LHC ARC DIPOLE STATUS REPORT

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Abstract

The LHC, a 7 Tev proton collider presently under construction at CERN, requires 1232 superconducting (SC) dipole magnets, featuring a nominal field of 8.33 T inside a cold beam tube of 50 mm inner diameter and a magnetic length of 14.3 m.

To achieve such high fields whilst retaining the well-proven fabrication methods of cables made with NbTi superconductors, it is necessary to operate the magnets at 1.9 K in superfluid helium. For reasons of space and economy, the two dipole apertures are incorporated into a single iron yoke and cryostat (two-in-one concept). The design considerations and the experimental results, which have led to the design adopted for series manufacture, are presented and discussed. The aims and status of the short model and full size prototype dipole programmes are subsequently reported. Finally, the major milestones of the schedule of the dipole magnets series manufacture are given and commented.

1 DESIGN REQUIREMENTS

The LHC dipole design aims at a nominal field of 8.33 T and at an ultimate one of 9 T. The first training quench of each magnet should be above the first value and the second one be reached with limited training. After cold tests and installation, no retraining up to 9 T should occur. The field quality at injection (0.54 T) is critical for machine performance and should be as close as technically feasible to beam optics requirements, to minimise imperfections at their source and limit the size and complexity of corrector magnets schemes. The design must be suitable for series production by several contractors: this implies 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. Last but not least, at the required performance the cost of components and labour is to be minimised.

2 DESIGN AND R&D WORK

The considerations which lead to the choice of the above field levels and basic magnet design can be found in the LHC Yellow Book (YB)[1]. The resulting dipole magnet main features are a twin-aperture structure, a margin of about 15% with regard to SC cables nominal short sample critical value reached at a dipole field of 9.65 T, an operating temperature of 1.9 K, an active protection system driving a fast quench propagation to the whole coils to avoid damages because of the high stored energy. Further, at the injection field, the effects on field of the strand persistent currents [2] and their time decay drive the choice of the SC filaments diameter and impose a tight control on the characteristics of the SC strands. Field quality considerations require also to limit the effect of eddy current effects during field ramping, imposing to control the cables inter-strand resistance [3] to within some 10 μΩ around its design value. The main magnet parameters are given in table 1.

	Value	Unit
Inj. field (0.45 TeV beam energy)	0.54	T
Nom. field (7 TeV beam energy)	8.33	T
Nominal current	11'800	A
Operating temperature	1.9	K
Magnetic length at 1.9 K	14.300	m
Stored energy (both apertures) at 7 TeV	7.1	MJ
Ultimate operational field	9.00	T
Nominal short sample field limit	9.65	T
Distance between aperture axis at 1.9 K	194.00	mm
Bending radius at 1.9 K	2804	m
Aperture axis distance at 293 K	194.52	mm
Approx. bending radius at 293 K	2812	m
Inner coil diameter at 293 K	56.00	mm
Outer coil diameter at 293 K	118.60	mm
Conductor blocks / pole	6	
Turns / pole, inner layer	15	
Turns / pole, outer layer	25	
E.m. forces/coil quadrant at 8.3 T Hor. force (inner and outer layer) Vertical force (inner layer) Vertical force (outer layer)	 1.7 -0.14 -0.60	 MN/m MN/m MN/m
Axial electromagnetic force on both ends at nominal field	0.50	MN
Cold bore inner diameter at 293 K	50.00	mm
Cold bore outer diameter at 293 K	53.00	mm
Cold mass length at 293 K (active part)	15'180	mm
Cold mass diameter at 293 K	570.0	mm
Overall length with ancillaries	16.8	M
Cold mass weight	≈ 30	tonne

Table 1: Main parameters and characteristics of the LHC dipole magnet cold mass

The magnet structure shown in Fig. 1 is the result of concomitant design studies and experimental work. The design studies addressed topics like optimum coil cross-section, field quality tuning range and sensitivity of field

