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STATUS OF THE LHC SHORT DIPOLE MODEL PROGRAMME

D.Tommasini, F.Arteche, S.Sanfilippo, A.Siemko, I.Vanenkov and C.Wyss

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The 1-m model program for the main LHC dipoles is now mainly focussed on double-aperture magnets. In the past years an intensive program based on single-aperture dipoles allowed to select the series-design features among several variants for the coil cross section, the material of the collars and of the coil end spacers, the coil pre-stress and the cable insulation. The recent double-aperture models are dedicated to the fine-tuning of the baseline design and the manufacture of the coil ends. This paper reports about the fabrication and testing of these magnets and the results relevant for the series production of the 15-m long full-size dipole cold masses.

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The 1-m model program for the main LHC dipoles is now mainly focussed on double-aperture magnets. In the past years an intensive program based on single-aperture dipoles allowed to select the series-design features among several variants for the coil cross section, the material of the collars and of the coil end spacers, the coil pre-stress and the cable insulation. The recent double-aperture models are dedicated to the fine-tuning of the baseline design and the manufacture of the coil ends. This paper reports about the fabrication and testing of these magnets and the results relevant for the series production of the 15-m long full-size dipole cold masses.

1 THE MODEL PROGRAMME

The CERN program of one-meter-long dipole models for the LHC started in 1995 with single-aperture magnets. In total 23 of such units were built until mid-1999: several of them were re-assembled into new variants, totalling thus 39 single-aperture models tested at cold at a rate of about one per month. This program allowed to validate important choices for the main LHC dipoles, like the cable insulation, the coil cross section, the material and geometry of the coil end spacers, the material of the collars and finally the choice of assembly parameters like the coil pre-stress and the relation between field harmonics and coil size [1,2,3,4].

Since August 1999 the model program is focussed on the fabrication of double-aperture models to study the training performance of the two-in-one structure. A next and final step will be reproducibility and field quality issues.

2 FEATURES OF RECENT MODELS

The layout of the short dipole single-aperture models was already presented in previous conference papers [5]. The same concept applies to the double-aperture versions, which feature the same collars and yoke laminations as the main dipoles, held together by a bolted shrinking cylinder for easy re-assembly of the structure. All the four double models and their different versions presented in this paper, in total ten magnets, were made with most of the baseline components and design features set for the series production of the LHC dipoles. In particular the cable characteristics, the coil cross section, the material of the coil end spacers and the collar geometry (with minor variants) were the same in all cases. Table 1 gives the main parameters.

Table 1: Main parameters of the short dipole models.

Cable inner layer mid-thickness / keystone angle	1.90 mm / 1.25 deg
Cable outer layer mid-thickness / keystone angle	1.48 mm / 0.90 deg
Coil inner diameter	56 mm
Coil length	1080 mm
Number of turns inner/outer layer	15 / 25
Nominal magnetic field	8.33 T
Nominal current	11.8 kA
Short sample limit	9.8 T

The differences between magnets concerned mainly the coil heads, which appeared in double aperture models to be weaker than in the single-aperture ones and require a tighter specification of assembly parameters. Table 2 summarises the specific features of these magnets with emphasis on the coil heads. All magnets feature austenitic steel collars, but in case of T4 the so-called "floating" collars (those which are not retained by the collaring rods) where made in aluminium, and in case of T5 they were in plastic for versions 2 and 3. In case of T6 and of T7 the material of all collars was the same austenitic steel as foreseen for the LHC series dipoles.

Table 2: Main specific features of recent short dipoles.

Magnet	Specific features
T4 V1	collared with high pre-stress gradient in the coil heads
V2	re-collared with aluminium collars in the coil heads
V3	re-collared with a longitudinal clamping structure in the heads
V4	ferromagnetic yoke more far away from non-connection side
V5	re-collared, longitudinal clamping structure not tightened
T5 V1	more uniform azimuthal pre-stress on the coil heads
V2	collared with different collars (austenitic steel + plastic)
V3	new assembly of non-connection side major end spacers
T6 V1	lower pre-stress in the non-connection side heads
T7 V1	lower pre-stress in connection and non-connection side heads

3 FABRICATION AND COOL DOWN

2.1 Coils

All coils have been wound in the same way with cables of similar characteristics. In all cases the cable was wrapped on line with the baseline all-polyimide insulation [4] during the winding process, its tension was of about 700 N for the inner layer and 500 N for the outer layer. All coils were built with the same type of end spacers, of the isoperimetric type and made in G-11 with the exception of the smallest ones (filled black in fig.1) which were in ULTEM^{TM} for magnets T4 and T5, in IXEF^{TM} for T6 and in G-11 for T7. The bonding-sizing cycle was the baseline foreseen for the series LHC dipoles, based on heating to 135°C for coil sizing under pressure (between 70 and 100 MPa), and further warming up to 185°C for turn-to-turn bonding. During this thermal cycle the coil extremities were blocked against stoppers.

