EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

*Large Hadron Collider Project*

**LHC Project Report 223**

# STATE OF THE SHORT DIPOLE MODEL PROGRAM FOR THE LHC

N. Andreev, K. Artoos, T. Kurtyka, L. Oberli, D. Perini, S. Russenschuck, N. Siegel, A. Siemko, D. Tommasini, I. Vanenkov, L. Walckiers

## Abstract

Superconducting single and twin aperture 1-m long dipole magnets are currently being fabricated at CERN at a rate of about one per month in the framework of the short dipole model program for the LHC. The program allows to study performance improvements coming from refinements in design, components and assembly options and to accumulate statistics based on a small-scale production. The experience thus gained provides in turn feedback into the long magnet program in industry. In recent models initial quenching fields above 9 T have been obtained and after a short training the conductor limit at 2 K is reached, resulting in a central bore field exceeding 10 T. The paper describes the features of recent single aperture models, the results obtained during cold tests and the plans to ensure the continuation of a vigorous model program providing input for the fabrication of the main LHC dipoles.

LHC Division, CERN, Geneva (Switzerland)

Presented at the EPAC'98 Conference, Stockholm, June 1998

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva,20 August 1998

# STATE OF THE SHORT DIPOLE MODEL PROGRAM FOR THE LHC

N. Andreev, K. Artoos, T. Kurtyka, L. Oberli, D. Perini, S. Russenschuck, N. Siegel, A. Siemko,
D. Tommasini, I. Vanenkov, L. Walckiers, CERN, Geneva, Switzerland

## *Abstract*

Superconducting single and twin aperture 1-m long dipole magnets are currently being fabricated at CERN at a rate of about one per month in the framework of the short dipole model program for the LHC. The program allows to study performance improvements coming from refinements in design, components and assembly options and to accumulate statistics based on a small-scale production. The experience thus gained provides in turn feedback into the long magnet program in industry. In recent models initial quenching fields above 9 T have been obtained and after a short training the conductor limit at 2 K is reached, resulting in a central bore field exceeding 10 T. The paper describes the features of recent single aperture models, the results obtained during cold tests and the plans to ensure the continuation of a vigorous model program providing input for the fabrication of the main LHC dipoles.

## 1 STATE OF MODEL PROGRAM

The regular CERN in-house model program, started in 1995, has been mainly devoted to fabricate 1-m long single aperture magnets, so-called MBSMS, of which 17 have been made so far. Several of these units were re-assembled into new variants, totalling thus 30 models tested at cold at a rate of about one per month. These models serve mainly to study and optimise the design, assembly and collaring parameters of the coils. The present aim is to build a small series of such models to study reproducibility and field quality issues and in parallel to increase the emphasis on the fabrication and testing of 1- m long twin aperture models, of which two units have been made and tested so far.

## 2 FEATURES OF RECENT MODELS

The design of the MBSMS models, presented in previous conference papers [1,2] is based on round collars of 196 mm outer diameter placed inside a vertically split yoke held together by a bolted shrinking cylinder for easy re-use of the structure. In order to study and optimise model performance and to qualify variants more suitable for series manufacture, materials as well as fabrication and assembly procedures have been checked. The new features incorporated in the most recent models are outlined hereunder.

### *2.1 Cable parameters*

As from unit S15, the coils are wound with cable corresponding to the LHC specification, which is slightly less compacted with more rounded corners than before and transposed in the same direction for inner and outer layer.

Table 1: Dipole cable characteristics

| Cable | Inner layer | Outer layer |
|---|---|---|
| Number of strands | 28 | 36 |
| Cable width (mm) | 15.1(+0,-.02) | 15.1(+0,-.02) |
| Mid-thickness (mm) | 1.900±0.006 | 1.480±0.006 |
| Keystone angle (deg) | 1.25±0.05 | 0.90±0.05 |
| Transposition direction | Left-handed screw | Left-handed screw |

### *2.2 Coil and coil geometry*

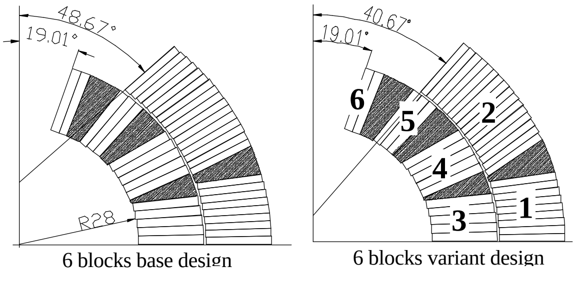
As from S15, the coil design has undergone a substantial evolution, with the previous standard 5-block version being replaced by a 6-block one. The choice of this new geometry comes from the requirement to compensate partially the persistent current multipoles at injection, together with ensuring sufficient tunability and flexibility in the coil design for later field adjustments, conditions which could not be met satisfactorily by the previous coil design [3]. The main parameters that changed in the new design are shown in Table 2. The quenching field is calculated using the lower Ic limit specified for the cable.

