Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

PERFORMANCE OF FIVE AND SIX BLOCK COIL GEOMETRIES IN SHORT SUPERCONDUCTING DIPOLE MODELS FOR THE LHC

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Abstract

A series of similar one meter long superconducting dipole models for the LHC is being manufactured and tested since 1995 for exploring design variants and assembly parameters. Until the end of 1997 all magnets of this series were based on a coil geometry subdividing the conductors in five distinctive winding blocks. In order to cope with new requirements of magnetic field distribution and coil design flexibility, one additional block has been added in the beginning of 1998.

A significant number of models of both types have been built and tested, some of them re-built in a different version, adding up in more than 40 models tested so far.

The paper reviews the performance of these two different coil designs in terms of manufacture, training behaviour and temperature margins as well as mechanical behaviour and magnetic field quality.

1 THE MODELS

The regular CERN in-house model program for the development of the LHC dipoles was started in 1995 with the fabrication of 1m-long single-aperture magnets, so-called MBSMS. The design of the MBSMS models, presented in previous conference papers [1] [2], is based on circular collars of 197 mm outer diameter placed inside a vertically split yoke, held together by a bolted shrinking cylinder for easy re-assembly of the structure.

2 COIL GEOMETRY:DESIGN FEATURES

The LHC dipole coils consist of two superposed layers, an internal layer and an external one. Each layer is subdivided in blocks of conductors separated by copper spacers. The two coil geometries tested on the models are shown in Fig.1 below.

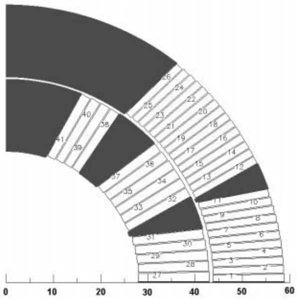

Fig. 1a : 5-block geometry

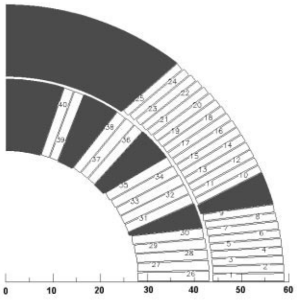

Fig. 1b : 6-block geometry

The first 13 magnets have been built with the 5-block version of the Yellow Book [3], consisting in 3 blocks of conductors in the inner layer and two in the outer layer (fig.1a). As from MBSMS15, the coil design has undergone a substantial evolution, being replaced by a 6-block one, consisting in four blocks of conductors in the inner layer and two in the outer layer (fig.1b). The last 6 magnets have been built according to this 6-block geometry.

2.1 Magnetic design

The original 5-block coil cross-section was optimized using deterministic techniques with the CERN program ROXIE [4]. First a preliminary geometric modelling was done with a given choice on cable dimensions and conductor blocks, thereafter the model was iterated to find an acceptable solution for field quality and peak field/main field ratio. This coil design however did not ensure sufficient tunability and flexibility for later field adjustments like compensating the persistent current multipoles at injection and fine-tuning of field quality. In particular a further compensation of the b3 term, if required, would have been impossible because the copper wedges would become too small at the inner edge. Moreover the performance of the magnets with 5-block coils and laboratory tests indicate that the stress distribution in the inner block of the inner layer is not favourable. With the implementation of genetic algorithms in ROXIE in 1997 [5] it was possible to make an extended the search for more appropriate designs considering all the constraints learned with the short model program based on 5 blocks. The study gave two alternative designs based on 6-block coils, all having similar field quality and quench margin, however with a different number of turns and coil-block layouts. The final choice of the geometry was based on mechanical considerations (see paragraph 2.2) and sensitivity to manufacturing tolerances [6]. Table 1 shows the optimized parameters of five and six-block geometries.

In the 6-block version the number of turns decreased by one (i.e. 40 per pole), but the margin to short sample limit increases by 0.11T, which is explained by the lower ratio of peak field to central field. Further, geometric multipoles were systematically introduced to partially compensate the persistent current effect at injection field level to ease correction scheme requirements.

0-7803-5573-3/99/$10.00@1999 IEEE.

