EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

*Large Hadron Collider Project*

**LHC Project Report 25**

# THE 1 M LONG SINGLE APERTURE DIPOLE COIL TEST PROGRAM FOR LHC

N. Andreev, K. Artoos, L. Bottura, G. Kirby, D. Leroy, L. Oberli, J. Ostler, D. Perini, A. Poncet, F. Rodriguez-Mateos, S. Russenschuck, T. Siambanis, N. Siegel, A. Siemko, D. Tommasini, G. Trinquart, I. Vanenkov, R. Veness, L. Walckiers and W. Weterings

## Abstract

The CERN short model activity on main dipole magnets is centred around the design, in-house fabrication and testing of single and twin aperture 1 m long magnets. In order to study the influence of individual coil parameters on the magnet behaviour with a fast turn around rate and to qualify the possible design solutions, priority was given to the fabrication of a certain number of single aperture dipole models. The collared coils are assembled in a reusable yoke structure and tested in a vertical cryostat at 2 K. The present paper reviews the aims of the program, the design and fabrication to date of single aperture models, their instrumentation and the preliminary results and conclusions.

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EPAC 96, Sitges, Spain, June 1996

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Geneva, 15/07/96

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## *Abstract*

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## 1 INTRODUCTION

The Large Hadron Collider (LHC) [1], approved by the CERN Council in December 1994, is a 7 TeV proton accelerator-collider operating at a nominal field of 8.3 T. Its main components are double aperture superconducting dipole magnets which have evolved for reasons of economy and machine requirements from 10 to 15 m in length, 50 to 56 mm in bore diametre, and 17 to 15 mm in cable width [2]. Of the former designs seven 10 m long double aperture dipoles and 14 short 1 m models (both single and double aperture with constructional variants) were built and tested, totalling nearly 70 test campaigns at cryogenic temperatures [3]. Results show that these magnets have similar performance and training behaviour, exhibiting comparable weak spots located especially in the coil ends, jump/splice regions, transitions of cross section and often in the innermost coil turn. Since improvements and design options can conveniently be studied with short magnets an intensive fabrication program of 1 m models of the new design started at CERN to provide the required input to the long magnet program presently in progress in industry.

## 2 AIMS OF THE MODEL PROGRAM

Priority was given to the fabrication, collaring and testing of model coils in a single aperture structure (MBSMS) to optimise specific components and procedures, implement new design features, check expected performances and provide a facility for testing cable performance and possible variants. Present rate of model completion is about one per month with a lead time of 3 to 4 months. This will allow in due time, to incorporate in the design lessons learned from the cold test results, to refine the assembly techniques and to accumulate statistics. Double aperture models will be built using the same collars and yoke laminations as for the long magnets. The first such model is planned for measurements in early autumn of this year.

## 3 DESIGN AND FABRICATION

The cross-section and main parameters of MBSMS models are shown in Fig. 1 and Table 1 below.

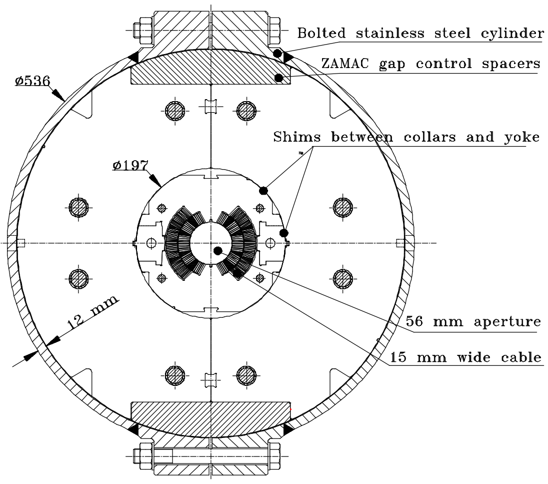

Fig. 1: Cross section of MBSMS type model.