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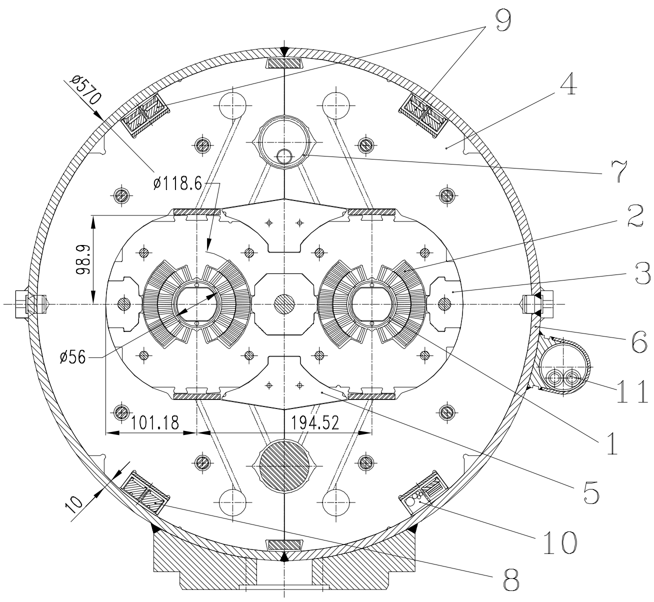

Figure 1: Series-manufacture cross-section of LHC dipoles. 1-beam tube; 2-SC coils; 3-austenitic steel collars; 4-iron yoke; 5-iron yoke "insert"; 6-shrinking cylinder / He II vessel; 7-heat exchanger tube; 8-dipole bus-bars; 9-arc quadrupole and "spool-pieces" bus-bars; 10-wires for magnet protection and instrumentation; 11-bus-bars for auxiliary magnets in the LHC arc short straight sections.

quality to the tolerances of coil components [4], stability at high field of the cold mass structure with respect to collar material and tolerances, yoke lamination tolerances, variations of coil pre-stress and shrinking cylinder stress [5, 6]. The experimental work comprised numerous 1-m long single aperture models, four 10-m long models of the YB design and one full size prototype, also of the YB design.

The aim of the ongoing 1-m model program [7] started in October 1995, is to assemble and test at CERN some 12 to 14 magnets per year, allowing to have fast answers on questions raised in design studies and/or experimental work. These questions include coil cross-section (5-and 6-blocks), SC cable characteristics, geometry and materials of coil components (e.g. end- and interlayer- spacers, quench heaters, cable and ground insulation, collar material), design of transition areas (e.g. inner layer "jump" and splice to the outer layer, transitions from straight to curved sections), optimum layer pre-stress level, manufacturing procedures (coil winding, layer curing and layer-end impregnation).

The 10-m, YB-design model program, initiated in 1996 and terminated in spring 1998, allowed to achieve several goals. The first was to continue to carry out coil winding and collaring in industry, so as to check tooling and manufacturing procedures in view of series production and foster know-how exchange with industry. The second was to assemble at CERN the collared coils into complete cold masses, gathering hands-on experience on issues like collared-coils and yoke interface, assembly procedures, welding technologies and procedures, cold mass geometry, cold mass assembly into cryostats delivered by industry. The third was obviously to assess the performance of the YB design in view of series production.

The first 15-m prototype, also of the YB design, jointly funded by CERN and INFN (Italy), was initiated in spring 1995 and delivered by end 1997. It allowed to gain experience with the manufacture of full-length components, assembly of a complete cold mass and its cryostating in industry, transport to CERN of the cryostated prototype, and to assess its performance. A comprehensive summary of the results from the four 10-m models and the above prototype is given in ref. [8].

The main design choices resulting from the above activities are reported in the following.