Table 2: MBSMS Parameters (6-block coil design)

| | |
|---|---|
| Turns: inner/outer (one quadrant) | 15 / 25 |
| Quenching field (T) | 9.7 at 1.9 K |
| Quenching current (kA) | 13.8 |
| Nominal current (kA) (at 8.33 T) | 11.8 |
| Ratio peak field to central field | 1.03 |

With respect to the 5-block version the number of turns decreases to 40, but quite remarkably the margin to short sample limit increases by 0.1 T, which is explained by the lower ratio of peak field to central field. Also, the first two turns of the inner layer are now aligned parallel to the field lines, reducing considerably the shear stress to which they are submitted during excitation. A variant 6-block design, with the conductors of the outer layer more radially disposed (Fig.1) was also built (S17) and tested.

A further change in the coil design is the different build-up of the all-polyimide cable insulation, chosen for



6 blocks base design

6 blocks variant design

Fig.1. Base and variant design of 6 blocks cross section

improved helium porosity and more economic wrapping of the cables. It consists of two 50 µm thick layers of 11 mm wide tape applied half-lapped (later butt-lapped and staggered by half the tape width), followed by an adhesive coated 9mm wide tape spiralling with 2mm spacing.

### *2.3 Structural and assembly variants*

The MBSMS base design relies on Al alloy collars of similar rigidity as those of the double aperture dipoles, with a nominal coil pre-stress at room temperature of 50 MPa. However, models have been assembled with alternative collar material (non-magnetic steel) and with glued Al collar packs to study the influence of rigidity, and also with different initial pre-stress to study acceptable limits of assembly tolerances as a function of performance. Typical coil pre-stress values during magnet assembly are shown in Fig. 2 both for Al and steel collar variants.

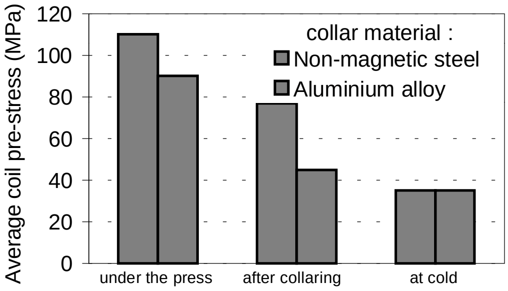


Fig. 2. Average coil pre-stress at RT and at cold.

The interference between collared coils and yoke is chosen such that at cold they are just in contact. Therefore at room temperature the yoke gap must be open for Al collars and can be closed for steel collars, which simplifies assembly. To study the added rigidity given by the yoke contact, one Al collared model and one steel collared model were assembled with sufficient margin around the collars such that there is no contact up to maximum field (free-standing collar packs).

### *2.4 Key features of recent models*

The salient parameters of recent and of some reference magnets are described in Table 3 hereunder.

Table 3:Description of recent models

| Magnet | Salient design and assembly features |
|---|---|
| MBSMS3.V1 | 15 mm cable (non-coated), 5-block coil geometry, Al collars, PEI end spacers in inner layer. |
| MBSMS3.V4 | Re-collared with steel collars |
| MBSMS3.V5 | Re-assembled with free-standing collars (steel). |
| MBSMS3.V6 | Long collars in steel, floating collars in Al. |
| MBSMS9.V1 | 15 mm coated cable, Al collars, lower pre-stress in inner layers (25 MPa at cold). |
| MBSMS9.V2 | Increased pre-stress in inner layer (35 MPa at cold) |
| MBSMS9.V3 | Re-assembled with free-standing collars (Al). |
| MBSMS13.V1 | 15 mm cable, end spacers with shoes, glued Al collar packs, radial shims, fishbone glued to first turns of inner layer. |
| MBSMS15.V1 | 15.1 mm cable, 6-block coil geometry, Al collars. |
| MBSMS15.V2 | Re-collared with steel collars. |
| MBSMS15.V3 | Re-collared with lower pre-stress in outer layer |
| MBSMS16.V1 | As MBSMS15.V1 |
| MBSMS17.V1 | As MBSMS15.V1, more radially oriented outer layer conductors. |

