling by He II. The interstrand resistance, one of the parameters governing the LHC ramping rate, is controlled by a SnAg strand coating followed by a heat treatment. The latter reduces in addition the cable contraction after coil curing.

The series dipole design satisfies as much as possible the field quality requirements from beam optics. Irreducible multipoles like a_3 (skew sextupole) and b_4 (normal octupole) are taken care of by corrector schemes.

With the improved field quality of the main dipoles and quadrupoles, the foreseen correction schemes and an optimized optics, the target of a D.A. of 12 σ of the injected beam size is achieved in simulations [2].

2.6 The Series Design Dipole Prototypes

To validate the series design of the dipoles, the manufacture of six full-size prototypes was launched in summer 1998. This programme comprises the manufacture by three firms of two collared coils per firm, and the assembly of the cold masses at the CERN Magnet Assembly Facility. Results from this work are reported in more detail in [14]. Three prototypes have been tested, the fourth and fifth are being assembled, the last collared coil will be delivered by early July. In the prototypes tested so far, the nominal 8.3 T field is exceeded after one to three quenches, quenches below 9 T occur only in the coil ends, a point which is being actively studied in the short model programme [15] and for which promising remedies (better geometry and compaction of the coil ends, appropriate pre-stress, lower fields) will be tested in the forthcoming months. The third prototype, where an improved matching between end-spacers and conductor was possible, exceeded 8.3 T after one quench and reached a field of 9.15 T (limited by the nominal power converter current of 13 kA) after the 5th quench. After thermal cycle, the first quench was at 8.75 T, and 9 T were exceeded after the second quench.

A first analysis of the field quality of these prototypes shows that the basic multipole content measured at RT in the collared coils and its design shifts introduced by the yoke, are essentially conserved throughout assembly and cool down. The field quality feature a spread in b_3 and b_5 stemming mainly from the different pole shim sizes used by the three firms in the prototypes for various reasons. A fine-tuning of the observed $b_{2,}$ b_3 and b_5 components by acting on the geometry of the magnetic insert (forb_2) and on that of the copper wedges of the inner layer (for b_3 and b_5,) will be proposed once all the prototypes have been measured.

2.8 The Series Design Quadrupole Prototypes

Three prototype quadrupole cold masses, named SSS3, SSS4 and SSS5, were assembled at the CEA-Saclay Laboratory [16] in France. SSS3 was cold tested at CERN this April, SSS4 will be tested this July, also at CERN, while SSS5 will be tested at Saclay in the second half of the year 2000. The main parameters of the quadrupole magnets are as per Table 6, apart an increase of the nominal current by 100 A. At its first powering SSS3 exceeded the nominal gradient of 223 T/m after only one training quench and the ultimate gradient of 242 T/m (at 13 kA) after the 3rd quench. After thermal cycle, SSS3 was ramped up to 13 kA without any quench. Concerning field quality, the measured value of the b_6 component was 2.6 units above the target one. This will be easily corrected for series manufacture by changing the pole shim thickness by some hundredths of mm.

3 SERIES MANUFACTURE

3.1 Dipole Cold Masses

Contracts for the manufacture of 3 x 30 pre-series dipole cold masses were signed in November 1999 with the three firms already involved in the above prototype work. These firms are being equipped by CERN with heavy tooling like collaring presses and welding presses (one per firm), devices for the measurement of coil geometry and Young's modulus, equipment for magnetic measurements. All major components will be provided via CERN-managed contracts, so as to achieve economies of scale and highest component uniformity. This includes SC cables, polyimide insulation material, quench heaters, collars, yoke laminations, shrinking-cylinder half-shells, heat exchanger tubes, cold bore tubes, sextupole and decapole correctors, bus-bars, end-covers. For the procurement of most of these components, 23 contracts with firms and one agreement (for bus-bars) with BINP in Novosibirsk have already been signed and production has started. A further seven call for tenders and contract adjudications will be carried out in the year 2000, for the delivery of the components presently procured via pilot orders for limited quantities.

The delivery of the first pre-series cold masses is expected by end 2000.

The call for tenders for the manufacture of the remaining 1160 dipole cold masses will be issued in the course of the year 2001, once pre-series contractors have manufactured a sufficient number of units, to be able to quote a competitive price for series manufacture. The adjudication will be made on the basis of bids for half the total quantity.

3.1 Quadrupole Cold Masses

The proposal for the contract adjudication for the manufacture by one single contractor of 400 quadrupole cold masses was agreed by the CERN Finance Committee in March 2000. In the case of the quadrupoles, CERN will provide to the contractor the SC cable, polyimide material, quench heaters, steel for collars and laminations, cold bore and heat exchanger tubes, correctors, diodes and beam position monitor supports. All the other components will be procured by the contractor itself. The delivery of the first series quadrupole cold mass is expected by end 2001.

4 CONCLUSION

The design of the LHC dipole cold masses has evolved, over ten years, from studies and conceptual designs to series design, validated by numerous model and prototypes magnets, where alternative concepts were tried out.

Essential design boundary conditions were on the technical side the constraints from beam dynamics (D.A., geometric aperture), lattice layout, and from the interconnection and alignment in the tunnel of the cryomagnets. It was possible to satisfy them as far as technically possible.

A major role in the decision making process over the years was also played by the steady aim at minimising the overall cost of the dipole magnet system and by project schedule considerations.

Industry was closely associated from the beginning to the magnet development by model and prototype work, to prepare the ground for competitive series manufacture.

The proposed series design can be considered as reasonably optimised. It has been carefully checked by Monte Carlo simulations with models describing the behaviour of its mechanical structure and the expected field imperfections [17], aiming at a robust design which can be implemented at an affordable price with practical tolerances for the components geometry, and has a tuning range sufficient for correcting manufacturing drifts.

The results from the ongoing prototype work for both dipoles and quadrupoles indicate that the design nominal bending field and focussing field gradient can be reached with a few initial quenches and without quenches after thermal cycle.

The manufacture of 3 x 30 pre-series dipole units has started, minor modifications resulting from prototype work will be incorporated as from the early units. The call for tenders for series manufacture will be issued in the year 2001, according to the LHC main schedule.

The challenge as from now will mainly lie in the industrial mass production of the main magnets, under strict quality control and according to schedule.

5 ACKNOWLEDGEMENTS

The design, validation and manufacture of the LHC main magnets constitute a major technical and human challenge, which is being achieved in a context of strictly controlled resources and schedules. This is made possible by the ingenuity, professional competence, steady determination, untiring efforts of all those who are contributing to the success of these activities.

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