Selection of the Cross-Section Design for the LHC Main Dipole

P. Fessia, D. Perini, S. Russenschuck, Ch. Voellinger, R. Vuillermet and C. Wyss
CERN, Geneva, Switzerland

Abstract — **With the aim of selecting the most suitable design for the series production of the LHC main dipoles, several possible configurations were analysed with respect to admissible component tolerances and structural stability, field level, field quality, number and weight of parts. Two alternatives designs, featuring common collars made out of aluminium alloy and austenitic steel, respectively, were finally compared in detail. Although both designs are almost equivalent at nominal conditions, the austenitic steel collar structure turned out to be far less sensitive to components dimensional variations. This paper reports the main results of the above evaluations, which lead to the choice of austenitic steel collars for the LHC main dipoles.**

I. INTRODUCTION

The design of the LHC two-in-one main dipole magnets [1] has to satisfy stringent requirements in view of their successful series manufacture and subsequent operation in the LHC. Their structure must, up to above the ultimate field of 9 T and in spite of electromagnetic forces reaching 400 t/m, prevent any systematic coil movement causing quenches. This aspect is particularly important for magnets operated at 1.9 K, where materials show no practical heat capacity and any energy dissipated must be removed via the superfluid helium. A predictable and controllable structure is required also to achieve the required tolerances on field quality of a few 10^{-4}. The component design and assembly must nevertheless allow for tolerances achievable in a cost effective way, to be suitable for magnet series production at an affordable price. We evaluated the behaviour of four different dipole cross-section designs in terms of: a) coil pre-stress during and after collaring, after welding of the shrinking cylinder, after cool-down to 1.8 K and during operation up to 9 T; b) strength and distribution of the mating forces within the dipole structural elements; c) sensitivity to the tolerances of the geometry of collars and laminations, and their assemblies; d) sensitivity to variations of coil pre-stress; e) deformation of the collar cavity after assembly, cool-down, and during magnet operation; f) field quality; g) quantities of materials and components. As result of this evaluation, a design was selected for series manufacture.

II. POSSIBLE MAGNET CROSS-SECTIONS

Four different two-in-one dipole cross-section designs, with the main features below, were considered:

A. double racetrack aluminum alloy (AA) collars, fitted with a magnetic insert (Fig. 1)
B. double AA collar, without magnetic insert (Fig. 2)
C. as above, but with austenitic steel (AS) collars
D. AS separated collars (Fig. 3)

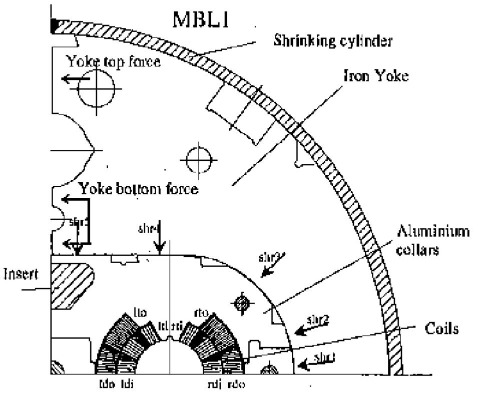

Fig. 1. Design A.

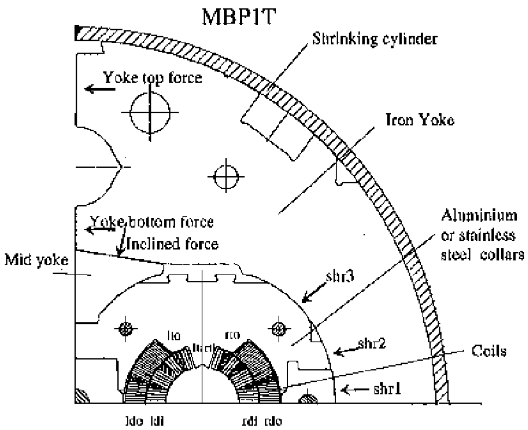

Fig. 2. Designs B (AA collars) and C (AS collars).