2.1 Coil cross-section

A 6-block coil cross-section, optimised thanks to the recent availability of genetic algorithms [9] allowing to consider discrete and continuous parameters at the same time, is chosen [10]. With regard to the previous 5-block coil design, it features a wider tuning range, a more stable mechanical behaviour because of a more favourable geometry and distribution of electromagnetic forces, a

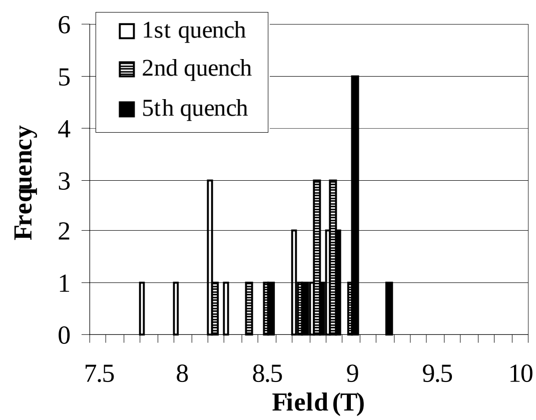

Figure 2: Quench levels in 1-m models with 5-block coil design

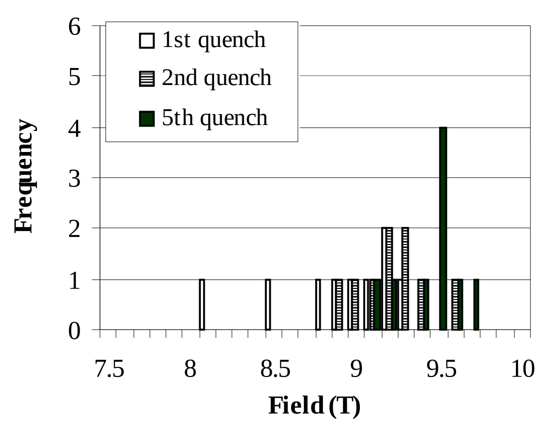

Figure 3: Quench levels in 1-m models with 6-block coil design

lower field at the inner layer turn which is submitted to the S-bend transition to the outer layer. The possible increase in winding time because of the additional wedge spacer in the inner layer is about compensated by the fact the 6-block design has one turn less in the outer layer. The training performance of 1-m long single-aperture models equipped with 5- and 6-block coils is shown in Figs. 2 and 3. It can be seen that the 6-block design consistently reaches a 0.5 T higher field than the 5-block one.

2.2 Collar-yoke "vertical" interface

The 10-m models and the prototype of the YB design feature a racetrack-shaped collar, containing an iron insert (needed for field quality reasons), fitted into the collar pairs prior to the assembly of the collar packs.

Experience has shown that small variations in the fitting of the soft iron insert and its possible plastic deformation during collaring lead to irreversible changes of the vertical dimensions of the collared coils. The achievement of the design value of these dimensions is critical, as they control the interference, necessary up to the highest field, between the yoke and the collared coil. This interference is essential for the stiffness of the cold mass structure and hence for the mechanical stability of the coil, particularly if alloyed aluminium (AA) is chosen as collar material. It was therefore decided to make the insert independent of the collars and shape it so as to provide inclined boundaries between collars and yoke (see Fig. 1). This geometry of the collar-insert-yoke interface, already used in a highly successful short twin-aperture model [11], leads to an increase by a factor 3 of the contact forces between collared coil and yoke.