Table 1: Design parameters of single aperture 5 and 6 block

	5 block	6 block
Turns inner layer	15	15
Turns outer layer	26	25
%load line (inner layer)	86.5	85.64
%load line (outer layer)	82.5	84.92
Peak/main field inner	1.05	1.03
Peak/main field outer	0.87	0.89
Current @ 8.36T	11.5 kA	11.8 kA
Maximum central field	9.65 T	9.76 T
Force parallel to cable broad side inner layer	34kN/m	17kN/m
b_3 geometric @ 17 mm	+ 0.3	+ 4.1
b_3 geo + pers @ 17 mm	-11.8	- 6.5

Finally the electromagnetic force parallel to the broad face of the cable has been considerably reduced.

The first two turns of the inner layer are now aligned parallel to the field direction, reducing considerably the shear stress to which they are submitted during excitation.

2.2 Radial supporting of inner layer.

In addition to a lower radial electromagnetic force on the first turns of the inner layer, the 6-block geometry provides a better radial support of these turns. This can be seen in fig 2a and 2b which show the measured distribution of radial pressure of a 5-block inner layer and a 6-block inner layer.

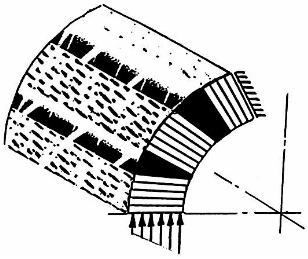
Fig. 2a : 5 blocks

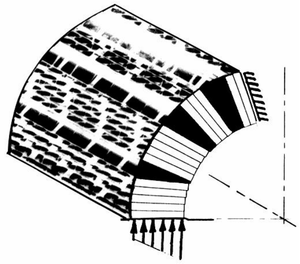
Fig. 2b : 6 blocks

The imprint was obtained with a pressure sensitive tape inserted between the inner layer coil and a mould compressing the coil in the azimuthal direction with a pressure of about 50MPa. The first upper turns of the five block coil in fig. 2a are not in good radial contact with the mould, whilst the six block geometry in fig. 2b provides a more uniform radial support to all the conductors.

3 CONSTRUCTIONAL VARIANTS

Variants explored through the model fabrication concern cable types, material of collars and coil pre-stress.

3.1 Cable types.

One 5-block magnet and all 6-block are made with the 15.1mm wide cable corresponding to the present LHC specification, which is slightly less compacted and with more rounded corners compared to the previous 15.0mm wide cable used for all other 5-block magnets [2].

3.2 Material of collars.

The MBSMS base design relied on aluminium collars, of similar rigidity as those of the twin aperture dipoles. Later, a number of magnets have been collared with austenitic steel collars, which is the present baseline for the LHC dipoles. In general, the use of austenitic steel improves the training behaviour of 5-block coils [2], but this effect is not noticeable in the 6-block coils which appear to have a more stable structure.

3.3 Coil pre-stress.

The coil stress of inner and outer layers has been measured on all models with specially developed strain gauge transducers and capacitive pressure transducers [7][8]. In terms of coil pre-stress the models made so far can be divided into two groups: one of high pre-stress in which coils are compressed by the collars up to the maximum excitation fields and the other of lower pre-stress in which the inner layer unloads from the collars before the magnet reaches 9T. To the first group belong most of 5-block magnets, and to the second group most of the 6-block magnets. Cold tests have shown that magnets of the second group have higher initial quenching fields than magnets of the first group. This effect appears to be less important for 6-block magnets. For simplicity the data presented later will not be grouped by coil pre-stress.

4 PERFORMANCE

The advantages foreseen for the 6-block coil geometry versus 5-block appear especially for the training behaviour. The dynamic behaviour and magnet protection are similar for both designs and linked to cable properties.

4.1 Training.

The 6-block magnets, both with aluminium and austenitic steel collars, show better performance compared to 5-block magnets. Fig. 3 shows the average quenching field of the 5 and 6-block magnets built so far, without distinction between collar material.