## 3 RESULTS OF COLD TESTS

### *3.1 Mechanical behaviour*

The mechanical instrumentation of the models is based on specially developed strain gauge transducers [4] and capacitive pressure transducers [5]. The measured mechanical parameters of recently tested 6-block coil models, using both Al and steel collars, show that they behave similarly to 5-block coil models, which have been described in detail in reference [4]. Model S3.V6 was made with the aim to check the performance of a steel collared magnet in which the floating collars are replaced by filler pieces. In this case, they were replaced by Al collars, which had little influence on the collared coil rigidity. This magnet showed good performance, proving that such a design, which would be more economical, is feasible. Recent models have been assembled with moderate coil pre-stress, around 30 MPa in the inner layer and 40 MPa in the outer layer at cold. Although in some models the inner layer reaches zero clamping pressure at fields as low as 7 T (unloading field), these models had good training behaviour at much higher fields. The evolution of coil stress as function of the excitation is shown for model S15 in Fig. 3. Table 4 shows the mechanical parameters of representative models of 5 and 6-block coil geometry collared both with Al and steel collars.

Table 4: Coil pre-stress and unloading rates and fields

| Model | Layer | RT (MPa) | Cold (MPa) | Unload. rate $(MPa/kA^2)$ | Unloading field (T) |
|---|---|---|---|---|---|
| S3.V1 | inner | 55 | 60 | -0.19 | 12 |
| 5-block | outer | 64 | 60 | -0.12 | (extrapol.) |
| S3.V4 | inner | 100 | 42 | -0.30 | 10.1 |
| 5-block | outer | 122 | 60 | -0.12 | |
| S3.V6 | inner | 86 | 38 | -0.37 | 8.8 |
| 5-block | outer | 104 | 48 | -0.16 | |
| S9.V1 | Inner | 31 | 23 | -0.31 | 6.2 |
| 5-block | outer | 55 | 38 | -0.11 | |
| S9.V2 | inner | 40 | 35 | -0.32 | 7.7 |
| 5-block | outer | 50 | 38 | -0.14 | |
| S15.V1 | inner | 33 | 25 | -0.37 | 7.1 |
| 6-block | outer | 52 | 37 | -0.12 | |
| S15.V2 | inner | 69 | 27 | -0.27 | 7.8 |
| 6-block | outer | 94 | 47 | -0.17 | |

### *3.2 Training*

***6-block coil design:*** The training behaviour of recent models is shown in Fig. 4. For S15.V1 the first quench occurred at 9.2 T, highest observed so far and the short sample limit was reached after 17 training quenches at a central bore field of 10.1 T. The magnet presents however the usual training pattern of MBSMS models, though at much higher field levels, with gradual training starting at 9.5 T. Contrary to 5-block coil models, where training quenches occur very often in the pole block of the inner layer, in S15 most of the training quenches are observed in the first turn of block No 5 (third turn from pole) which in this design is the most critical one in terms of thermal margin. Following a thermal cycle to

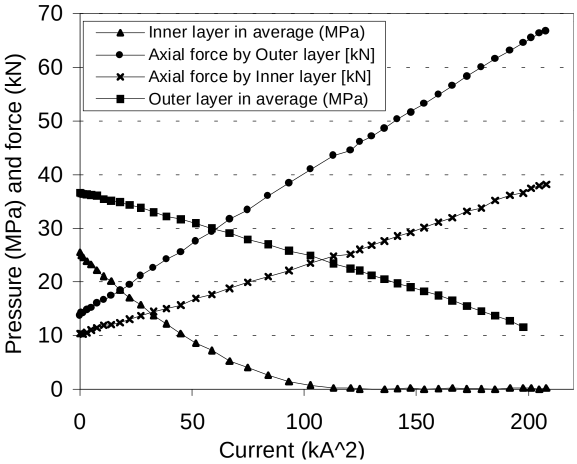


Fig. 3. Coil stress and axial forces of S15.

room temperature, the magnet retrained at 9.6 T showing that there is no memory of the slow training. After quenching without energy extraction, the training location switches to the outer layer, as observed with previous models, with the magnet "detraining" to lower quenching fields [2]. S15 detrained from 10 T to fields between 9.5 and 8.7 T. After such quenches the ∫i²dt reached 30 MIIT's with a hot spot temperature of 340 K, higher than for the series of 5-block models, an increase not yet fully understood. Model S16, assembled similarly to S15, showed a weak spot in the straight part of the third turn of the inner layer, which limited the training performance between 8 to 9 T. Model S17, with the variant coil design of Fig. 1, is now being tested and had its first quench at 9.2 T.