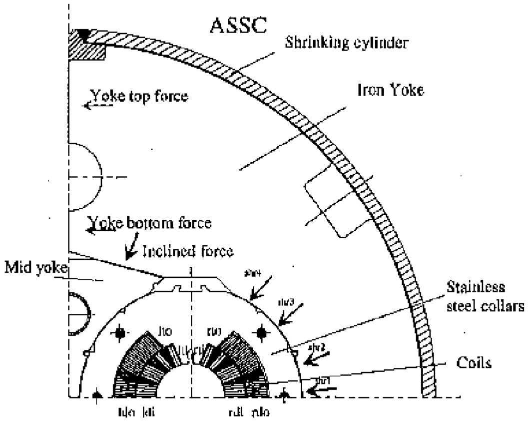

Fig.3. Design D.

Manuscript received on 27 September 1999

These structures present essentially four main components, the behaviour of which must remain matched from assembly at room temperature (RT) to cool-down at 1.9 K and operation up to a magnetic induction of 9 T:

1) the coils; their assembly pre-stress at RT, later removed by the action of the electromagnetic forces at cold, causes the vertical dimensions of the collared coils to vary from 0.3 mm to 0.15 mm, depending on collar material and design pre-stress;

2) the collars; the difference in thermal contraction of their material with respect to that of the coils determines the values of coil pre-stress during collaring and after collaring necessary to achieve the design pre-stress at 1.9 K,

3) the vertically split yoke, always showing a gap before the assembly of the cold mass; the size of this gap and its presence or absence after the welding of the shrinking cylinder, depend on the difference in thermal contraction between the yoke and the collar material;

4) the shrinking cylinder, which assures, by its difference in thermal contraction with respect to that of the yoke, the presence of the mating forces between the yoke halves necessary to take up the e.m. forces transmitted via the collars and to guarantee the mechanical stability of the structure, and hence limit coil deformations.

III. Finite Element Models, Optimization, Results

Four, 2-D models were meshed and the plane-stress option was used for the elements. It is possible to simulate the collar structures by creating two layers of a 0.5-mm thick mesh. For the coils, iron yoke, cylinder, insert and locking rods a 1- mm thick layer was meshed. The pre-stress of the coils is imposed by giving an interference at the interfaces between the collars and the coil. The external cylinder pre-stress is also simulated by giving an interference between the iron yoke and cylinder. The geometry is modeled at room temperature and in non-deformed conditions, i.e. the dimension used in the model are for parts at their nominal size. The areas were meshed using two-dimensional linear elements (plane 42) and contact surfaces with three-dimensional contact elements (contac 52). Further information concerning these elements is available from the ANSYS manuals [2]. Magnet operation is simulated by loading the coils with the electro-magnetic forces computed with the same code. Iron saturation was taken into account. No friction was considered between the different components in case of relative displacements. The effect of friction was later computed for the B and C designs only [3]. The mesh considers a one-quarter structure (with appropriate boundary conditions for the simulation of two layers of collars).

Each of the above cross-sections was optimised, so as to:

a) provide the design coil pre-stress at cold, avoiding at the same time unsafe stresses during collaring, welding of the shrinking cylinder under the assembly press and after assembly. Average compressive values above 130 MPa maintained for more than a few minutes can be dangerous for the coil insulation (creep);

b) provide between the yoke halves balanced mating forces larger than the e.m. forces generated during magnet excitation, so as to avoid displacements and instabilities of the mechanical structure;

c) maintain contact between the collared coils and the yoke, in the vertical plane for the whole excitation range, so as to stiffen the dipole structure, and in the horizontal plane preferably also for the whole excitation range, so as to avoid coil deformations during magnet excitation.

The detailed description of the behaviour of the designs A, B, C and D from assembly to high field operation is given in [4]. For the four designs, Table I, provides a summary of the layer pre-stresses; Table II gives the size of the open vertical yoke gaps prior to welding of the shrinking cylinder; Tables III and IV show the level of the mating forces. It can be seen from the 2nd column for each desing of Table I, that with doucle collars, the layers "central" sides (Ido, Idi in Fig. 1) are less prestressed than the layers "lateral" sides (rdo, rdi in Fig. 1). This effect stems from the different width (and hence mechanical strength) available for the collars central and lateral legs, fixed by the choice of the 194 mm distance between beam axis and by the iron yoke optimisation (field level and quality). A 5 MPa prestress unbalance leads to a left/rigth asymmetry of the layers azimuthal lengths of about 0.025 mm. This effect is less pronounced for AS collars and does not occur with separate AS collars.

