MANUFACTURING FEATURES AND PERFORMANCES OF LONG MODELS AND FIRST PROTOTYPE FOR THE LHC PROJECT

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Abstract

This paper reports about the 10-m-long models and one 15-m-long prototype. Their main design deatures are a 5-block coil cross section, an intra-beam distance of 194 mm at room temperature and a 15-mm-wide superconducting cable. The collared coil of the 10-m-long models were built in Industry and the assembly of the magnetic circuit and cold mass was done at CERN while the 15-m-long prototype was entirely made in Industry. Manufacturing features, assembly steps and quench performances of each magnet are presented. Results of magnetic measurements taken in the course of magnet assembly, during and after the cold test campaigns are also given.

1 INTRODUCTION

In order to evaluate the design changes implemented after the review of the LHC Conceptual Design Study [1], as given in the so-called "Yellow Book" published in October 1995 [2], four 10-m-long superconducting (sc) twin dipoles and one full length (15 m) prototype (INFN-CERN collaboration) [3] were built in close collaboration between CERN and Industry and their testing at CERN is nearly completed. These dipoles have an aperture of 56 mm and a separation between the beams of 194 mm. Their main features are aluminium collars, a common structure pre-stressing the sc coils, and an open yoke gap at room temperature which closes during the cooldown to 1.9 K, which is the magnet working temperature, setting up on the vertical yoke mating faces a force at least equal to the electromagnetic forces produced up to 9 T.

The magnet cross-section is shown in Fig.1, the main parameters of the long model dipoles and the full scale prototype are listed in Table I. This report will describe the main manufacturing features, the assembly process adopted, the results of warm an cold magnetic measurements as well as the quench behaviour of the magnets tested so far.

2 DESCRIPTION OF THE MAGNET

The LHC dipole magnets are of the so-called twin-aperture design which combines two identical coil assemblies in the same cold mass. The 15-mm-wide NbTi sc cables have different trapezoidal shapes and mid-thicknesses to

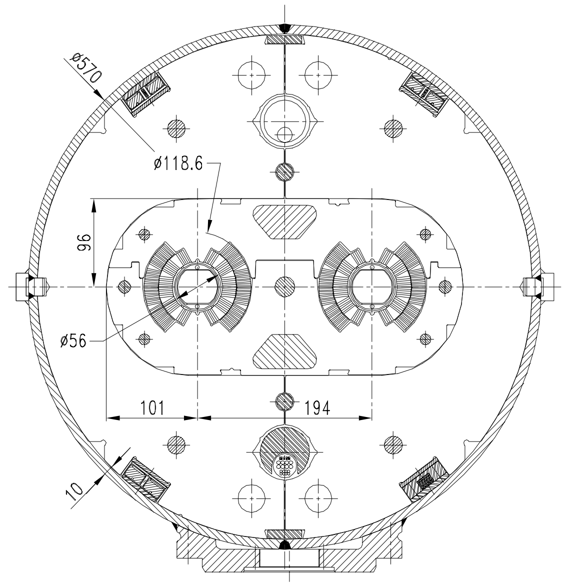

Fig.1 MBL Cross-section

adapt the current density to the maximum magnetic field seen by the sc coils and permit a correct conductor placement on the circular winding mandrel for good field quality. The centring and alignment of the collared coil in the yoke structure is obtained by shaping the internal surface of the yoke so that it closely matches that of the collared coil horizontally and vertically. At room temperature, the two yoke halves are kept around the collared coil with a force of about 360 kN/m after the welding of the 10-mm-thick shrinking austenitic steel cylinder. The magnet assembly is, in principle, very robust and permits a good transmission of the horizontal component of the magnetic forces implying a negligible deformation of the collared coil and practically constant field quality throughout excitation.