2.3 Layer pre-stress and choice of collar material

Several short models were devoted to the study of the influence of coil pre-stress on training behaviour. These studies have shown that for the LHC dipoles, nominal pre-stresses of 30 MPa and 40 MPa at 1.9 K for the inner and outer layer, respectively, allow to reach field levels in excess of 9 T within a few quenches, and eventually field levels of up 10 T after 15 quenches. Pre-stress values some 10 MPa lower than the above may lead to an erratic training behaviour above 9 T, while values higher by 10-20 MPa may lead to slower training and lower final field levels. A few more short models will be assembled to complete the definition of the admissible pre-stress window. The above values of nominal pre-stress lead to an unloading of the inner and outer layer at about 8.4 T and 9 T, respectively. They are comfortably lower than the 50 to 60 MPa which were sought in previous work, where it was considered important to maintain some 10 MPa pre-stress up to field levels above 9 T. A lower collaring force and hence a lower collar deformation after collaring are thus possible, easing at the same time the collaring operation and the matching of collar and yoke geometries throughout magnet assembly, cool down and operation. Moreover, and most important, the above values of nominal pre-stress allow to consider austenitic steel as collar material. Because of the lower integrated thermal contraction coefficient of austenitic steel (AS) with respect to that of alumimium, the letter being close to that of the SC coil layers, the loss of coil pre-stress during cold mass cool-down from 290 to 1.9 K is of 10-15 MPa and about 30 MPa for AA and AS collars, respectively. Coil prestresses at room temperature higher than 80 MPa lead to creep of the polyimide SC cable insulation and are therefore to be avoided, thus limiting for AS collars the maximum design layer prestress at 1.9 K at 40-45 MPa, values which turned out to be compatible with a satisfactory training performance. The possibility to consider AS for the collar material has far reaching consequences on the design and assembly of the cold mass structure, as shown later.

2.4 Structure behaviour with regard to components and assembly tolerances

Considering that series manufacture is likely to take place at three different sites at an expected rate of some 20 cold masses per month, in two-shift work, design simplicity and robustness are considered to be of highest importance in view of minimising labour cost and maximising the likelihood that each magnet be well within the specified requirements.

In a first phase, the impact of the dimensional tolerances of collars, laminations and collared coil on the distribution of forces between collared coils and yoke, and hence on structural stability, was studied by means of F.E computations. The component tolerances lead to variations of the nominal gap/interference, before longitudinal welding the shrinking cylinder half-shells, between yoke halves and between collared coils and yoke. The width of latter gaps was scanned, one at a time, in steps of 0.05 mm. Three designs were considered at this stage: combined AA collars and combined AS collars of identical geometry, and separated AS collars optimised for minimum material usage. It was thus shown that the collar material plays a major role: the higher E-modulus and lower thermal expansion coefficient of AS with respect to AA collars entail smaller displacements and deformations. Whilst maintaining positive contact forces among collared coils and yoke up to ultimate field, combined and separated AS collars designs allow for tolerances of about ±0.2 mm and ±0.3 mm for the fitting of the collars and laminations transmitting horizontal and vertical forces, respectively. Combined AA collars allow for ± 0.1 mm only in both directions. These values are to be compared with the ± 0.1 mm obtained when summing up the nominal tolerances (not achieved in the 10-m long models) on collars, laminations and their assemblies.

Computations showed that the choice of separated AS collars would not bring decisive advantages over AS combined ones, in terms of field level and quality. Moreover, a complete new qualification and tooling programme with its inherent costs and time schedule would be necessary to assess in detail such a major design change. It was therefore chosen not to depart from the combined collar design. Strong AS-combined collars, with the same geometry of the AA ones, entail only minor changes to existing tooling and drawings. Moreover, they minimise the coupling between collared coils and cold mass assembly, so as to make field quality and cold mass behaviour only weakly dependent on assembly history, which is a positive feature for a large series production.

In a second phase, the widths of the horizontal gaps between yoke halves, above (upper gap) and below (inner gap) the heat exchanger tube were varied simultaneously. These widths were determined by assuming a linear sum of components (3σ = 0.02 mm) and assembly (3σ = 0.05 mm) design tolerances.

Statistical draws from data provided by a deterministic multidimensional F.E. model, showed (see Fig. 4) that for AA collar the 1σ width of the tolerance of the above gaps must be < 0.05 mm (instead of 0.1 mm for AS collars) in order to guarantee (probability P = 1 in the above figure) a positive mating force between yoke halves at high field, i.e. prevent an opening of the yoke and subsequent mechanical instabilities of the collared coil.