The main coil fabrication detail of the models discussed in this paper is the assembly of the major end spacer of the outer layer (fig.1).

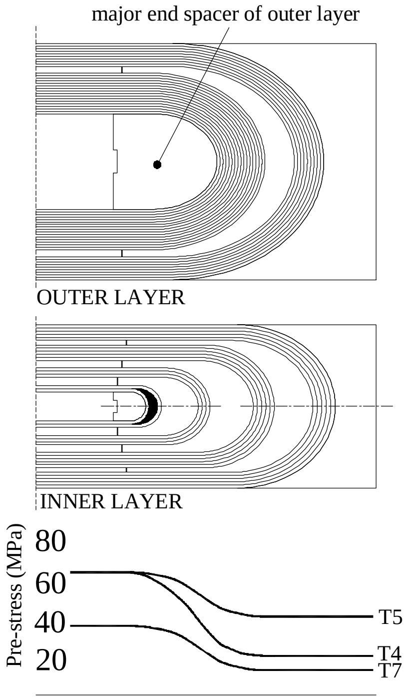

Figure 1: Layout of inner and outer layer ends and azimuthal pressure distribution.

The usual way of coil fabrication is to start winding around a metallic end spacer, which is, after the bonding-sizing cycle, replaced by a G-11 spacer glued onto the coil with epoxy resin.

In case of T5.V3 the major end-spacer of the previous version was re-glued with a 0.2 mm thick B-stage epoxy pre-preg tape placed between the spacer and the cable. This operation had two purposes :

1. provide a better matching between cable-end and spacer;
2. match the end-spacer size to the coil geometry of straight section

In case of T7 the G-11 major end-spacers of both inner and outer layer were mounted already during winding and, as for T5.V3, a pre-preg tape was inserted between the spacers and the cable.

2.2 Assembly parameters

The main assembly parameters explored in these magnets concern the coil heads, the confirmation of the good performance of mixed-material collar-packs and the effect of moving the ferromagnetic part of the yoke more far away from the non-connection coil end.

1. Pre-stress profile in the coil heads.

To confirm the results obtained on single aperture models [4] the four magnets have been assembled with different pre-stress profiles in the coil ends. T4.V1 has the typical profile of single aperture magnets, T5.V1 a more uniform pre-stress distribution like the single aperture magnet S23.V3 [4], T6.V1 a base pre-stress in the non-connection head of 40 MPa instead of the usual 65 MPa, and T7 only 35 MPa this time in both connection and non-connection heads (fig.1).

2. Use of different clamping structures in the heads.

A longitudinal clamping structure, referred as "end-cage", was used for pulling the coil ends against the magnet end plates by tie bolts acting through the collars between the major end-spacers and the end-plate. This end-cage was used for T4.V3 and T4.V4, thereafter released for T4.V5.

3. Ferromagnetic yoke further away from coil heads.

The ferromagnetic yoke of the LHC dipoles does not cover the coil ends, but is at about 80 mm from the beginning of the major end-spacers. On T4.V4 and T4.V5 the above distance was increased by 110 mm.

4. Use of mixed-material collar-packs.

This concept was already explored on single aperture magnets [4]. T4.V1 was collared with the main collars in austenitic steel and the so-called "floating" collars in aluminium, T5.V2 and its subsequent versions were collared with the floating collars made out of plastic material.

2.3 Coil pre-stress at cold & during excitation

The inner and outer layer azimuthal stress, measured at different assembly phases and at cold with capacitive gauges [7], is reported in Table 3. The design pre-stress values were chosen based on single aperture model results : between 50 and 60 MPa for the inner layer and between 60 and 80 MPa for the outer layer. In these conditions the inner layer loses pre-stress at a magnetic field of about 7 T and the outer layer not before 9 T.

In all cases the pre-stress loss between ambient temperature (after collaring) and cold follows approximately the rule (in MPa):

$$\sigma_{cold} \approx 0.5 \cdot (\sigma_{collaring} - 15)$$

Table 3: Coil stress (MPa) in inner/outer layers.

agnet	After ollaring	After yoking	At cold		
			B = 0 T	B = 9 T	Unloading field (T)
4 V1	56 / 85	60 / 87	18 / 32	0 / 4	7.1 / 9.5
V2	50 / 76	55 / 82	18 / 31	0 / 4	7.1 / 9.5
V3	50 / 74	55 / 80	18 / 30	0 / 4	7.1 / 9.5
V4	- / -	55 / 80	17 / 28	0 / 3	7.0 / 9.3
V5	50 / 74	55 / 80	17 / 28	0 / 3	7.0 / 9.3
5 V1	50 / 62	52 / 64	16 / 24	0 / 0	7.0 / 8.8
6 V1	44 / 87	50 / 97	13 / 36	0 / 7	7.0 / ~9.8
7 V1	59 / 83	65 / 90	22 / 32	0 / 6	7.0 / ~9.6

4 TRAINING PERFORMANCE

In all double-aperture models, practically no quenches below 9 T occurred in the straight part. However, compared to single-aperture magnets, in the double-aperture design, because of the cross talk between the two apertures, the peak magnetic field in the outer layer heads is about 0.5 T higher and the central coil sides are exposed to a field higher than that seen by the lateral coil sides. This difference is reflected in the training performance: the optimization of the straight section given by single-aperture models in terms of coil cross-section and pre-stress parameters is still valid for the double-aperture magnets, but the coil heads appear to be weaker.