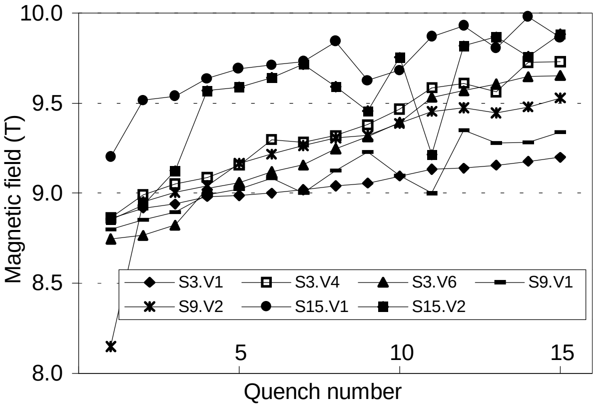


Fig.4 First 15 training quenches of recently tested models

***Coil pre-stress and unloading field:*** Magnets with good initial training have unloading fields for the inner layer ranging from 7 up to 10 T. At cold they have in the inner layer moderate pre-stress ranging from 25 to 40 MPa and unloading rates from –0.3 to –0.45 MPa/kA². In general, too low pre-stress or unloading field like in S9.V1 can result in irregular training behaviour, whereas too high values, e.g. 60 MPa in S3.V1, result in the usual slow training. For the outer layer, pre-stress at cold ranging from 40 to 60 MPa has been found adequate, whereas a too low pre-stress will degrade performance (S15.V3).

***Collar material and structural rigidity:*** Several models made first with Al collars have been re-collared with steel collars. The latter perform usually equally well or better. Model S13 made with glued Al collar packs, which are more rigid since the floating collars fully participate in the structure, performed better than models made with standard unglued collar packs. Model S3.V5 assembled with free-standing steel collars showed much better initial training, though with unstable behaviour at fields approaching 10 T, whereas model S9.V3 with Al free-standing collars had a degraded performance.

## 4 NEXT STEPS AND CONCLUSIONS

Experience so far shows that properties and phenomena in close relation to the cable and the coil play a major role in the model behaviour. Further, confinement of the coil in a more rigid structure has shown to improve initial training (e.g. S3.V4 vs. S3.V1, in Fig. 4) and field reproducibility. Consequently refinements in the design of coil components like the coil layer separation sheet (so-called fishbone), the layer jump, the coil end spacers, the coil insulation, etc., will be actively pursued. Further tests will be made to better define the acceptable pre-stress and unloading windows including Al and steel collars. At the same time models will be built using materials from alternative suppliers for material and component qualification.

In conclusion, recent model tests have shown that the 6-block coil geometry allows to obtain initial training quenches above 9 T and to reach short sample field at 2 K. Also, after a thermal cycle to room temperature, such models retrain above 9.5 T. Porting the experience gained with single aperture model magnets to build twin aperture models should now be the next priority.

## 6 ACKNOWLEDGEMENTS

We wish to express our warmest thanks to L. Evans, J.P. Gourber and C. Wyss for their continued and inspiring support, to our colleagues and to the model and test teams for their excellent work in designing, building and cold-testing these magnets as well as industry for the supply of materials and components.

## REFERENCES

[1] N. Andreev et al., "The 1 m long single aperture dipole coil test program for LHC", EPAC'96, Sitges, June1996.

[2] N. Andreev et al., "Present state of the single and twin aperture short dipole model program for the LHC", MT15, Beijing, October 1997.

[3] S. Ramberger, S. Russenschuck, "Genetic algorithms for the optimal design of superconducting accelerator magnets", this conference.

[4] N. Andreev et al., "Mechanical behaviour of the short models of LHC main dipole magnets", MT15, Beijing, October 1997.

[5] N. Siegel, D. Tommasini, I. Vanenkov, "Design and use of capacitive force transducers for superconducting magnet models for the LHC", MT15, Beijing, October 1997.