Table II shows that prior to the welding of the shrinking cylinder, AS collars require a vertical yoke gap 3 to 4 times smaller then AA collars. This smaller gap can be safely closed, without damaging the coils, by the force applied by the cold mass assembly press first and subsequently by the weldments of the shrinking cylinder half-shells.

From Table III it can be seen that for design B, with respect to the A one: a) the vertical "inclined force" (or "shr5" for design A) between yoke lamination and insert is at cold and during powering three times higher, leading to an enhanced stiffness of the whole structure; b) the "yoke bottom" force at 9 T is also about three times higher.

Comparing the figures in Tables III and IV, it can be seen that, for a same stress level in the shrinking cylinder after its welding, the yoke gap is closed (presence of mating forces "yoke top" and "yoke bottom") for designs C and D, featuring AS collars. As a consequence, at 2 K the azimuthal stress in the cylinder is 65% higher than in designs A and B with AA collars, leading to high horizontal and vertical mating forces between yoke elements up to 9 T.

TABLE I

Average Coil Pre-Stress (MPa) of the Inner and Outer Layers (First Column) and Pre-Stress Difference (Asymmetry) Between the Inner and Outer Layers Central and Lateral Sides (Second Column). For Designs A and B, After Cylinder Welding, the Pre-Stress in the Inner Layer (60 MPa) is Higher then in the Outer Layer (55 MPa)

Design	A, B		C		D	
At collaring	90	0	87	0	100	0
After collaring	45	5	65	2	55	0
After welding	60/55	5	70	2	60	0
T = 2 K, B = 0 T	45	5	40	2	30	0
T = 2 K, B = 8.3 T	5	1	5	0	2	0
T = 2 K, B = 9 T	0	0	0	0	0	0

TABLE II
HALF-SIZE OF THE OPEN VERTICAL YOKE GAP (MM) FOR THE DESIGNS A, B, C AND D. IG IS THE HALF-SIZE AT THE INNER RADIUS OF THE YOKE LAMINATION, OG IS THE HALF-SIZE AT ITS OUTER RADIUS

Design	OG	IG
A	0.657	0.482
B	0.570	0.430
C	0.240	0.130
D	0.085	0.085

TABLE III
FIRST ROW: CYLINDER STRESS IN MPA FOR DESIGNS A/B. FOLLOWING ROWS: MATING FORCE (N/MM OF THICKNESS) AT THE STRUCTURE INTERFACES SHOWN ON FIGS. 1 AND 2 FOR DESIGNS A/B

Location	T = 293 K B = 0 T	T = 2 K B = 0 T	T = 2 K B = 8.3 T	T = 2 K B = 9.0 T
Cylinder	159 / 154	206 / 185	206 / 185	207 / 184
Yoke top	0 / 0	1093 / 469	1097 / 480	1071 / 468
Yoke bottom	0 / 0	818 / 1102	208 / 421	114 / 300
Shr5/Inclined	607 / 594	83 / 460	167 / 581	210 / 616
Shr 1	410 / 287	52 / 6	418 / 382	693 / 604
Shr 2	602 / 607	114 / 215	374 / 521	303 / 423
Shr 3	1342 / 1544	0 / 0	0 / 0	0 / 0

TABLE IV
FIRST ROW: CYLINDER STRESS IN MPA FOR DESIGNS C/D. FOLLOWING ROWS: MATING FORCE (N/MM OF THICKNESS) AT THE STRUCTURE INTERFACES SHOWN ON FIGS. 2 AND 3 FOR DESIGNS C/D