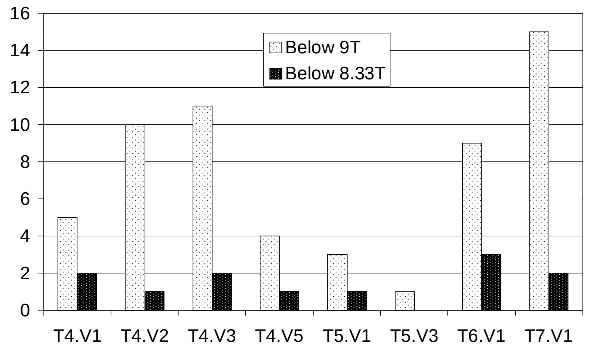

Fig. 2 : number of training quenches in the coil heads.

In fact, as shown in fig. 2, all the double-aperture models still show training quenches in the ends below 9 T. From the good results obtained with T5.V3, it appears that a particular care is required in the assembly of the major end spacers and in providing a sufficiently high and relatively uniform azimuthal pre-stress in the coil heads with tighter tolerances than what was allowed on single-aperture magnets. The importance of these parameters seems to be confirmed by the bad performance of T6 and T7, which were assembled with low pre-stress in the coil ends. To verify this assessment T7 will be reassembled with higher pre-stress.

Other options, like the use of longitudinal clamping structures or the use of aluminium collar packs in the ends, do not seem to bring an advantage in terms of training performance. The effect of shifting the ferromagnetic yoke further away from the coil ends is still under investigation. Preliminary results on T4.V4 and on T4.V5 suggest a gain of about 0.2 T in the training performance.

In reality most important for the LHC is the quench level after a thermal cycle, and from this point the models with sufficient high pre-stress in the coil heads, like T4 and T5, confirm the robustness of the present design. In fact the first quench level after thermal cycle was for example 9.15 T for T4.V4 and 9.4 T for T5.V3 (these magnets reached a maximum field of about 9.7 T).

Finally the two magnets made with mixed-material collar-packs showed again, as in the case of single-aperture models, the same performance as that of magnets collared with all-austenitic steel collars.

5 CONCLUSIONS AND NEXT STEPS

The excellent training performance of the straight section of all the ten models confirm the robustness of the coil cross section and the correct choice of the design pre-stress levels with austenitic steel collars.

Concerning the training performance of the coil ends, three outcomes can be derived from these models :

1. first quench levels after the thermal cycle above 9.0 T could be obtained with a particular care in the assembly of the major end spacers and a tight control of the pre-stress profiles in the ends;
2. first results obtained on T4 with the ferromagnetic yoke longitudinally shifted 190 mm away for the coil ends are encouraging and are to be confirmed after a thermal cycle and on other models;
3. the use of a longitudinal clamping structure with the present design of end spacers does not seem to improve the training performance of the coil ends.

At present, even if performances acceptable for the LHC machine can be already achieved, the coil ends remain the weak point of these magnets. Model work is still under way to understand and solve these last problems during this year.

Finally, the short dipole model program will come to an end next year with the fabrication of three identical magnets for studying the reproducibility of training performance and of magnetic field quality.

6 ACKNOWLEDGMENTS

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REFERENCES

[1] N.Andreev et al :" Mechanical behaviour of the short models of LHC Main Dipole magnets", MT-15, Beijing, China, October 1997.

[2] N.Andreev et al : " Performance of Five and Six Block Coil Geometries in Short Superconducting Dipole Models for the LHC", PAC-99, New York, USA, March 1999.

[3] Z Ang, L.Bottura, S.Russeschuck, A.Siemko, D.Tommasini, L.Walckieers : "Coil Size and Geometric Field Quality in Short Model Dipoles for LHC", MT-16, USA, 1999.

[4] K.Artoos et al : " Status of the Short Dipole Model Program for the LHC MT-16, USA, 1999.

[5] N.Andreev et al: " The 1m Long Single Aperture Coil test Program for LHC", EPAC-96, Sitges, Spain, June 1996.

[6] N.Siegel, D.Tommasini, I.Vanenkov : "Design and use of capacitive force transducers for superconducting magnet models for the LHC", MT-15, Beijing, China, October 1997.