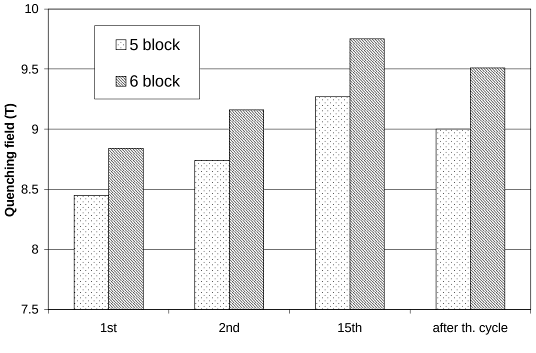

Fig.3 : average quenching field of 5 and 6-block magnets

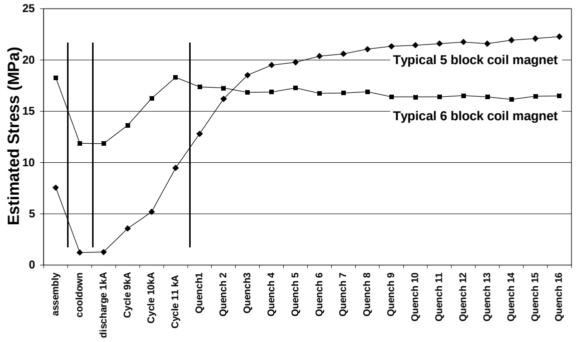

Fig.4: radial pressure between collars and inner layer conductors.

Six-block magnets allow to gain in average about 0.5T in terms of quench performance. One possible reason for this better performance of 6-block can be found in a more stable radial support of the conductors of the inner layer close to the collar pole as suggested from the test in fig. 2. This effect is confirmed by the smaller variation of the radial pressure between the collars and the first turns of the inner layer measured at zero current during the cool-down and the training tests (fig.4).

4.2 Magnetic field.

The six block geometry, having one more block of conductors in the inner layer, allows more freedom for possible adjustements of the high order field harmonics. However, in terms of sensitivity of magnetic field quality to manufacturing tolerances (in particular final coil size after collaring), the two coil geometries are identical. In table2 are shown the change of geometric field harmonics for an increase of 0.1mm in the inner layer coil size after collaring, extrapolated from measurements on 13 five-block magnets and 11 six-block magnets. Concerning the outer layer, in both cases its size has an important effect only on b3, of about 1.3 units per 0.1mm.

Table 2: Change of geometric field harmonics (units 10-4 at a reference radius of 17mm) versus a change of 0.10mm in the inner layer size,measured data.

	b3	b5	b7	b9
5 block magnets	-1.7	+0.4	-0.1	0.05
6 block magnets	-1.6	+0.4	-0.2	*

*range of b_9 for all magnets between 0.02 and 0.10 units.

Finally, the measured non allowed multipoles were similar in both cases, showing that the introduction of one more spacer does not affect the quality of assembly.

4.3 Magnet protection.

In terms of magnet protection no substantial difference was observed between 5 and 6-block design. The hot spot temperatures (fig.5) at 9T range from 200K to 270K and depend in both cases on cable parameters like RRR and Cu/Sc ratio [9].

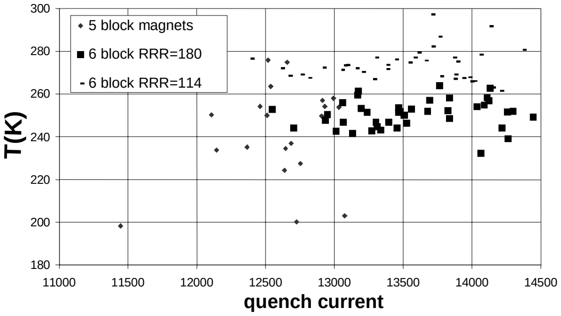

Fig. 5: hot spot temperature for 5 and 6-block magnets

Finally, at nominal current, the time between firing the quench heaters and start of quench (heater delay) was the same for 5 and 6-block magnet (about 50ms).

5 CONCLUSIONS

The advantages foreseen for the 6-block coil cross section of the LHC main superconducting dipoles have been confirmed experimentally on short models. The 6-block geometry has proven to be better performing than the 5-block in terms of mechanical stability of the conductor blocks and of quench behaviour. Concerning magnetic field reproducibility and sensitivity to coil size tolerances the two coil geometries are equivalent. Finally magnet protection parameters are very similar for the two designs, and are dominated by the cable characteristics.

6 ACKNOWLEDGEMENTS

The authors would like to thank C.Wyss and L.Evans for their support to the short dipole model program, and all the teams involved in magnet fabrication and testing.

7 REFERENCES

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