Location	T = 293 K B = 0 T	T = 2 K B = 0 T	T = 2 K B = 8.3 T	T = 2 K B = 9.0 T
Cylinder	151/144	320/322	321/326	329/326
Yoke top	102/358	1449/1645	1393/1492	1571/1491
Yoke bottom	57/75	1408/1340	937/716	888/716
Inclined	622/722	396/651	531/985	557/985
Shr 1	167/228	0/57	200/452	292/577
Shr 2	689/145	28/0	356/325	439/224
Shr 3	606/225	0/0	0/25	0/0
Shr 4	0/459	0/0	0/0	0/0

TABLE V
ACCEPTABLE COMPONENT TOLERANCE RANGE

Design	Horizontal axis	Vertical axis
A / B	± 0.1 mm	± 0.1 mm
C / D	± 0.2 mm	± 0.3 mm

IV. SENSITIVITY ANALYSIS

Calculations were made to assess which structure is most robust with regard to components and assembly tolerances (hence more appropriate for series manufacture), and to assess the stability of the geometry of the collar cavity.

A. *Effect of Dimensional Tolerances*

The mechanical behaviour of a dipole structure is governed by the geometry of its components (precise to ± 0.02 mm at best) and their subassemblies (precise to ± 0.04 mm at best). The determinant factors are the tolerances of the dimensions of the fine-blanked collars, laminations and inserts and of the collared coils. The dimensions of the latter depend on coil pre-stress (a variation of ± 5 MPa coil pre-stress changes the vertical dimensions of AA and AS collars by ± 0.05 and ± 0.02 mm, respectively).

In the course of assembly, tolerances add up and result in a gap or an interference among components. Tolerances along the horizontal axis lead to an overall tolerance of the vertical yoke gap. The size of this gap governs the strength of the mating forces "yoke top", yoke bottom" and "Shr 1". Tolerances along the vertical axis lead to an overall tolerance of the match between yoke halves and the insert ("inclined force"). The presence of vertical mating forces is essential to maintain the structural stiffness, especially at high field, where the vertical dimensions of the collared coil decrease (depending on collar material) because of the unloading of the coil pre-stress by the electro-magnetic forces.

The overall horizontal and vertical tolerances along the cross-section axis were scanned systematically by varying one dimension at a time, the allowable range being defined as the one within which the various mating forces are always positive up to 9 T. The results are given in Table V, showing that the higher strength (and hence smaller deformation) and smaller thermal contraction of AS collars with respect to AA ones, allow for a wider tolerance band for components and their assembly.

Following the work presented in this paper, further FEM computations were carried out [5], exploring at a same time the impact on structural behaviour of the tolerances of several components, as actually observed in the course of model and prototype work, using a statistical approach. The outcome clearly showed that for a large series production, only AS collars can reliably provide the necessary structural stability of the two-in-one LHC main dipole magnet.

B. *Deformation of the Collar Cavity*

The horizontal inward displacement of the dipole aperture centre at assembly, cooldown and operation at 8.3 T was also computed with the FE models, the results is shown in Table VI.

It can be seen that the relative collar movements are minimum for the designs with AS collars.

Other results reported in [4] show that the radial and azimuthal deformation of a collar with respect to its theoretical circular shape are minimum with AS collars, providing a better stability of field quality.

TABLE VI
HORIZONTAL INWARD DISPLACEMENT (MM) OF THE APERTURE CENTRE

Design	T = 293 K B = 0 T	T = 2 K B = 0 T	T = 2 K B = 8.3 T
A	0.09	0.42	0.39
B	0.06	0.40	0.37
C	0.02	0.23	0.24
D	0.04	0.26	0.24

TABLE VII

COMPARISON OF MAIN PARAMETERS, IDEAL GEOMETRIES (NO MECHANICAL STRESSES AND THERMAL SHRINKAGE).

