FINAL PROTOTYPES, FIRST PRE-SERIES UNITS AND STEPS TOWARDS SERIES PRODUCTION OF THE LHC MAIN DIPOLES

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Abstract

The LHC, a 7 TeV proton collider presently under construction at CERN, requires 1232 superconducting dipole magnets, featuring a nominal field of 8.33 T inside a cold bore tube of 50 mm inner diameter and a magnetic length of 14.3 m. This paper summarises the results of the program of the six LHC main dipole final prototypes and presents the performance measurements of the first magnets of the 90 pre-series units currently under manufacture by industry. Results of geometric and magnetic measurements are given and discussed. Finally, the major milestones towards the dipole magnets series manufacture are given and commented.

1. INTRODUCTION

As the last step of the prototype phase for the finalisation of the LHC Main dipole design, six full-scale dipole prototype collared coils were built by European firms and then assembled into cryo-dipoles at CERN. Five prototypes were fully tested at the operating temperature of 1.9 K at CERN. This prototype program, started in 1998, was completed in 2000.

The main parameters of the LHC dipole cryo-magnet are recalled in Table 1, and the cross section of the cold mass is presented in Fig. 1.

Table 1: Main parameters of the dipole cryo-magnet.

	Value	Unit
Inject. field (0.45 TeV beam energy)	0.54	T
Nom. field (7 TeV beam energy)	8.33	T
Nominal current	11800	A
Stored energy at 7 Tev	7.1	MJ
Operating temperature	1.9	K
Magnetic length at 1.9 K	14.3	m
Ultimate operational field	9.0	T
Nominal short sample field limit	9.65	T
Overall length with ancillaries	16.8	m
Bending radius(*)	2812.36	m
Cold bore inner diameter(*)	50	mm
Distance between apertures(*)	194.52	mm
Cold mass diameter(*)	570	mm
Mass of the assembly	~ 27.5	tonne

(*) Values at room temperature

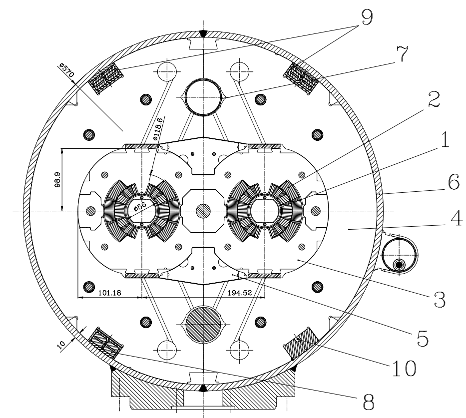

Fig. 1: Cross-section of LHC pre-series dipole cold mass: *1-beam tube; 2-SC coils, "6-block" design; 3-austenitic steel collars; 4-iron yoke; 5-iron yoke "insert", 6-shrinking cylinder / He II vessel; 7-heat exchanger tube; 8-dipole bus-bars; 9-arc quadrupole and "spool-pieces" bus-bars; 10-wires for magnet protection and instrumentation.*

More information and detailed descriptions of the main parameters and assembly are reported in references [1,2].

In November 1999, CERN has placed, with three European firms, a first order for 3x30 dipole cold masses. The first six pre-series cold masses (two per company) were assembled as the prototypes, i.e., the cold mass assembly and welding were done at CERN using collared coils from industry. This was because some major tooling necessary for cold mass assembly was unavailable in industry. At this moment (June 2001) two pre-series cryo-dipoles are completed and another five are at CERN, at different stages of assembly or cryostatting. This paper presents and briefly analyses the results in terms of field quality and quench performance of four prototypes and the first pre-series cold masses (which are comparable in terms of components and assembly features).

2. COLD MASSES' MAIN FEATURES

Two of the six prototypes are not presented here for the following reasons: the first prototypes (MBP2N1) was still equipped with aluminium collars of a hybrid design, the last delivered prototype (MBP2A1) was not fully assembled because of other priorities. Some

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manufacturing parameters and procedures (like the coil and shrinking cylinder pre-stresses, the collaring procedure) were different for different prototypes.

The welding technique chosen for the longitudinal welding of the shrinking cylinder is: root pass made by STT welding technology and three filling passes by MIG (Ar 98% CO_2 2%). This choice has shown advantages in a larger, well controllable weld contraction and an acceptance of larger tolerances for the gap between the shrinking cylinder half-shells.

The main characteristics for the analysed cryo-magnets are given in Table 2.