Finally, the influence of actual tolerances, as observed in 10-m models, of 11 main parameters (various dimensions of collars, inserts, laminations, coils, and stress in the shrinking cylinder) to be controlled in the cold mass assembly, were evaluated by a Monte Carlo analysis of the F.E. model of the cold mass. The outcome of this work is summarised in Fig. 5, which shows the probabilistic distribution of the mating force at nominal field at the “inner” yoke gap. For AA collars, for about 25% of the magnets this force is likely to be non-existent and its average value is 230 N per mm of magnet length. For AS collars, the mating force is always present and its average value is about four times higher.

Moreover, because of relative differences of the thermal expansion coefficients of collared coils and yoke, AA collars require, after assembly at room temperature, an horizontal gap of about 0.5 ± 0.05 mm between yoke halves. This in order not to damage the coils by overstressing them and to obtain then at 1.9 K the required contact forces between collars and yoke in the horizontal plane. Experience has shown that this gap is difficult to measure and control.

By choosing AS collars, the yoke halves can be made to mate (no gap) already after assembly at room temperature, making the cold mass to behave as a continuous, stiff structure throughout thermal and excitation cycles. Considering all the above, austenitic steel was chosen as collar material for series manufacture.

2.5 Field quality, analysis and control

Further to the field quality characteristics of the YB 10-m models and prototype reported in ref. [8], the study made in ref [12] gives insight on the links between field quality and coil geometry in the YB long models. Methods to ease field quality analysis in view of its reliable fine tuning during series productions are being investigated [13].

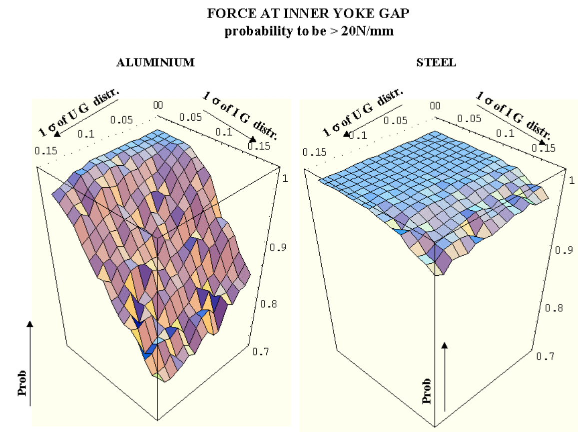

Figure 4: Estimated probability of conformity of the forces along the inner gap in function of the tolerances of dimensions (mm) of the upper (UG) and inner gap (IG)

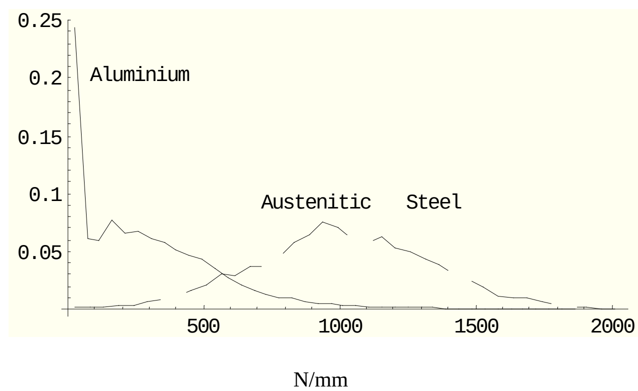

Figure 5: Probability distribution of the force (at 8.33 T) along the inner gap, following Monte Carlo analysis

3 NEXT PROTOTYPES

CERN has launched in summer 98 the manufacture by industry of 3 x 2 full-length prototype collared coils, featuring 6-block coil cross-section, inclined interface between collars and yoke, AS collars (but for the first of them, which still has AA collars for reasons of component availability). These collared coils are assembled into cold masses at CERN; the first of them (called MBP2N1) was completed on 21 February 1999. Its geometry is within the expected values of imposed horizontal sagitta and natural vertical deflection (see Figs. 6 and 7), apart for the ends, where improvements of the procedure for welding the beam pipe to the cold mass end-covers are being studied. A second prototype, MBP2N2, equipped with AS collars, will be assembled as from end April and tested this July. Two of the four remaining prototypes will be tested in autumn 99 and the two last one in February and March 2000.