3 MANUFACTURING FEATURES

The dipole long models and the prototype followed the same baseline design, but manufacturing variants of the collared coils were allowed for evaluation towards the series production [3]. A significant singularity of the 15-m-long prototype with respect to all the long models is the coil outer layer wound directly on top of the already cured inner layer. This implies that the insulation of the cable (two 50% overlapped layers of 25-μm-thick polyimide tapes and one layer of 120-μm-thick pre-preg

TABLE I

MBL LONG MODEL AND PROTOTYPE PARAMETERS

Nominal operating field	[T]	8.36
Nominal quench field	[T]	9.65
Coil aperture	[mm]	56
Magnetic length	[m]	9.27/14.2
Nominal operating current	[A]	11500
Operating temperature	[K]	1.9
Coil poles (two-layer construction)		
Pole inner diameter	[mm]	56
Pole outer diameter (incl. insulation to ground)	[mm]	120.5
Pole length prototype (including end pieces)	[mm]	14467
Inner layer		
turns per beam channel		30
cable width	[mm]	15
thickness	[mm]	1.72/2.06
No. of strands		28
strand diameter	[mm]	1.065
filament diameter	[μm]	7
copper to superconductor ratio		1.6
Outer layer		
turns per beam channel		52
cable width	[mm]	15
thickness	[mm]	1.34/1.60
No. of strands		36
strand diameter	[mm]	0.825
filament diameter	[μm]	6
copper to superconductor ratio		1.9
Structure		
Distance between aperture axes	[mm]	194
Collar height	[mm]	192
Collar width	[mm]	396
Yoke outer diameter	[mm]	550
Shrinking cylinder outer diameter	[mm]	570
Overall length of magnet cold mass	[mm]	10 -15 m
Mass of magnet cold mass	[t]	16-25
Other characteristics at 8.36 T		
Stored energy for both channels (500 kJ/m)	[MJ]	4.64
Self-inductance for both channels (7.6 mH/m)	[mH]	71
Resultant of e.m. forces in the first coil quadrant:		
$\sum$Fx	[MN/m]	1.7
$\sum$Fy (inner layer)	[MN/m]	- 0.14
$\sum$Fy (outer layer)	[MN/m]	- 0.60
Axial e.m. force (for both channels)	[MN]	0.50

wound around the polyimide insulation with 2 mm spacing) is submitted twice to the curing cycle in the case of the inner layer (curing temperature of 145 °C during 1 hour under 80 MPa azimuthal compression). Apparently this double curing cycle did not cause any problem. After collaring, the average coil azimuthal prestress, along the coil length was around 50 ± 10 MPa for both inner and outer layers in all long models while for the prototype it was lower by 5 to 10 MPa. The yoke halves and the half-shells of the shrinking cylinder were then assembled around the collared coil and the whole assembly slid into the press to measure its apparent spring constant. The two calculated extreme values range between 7 to 14 GN/(m*m). The first value corresponds to only midplane contact between collared coil and yoke while the second corresponds to a full line-to-line fit between the collared coil and the yoke. For the good behaviour of the cold mass, the design value of the yoke gap is 0.57 mm and during manufacturing of the long dipoles this figure was reached closely with a left-right variation smaller than 0.05 while for the prototype the mean value was 0.37 mm with a greater left-right variation [4] (in any case, this asymmetry was greatly reduced by thermal cycles). The fabrication procedure of the three first long models (MBL1N1, MBL1JA1, MBL1JA2) was very similar and almost no changes were made to obtain a small statistics and, then, check the influence of the main manufacturing parameters on the assembly process. It has been observed that the different values of the apparent spring constant were, as expected, highly dependent on the value of the mechanical interference between the collared coil and the yoke in the zone located above the collar magnetic insert. For this reason, in the last magnet assembled (MBL1N2) a particular shimming and assembly procedure was adopted to reduce frictional effects in the above mentioned zone. As shown in Table II, the apparent spring constant went down by about 25-30% and this can be an indication that the half-yokes touches the collared coil only in areas close to its midplane. In this last magnet, since it was observed that the in the collared coil ramp splice zone, the yoke gap always resulted larger than in the straight part [4], this was shimmed to obtain a value close to that of the straight part. This implies that, with respect to the other models, this magnet has a sounder mechanical structure all over its length and a more uniform overall rigidity to better counteract the magnetic forces during excitation and, in principle, a better quench behaviour. The assembly of the magnets was described in more detail in a previous paper [3], but it is worth mentioning that, in the shrinking cylinder, the yield point in areas close to the weld seams was found to be limited 180 MPa. This limited the azimuthal stress of the austenitic steel shell, at room temperature, to 185 ± 15 MPa. The mean value of the obtained sagitta of all dipole models was around 4.7 mm (nominal value of 4.4 mm) after completion of the longitudinal weldings starting from an initial curvature of 6.8 mm. The final azimuthal stress of the shrinking cylinder in the 15-m-long prototype welded with TIG process resulted to be around 225 ± 25 MPa and the obtained sagitta, after a pre-bending of the whole structure by means of metallic belts (around 15 mm), was to be very close to the nominal one (9.7 mm).