Table 2: Manufacturing parameters

Magnet	Collar Packs	Collaring mandrel	Coil Pre-stress at 293 K (*)	Shrink.Cyl. Pre-stress (**)
MBP2N2	32 pairs	Expandable	72/85	140
MBP2O1	1 pair	none	62/62	143
MBP2A2	32 pairs	Rigid (***)	56/60	140
MBP2O2	1 pair	none	54/63	156
preseries psO1	1 pair	none	90/90	180

(*) values in MPa for Inner/Outer layer. Prestress at 1.9 K ($\sigma_{1.9}$) is evaluated as: $\sigma_{1.9} \approx 0.5(\sigma_{293}\text{-}15)$ [MPa]
(**) Values in MPa. 150 MPa at room temperature are extimated to become ~ 300 MPa at 1.9 K.
(***) Only in the layer-jump region.

3. MAGNETIC MEASUREMENTS

The following magnetic measurements were carried out and used to analyse the field quality of the dipoles:

- Collared coils, at 293 K: four P2 prototypes and four pre-series magnets
- Assembled cold masses, at 293 K: three P2 prototypes and one pre-series magnet.
- Test at injection and at high field, at 1.9 K: four P2 prototypes and one pre-series magnet.

3.1 Normal odd multipoles

These multipoles are strongly affected by the presence of pole shims that differ from the nominal values by up to 0.3 mm (see for instance PSO1 in Table 3 and 4). These relevant differences with respect to nominal design were implemented to compensate for out-of-tolerance of azimuthal coil length or of prototype components, and to explore the widest possible window in azimuthal coil pre-stress. Steps have been taken to uniformize the azimuthal coil length of all manufacturers.

Field quality data were therefore post-processed to normalize the measured values to nominal coils built with nominal shims, using the known sensitivity tables [3]. Results show an offset of +3.2 units in b_3 and +1.0 units in b_5 respect to optimal values. High order odd normal multipoles are within the acceptable ranges. Whilst for b_3 we are at the limit of the requested range by beam dynamics, (half range-width is 3 units [4]), for b_5 we are out (half range-width is 0.3 units). In order to start the production around the optimal values, a correction for both multipoles is necessary. The correction will be done through a small change of the coil copper wedges (up to 0.5 mm), leaving the coil azimuthal length unchanged.

3.2 Normal even multipoles

A very high value of b_2 (4-5 units) was found in the first two P2 prototypes [3,4]. This was due to a mismatch between the mechanical and the magnetic design of the insert. Even though this is a linear error, it has been shown to be intolerable for beam dynamics due to beta beating [4]. Different geometries have been tested in two prototypes to measure the sensitivity of b_2 on the insert shape following numerical simulations carried out with ROXIE [5]. The optimized insert was already used in the first pre-series magnet, bringing b_2 close to zero (see Table 4). Now both b_2 and b_4 are well within the tight limits imposed by beam dynamics.

Table 3: Multipoles measured at 300 K in collared coils of four pre-series magnets, (R_{ref}=17 mm, 10^{-4}units):

c.coils	*Allowed*			*Non-allowed*				
(*)	b_3	b_5	b_7	b_2	a_2	a_3	b_4	a_4
PSO1–1	8.3	-0.8	1.1	0.3	0.3	-0.7	0.3	-0.2
PSO1–2	8.9	-1.0	1.1	0.4	-1.5	-0.4	0.0	0.3
PSO2–1	5.9	-0.1	1.0	0.0	-0.3	0.3	0.0	0.2
PSO2–2	5.6	-0.1	1.0	1.0	0.3	0.6	0.1	-0.1
PSA1–1	0.3	1.5	0.7	-0.6	0.9	0.3	-0.1	-0.3
PSA1–2	-0.5	1.1	0.6	0.1	1.2	0.7	0.1	0.5
PSN1–1	-0.8	0.8	0.6	-0.4	-0.3	0.1	-0.2	-0.1
PSN1- 2	-1.5	0.8	0.7	0.4	0.0	0.1	0.1	0.3

(*) "–1" and "–2" indicate the collared coils aperture

Table 4: Multipole at injection and at nominal field in the first pre-series magnet (R_{ref}=17 mm, 10^{-4}units)

Inject.	*Allowed*					*Non-allowed*		
	b_3	b_5	b_7	b_2	b_4	a_2	a_3	a_4
PSO1–1	4.5	0.1	0.5	1.5	0.2	-0.8	0.4	0.1
PSO1–2	4.9	0.0	0.6	-0.8	0.1	1.0	0.1	-0.3
Nom.	*Allowed*					*Non-allowed*		
PSO1–1	12.3	-1.1	0.9	-0.5	0.4	-0.3	0.4	0.2
PSO1–2	12.8	-1.2	1.0	0.9	0.3	0.9	0.1	-0.3