MULTIPOLAR COMPONENTS IN 10^{-4} UNITS AT R = 17 MM

	Design C		Design D	
Yoke radius	265.5 mm		270 mm	
I (A) at 8.36	11772 A		11500 A	
Bss	9.68 T		9.75 T	
Field quality	inj	nom	inj	nom
Quadrupole	0.64	-0.82	-0.06	0.03
Sextupole	5.78	6.18	11.00	11.44
Octupole	0.22	0.06	0.00	-0.18
Decapole	-0.91	-0.91	-1.14	-1.02

V. FIELD LEVEL AND QUALITY

Following the results presented so far, AS collars were selected as baseline design. To chose between designs C and D, they were optimised [6] from the point of view of field level and quality. The coil geometry considered was the 6-block geometry already validated by extensive model work [7] and for which 15-m-long tooling was being manufactured by three firms in charge of prototype work. The optimisation objectives were: a) maximum short-sample field Bss; b) small quadrupole and octupole field components at injection field level; c) low variation of quadrupole, sextupole and octupole components from injection to nominal field level d) low sensitivity to tolerances of the yoke geometry e) small yoke outer radius. The optimisation led for design D to an insert shape slightly different from the one shown in Fig. 3, featuring a drop-shaped hole instead of a round one, to reduce the quadrupole component at high field. Main parameters are shown in Table VII.

It can be seen from the above that, with respect to design C, design D requires a marginally larger yoke radius, achieves nominal field at 2.3% smaller current (thanks to the larger contribution of the yoke), has to within 0.7% the same short sample field, presents a sextupole component higher by about 5 units (requiring a coil redesign to satisfy LHC beam optics) and finally shows (for an ideal geometry) at injection field practically no quadrupole and octupole components (the iron insert acts as a perfectly symmetric screen between the two apertures). Concerning field quality, it is to be noted, however, that the quadrupole and octupole components present at injection field with the C design do not constitute a difficulty [8].

VI. QUANTITIES OF MATERIAL AND COLLARS

Designs C and D are compared in Table VIII concerning quantity of collar raw material and collar number per magnet unit.

TABLE VIII

AUSTENITIC STEEL QUANTITY AND COLLAR NUMBER PER DIPOLE UNIT

	Design C	Design D
Austenitic steel	8770 kg	6355 kg
Number of collars	9400	18800

For design D, the larger number of collars to be fine-blanked partially compensates the lower cost of the raw material. This cost difference is estimated at below 2% of the cold mass value. Cost variations resulting from the further handling of different numbers of collars are not considered here.

VII. CONCLUDING REMARKS

The considerations made in Sections III and IV lead to the choice of AS as collar material. The merits of this choice are: a) the required structural behaviour can be achieved with realistic components tolerances, making series production possible at affordable conditions; b) the yoke halves can be made to mate (no gap) after assembly at room temperature. (Experience with AA collars has shown that such a gap is difficult to control within the required tolerance of ± 0.05 mm).

The comparison in terms of magnetic performance and cost of collars shows a marginal advantage for design D (separate collars). The implementation of the latter would however require the redesign of already available 6-block coil design, of winding, curing and collaring tooling, with its inherent costs and time schedules. It was therefore chosen not to depart from the combined collar design. Strong AS-combined collars 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.

REFERENCES

[1] The Large Hadron Collider CERN/AC/95-05 (LHC), October 1995

[2] Ansys User's Manual for Revision 5.4, Huston 1997. Swanson Analysis Syste Inc.

[3] M. Bajko, P.Fessia, D.Perini, "FEM computations about the effect of friction in two LHC main dipole structures", this Conference.

[4] D.Perini, R.Vuillermet, C.Wyss, "Comparative study of different designs of the mechanical structure of the LHC main dipoles", LHC Report, unpublished.

[5] M. Bajko, P.Fessia, D.Perini, "Statistical studies of the robustness of the LHC main dipole mechanical structure", this Conf.

[6] S.Russenschuck, "ROXIE: the routine for the optimization of magnet X-sections, Inverse field calculation and coil end design", Proc. of the 1st Int. Roxie Users Meeting and Workshop, Yellow Report CERN 99-01, ISBN 92-9083-140-5.

[7] N.Andreev et al, "Performance of five and six block coil geometries in short superconducting dipole models for the LHC", PAC 99, New York.

[8] J.P.Koutchouk, "The LHC dynamic aperture", PAC99, New York.