TABLE II

RIGIDITY AND YOKE GAP

Name	Rigidity	Gap before/after welding		Press force during welding	Azimuthal stress in cyclinder
	GN/(m*m)	mm	mm	MN/m	MPa
MBL1 N1	8.21	0.51	0.49	3.45	168
MBL1 N2	6.70	0.30	0.36	4.50	175
MBL1 JA1	9.40	0.39	0.53	5.50	165
MBL1 JA2	9.87	0.54	0.61	4.40	181

4 TEST RESULTS

4.1. Field Quality Measurements

The magnetic field quality and, then, the field harmonic components were measured by using rotating coils after manufacturing of the collared coil and the cold mass and during the tests, then, the field manufacturing operating field range (from 100 µT to the maximum field reached by the magnet). The results of the cold measurements at field injection, averaged along the length of the dipole, are summarized in Fig.2. Note that the normal and the skew 2*n*-pole coefficient b_n and a_n (where n=1 is the dipole) are expressed in normalized units at a reference radius of 10 mm.

4.2 Power tests

The power test campaigns of all dipole models, on the Magnet Test Bench facility [6], were carried out in two main runs separated by a thermal cycle from 1.8 K to 300 K and back to 1.8 K except for the MBL1J1 for which the second cool down to 1.8 K and the second test run are still to be done. The magnets are protected [7] against quench induced damages by means of quench heaters and extraction of 20-25% of the stored energy, dissipated in a dump resistor. The protection system is triggered when the differencial voltage measured across the terminals of the various sc layers reaches given thresholds. For all magnets, the quench current was reached with a linear ramp rate of 10 A/s. All magnets have shown so-called spikes [8] (sharp increase of the differential voltages) and for two of them had spikes of unusual amplitude (around 1.5-2 V with respect to 50-200 mV), pointing to conductor displacements resulting from a release of a portion of mechanical energy stored in the windings (bending and shear stresses introduced during the collaring phase). These effects may be enhanced by possible structural weaknesses, e.g. opening of the yoke gap at high fields, clearly observed on one magnet. The comparison of the field quality measurements at room temperature made before and after the cold tests shows an improvement which demonstrate that conductor adjustments have taken place during the training campaigns. One should notice that the quench performance of the MBL1AJ2 magnet was untypical for LHC magnets. The magnet quenched in an irregular way and all quenches after the first five were localised in the outer layer conductor in proximity of the splice region of a particular sc pole (weak splice).

5 CONCLUSION

Apart from MBL1AJ2, limited as explained above, nominal field was reached and surpassed by all the other model magnets and by the first full-lenght prototype. The best among them nearly reached the nominal quench

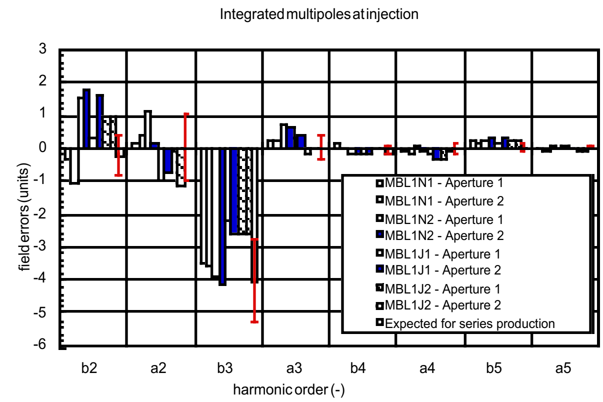

Fig.2 Values of the a2,b2 to a5,b5 harmonics measured at injection field for all long models.

field of 9.65 T, with a number of training quenches in line with the results obtained on the best 1-m-long models. These dipoles of final aperture have provided very useful experience on design and manufacturing features. In view of series production, the acquired experience stresses the importance of tooling of the highest quality and strictly defined and controlled assembly and quality assurance procedures.

6 ACKNOWLEDGEMENTS

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