4. COLD MASS GEOMETRY

The cold mass horizontal curvature, vertical straightness and twist are checked by 3-D measurements carried out with a laser tracker device. Curvature and straightness tolerances of ± 1 mm, and the twist tolerance of ± 3 mrad (locally) and ± 1 mrad (averaged on the 15-m length) has shown to be achievable. More details can be found in [1]. Work is in progress to optimize the time necessary for the alignment procedure during assembly.

Table 5: Quench (Q.) levels in 15-m long dipole prototypes and first pre-series cold masses.

Magnet	Field level at 1st Q.	N. of Q. at field ≤ 8.33 T(1)	N. of Q. at field ≤ 9.0 T(1)	1st Q. after the 1st thermal cycle	Q. in C.Ends (2)	Q. in Straight Part (2)	Q. in N.C. Ends (2)
MBP2N2	7.46 T	2	8	Not performed(4)	7/16	1/16	7/16
MBP2O1	8.23 T	1	5	8.76 T	6/22	0/22	14/22
MBP2A2	7.24 T	3	Not reached(3)	7.98 T	7/45	0/45	35/45
MBP2O2	8.64 T	0	1	8.85 T	3/11	2/11	6/11
1st Pre-series	8.31 T	1	1	No Q. up to 9 T	1/5	2/5	1/5

(1) From the first run of cold tests.
(2) Proportions given with respect to the total number of training quenches performed at 1.9 K. Quenches appearing during magnetic measurements cannot be localized, therefore the total sum can be less than 100%.
(3) Quenches at the non-connection side are all at the same point (35/45). Typical evidence of a weak point due to manufacture that has prevented the magnet from reaching the provisional ultimate field.
(4) Due to a short circuit between coil and cold bore tubes appearing after quench 16, this prototype could not be tested further.

5. POWER TESTS

Table 5 shows the quench history for the five presented cold masses. A first look at the results shows that a minimum number of quenches occurs in the coil straight sections. This confirms the soundness of the coil cross-section design. The quenches occur in the coil ends, mostly in the non-connection one. Several parameters like the pre-stress level, its longitudinal gradient, and other manufacturing details are supposed to have an impact on the coil end behaviour. In fact it is in the coil ends that the manufacturing procedures are less automated and where several operations (e.g., positioning of the end spacers and control of the cable tension, coil ends impregnation, shimming procedure) will benefit from future optimisation and experience. The positive results of the last prototypes and of the 1st pre-series magnet seems to show the right direction taken in the comprehension and control of the design and manufacturing features of the coil extremities.

6. TOWARD MASS PRODUCTION

As mentioned, the first pre-series cold masses were welded at CERN due to unavailability of welding equipment at the manufacturers' premises. The major milestones toward the series production (including the main tooling availability) are the following:

- At the end of year 2000, CERN approved and financed a second coil production line (including winding machine and curing press) per manufacturer. These new lines are expected to become operational in spring 2002.
- In May 2001, an Invitation to Tender for the series production was sent out. The evaluation of the offers and the adjudication proposal will take place in the second part of this year. Contracts for series production (1158 cold masses) are expected to be placed before the end of the year with two or three contractors.
- During the second part of 2001 all remaining major tooling will be commissioned at each of the manufacturer sites. Thus all the contractors will become fully independent in manufacturing capability. The welding presses, the largest tooling necessary for the series, are already installed; welding parameter optimisation and welding machine commissioning are ongoing.

7. CONCLUSION

The programme of six final design prototypes launched in 1998 to validate the design of the LHC main dipoles is now concluded. The design of the dipole has been finalised using the experience obtained from this programme. In order to centre the production in the permitted ranges for the multipoles components a fine tuning of the coil cross section (by minor changes in copper wedges section of the inner layer coil) is ongoing. The pre-series production is now started and the first seven assembled cold masses are at CERN in different stages of assembly, cryostatting and testing. The evaluation of the comparable cryo-magnets (four prototypes and the 1st pre-series magnet) shows that the nominal field is exceeded after one to three quenches. The manufacturing parameters and details of the coil ends seems to be one important aspect to be settled and controlled. The main milestones toward the series production are the commissioning of the major manufacturing tooling (that is expected for the second part of this year) and the contracts assignment for the series production expected for the end of the year.

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