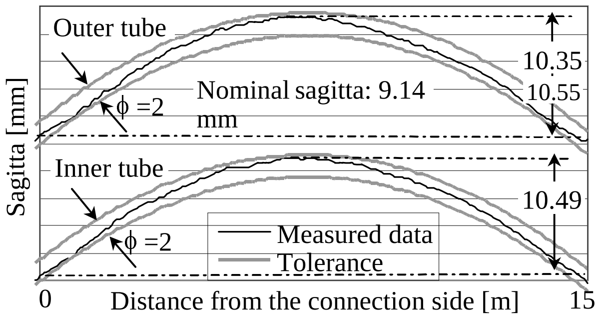

Figure 6: MBP2N1 prototype: horizontal sagitta of the beam tubes axis

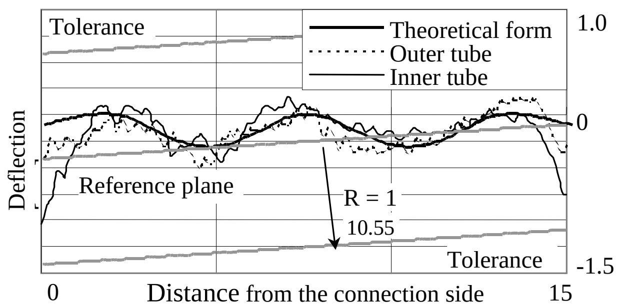

Figure 7: MBP2N1 prototype: deflection in the vertical plane of the beam tubes axis

4 TOWARDS SERIES PRODUCTION

4.1 Procurement of SC cables

Invitation to tenders were issued in August 1997 for the supply of NbTi bars and Nb sheet (funded by the U.S.A. contribution to the LHC project) and that of a total of 6840 km of SC cables, of two different types. The arc dipoles use about 2370 km of “Cable 1” for the inner layer and about 3740 km of “Cable 2” for the outer layer, while the arc quadrupoles use only “Cable 2”. The corresponding contracts were placed in the course of 1998. The deliveries of the raw materials (by now about 15 tonnes) by one US firm started in autumn 1998. The supply of Cable 1 was entrusted to two European firms, that of Cable 2 also to two European firms for a total of 3320 km and one US and one Japanese firm, each for a length of 575 km. The SC strand pilot production is starting, by the end of 1999 a pilot cable production corresponding to 1% of the European supplies is expected. The cable supply is scheduled to finish by end 2004. A new test facility for the reception tests of SC strands and cables [14] is being set-up at CERN, it will be operational in the next months.

4.2 Procurement of cold masses

A call for tender for the supply of a total of 468 cold masses for three LHC octants was issued on 17 December 1998. The bids will be in by 31 March 1999. It is expected to present the adjudication proposals to the CERN Finance Committee in June 1999. It is likely that three different contractors be retained; under best conditions, the first cold masses are expected in the first months of the year 2000. During the first 2 years, the cold mass contracts will be carried out under a cost reimbursement (with ceiling) and fixed benefit scheme. The contractors will subsequently be asked by spring 2001 to bid fixed prices for up to four octants, including the octant already being manufactured. Present planning foresees the end of the cold mass deliveries by early 2005.

5 CONCLUSION

The R & D program for the LHC dipole magnets is approaching its completion, the design chosen for series manufacture is being validated this year with a set of six full-length prototypes. Industrial production of SC cable has begun, that of dipole cold masses is expected to start by autumn 1999.

6 ACKNOWLEDGMENTS

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