Table 1. Main design parameters

| | |
|---|---|
| Coil inner diameter | 56 mm |
| Quenching field | 9.6T @1.9K and 13240 A |
| Nominal current (Inom) @ 8.368T | 11460 A |
| Ratio of peak field to central field | 1.05 |
| Overall coil length | 1080 mm |
| Length of magnetic steel in the yoke | 560 mm |
| Magnetic length | 862 mm |
| Total inductance | 3.2 mH |
| Magnetic forces per quadrant @ Inom | Σ Fx = 1650 N/mm<br>Σ Fy = -820 N/mm |
| Total axial force @ Inom | 19 tons |
| Cu/SC ratio of inner / outer strands | 1.60 / 1.90 |
| Ic / dIc/dB of inner cable @ 1.9 K, 10 T | ≥13.75 kA / 4.8 kA/T |
| Ic / dIc/dB of outer cable @ 1.9 K, 9 T | ≥12.95 kA / 3.65 kA/T |

### 3.1 Magnetic design

The coils have two layers, made of graded cables with 28 strands of 1.065 mm diameter for the inner layer and with 36 strands of 0.825 mm for the outer layer. The conductors are distributed in five blocks giving the required low content of b7 and b9 components. The load line and expected quench fields calculated with the programs ROXIE and POISOPT are shown in Fig. 2. Three basic types of coil end geometries were designed (see Table 2). Around both coil ends the yoke is made of non-magnetic laminations to reduce the peak field in these critical regions.

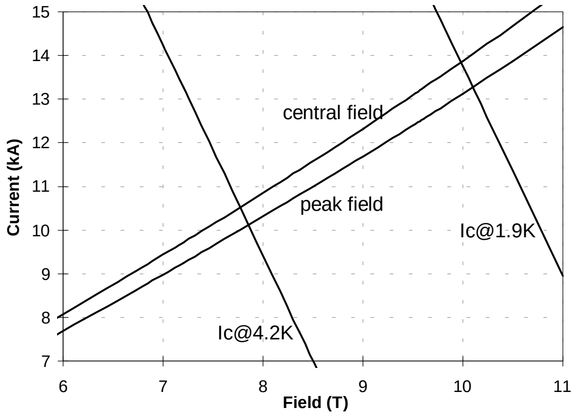

Figure 2. Load line for MBSMS magnets.

### 3.2 Mechanical design

The MBSMS design concept [4] is to allow reproducible coil testing conditions. The collars, made of Al-alloy type 5083, are of similar mechanical rigidity as adopted for the double aperture design and locked by stainless steel rods. The yoke is vertically split with an open gap at room temperature, controlled by spacers made of Zn/Al alloy, and held together by an outer stainless steel bolted shrinking cylinder which has an azimuthal pre-stress of 150 MPa at ambient temperature. This design permits an easy assembly and reuse of the yoke structure. The gap control spacers limit coil compression during assembly but shrink away at cold so that under nominal conditions the gap is closed and the collars are just in contact with the yoke laminations. The gap remains closed up to 9.7 T. The design azimuthal coil pre-stress after assembly at room temperature is 50 MPa, both for inner and outer layers. Since longitudinal compression of the coil heads may improve their training performance, so-called end-cages consisting of a glued collar pack, a flange at the coil end and four tie rods, allow to pre-load the coil heads up to 8 tons.

### 3.3 Instrumentation and Protection

The following instrumentation, needed to monitor assembly and testing is implemented in all models:

- Two spot heaters, to trigger transitions for quench studies, are placed one in the inner and one in the outer layer between the cable and the innermost end spacer, made of 50 μm thick stainless steel foil glued between two 25 μm thick polyimide foils.
- Voltage taps, in total 50 per model, for quench detection and location.
- Special collars with strain gauges near the poles to monitor the coil pre-stress in the inner and outer layers during magnet assembly, cool down and power testing. New capacitive pressure transducers were developed and already used at ambient and LN2 temperatures for collaring tests and coil modulus tests.
- End cage tie rods with strain gauges.
- Bullet gauges to monitor the force exerted by the coils against the thick end plates of the magnet.
- Gap opening transducers to monitor the status of the vertical yoke gap.

The mechanical instrumentation is calibrated both at ambient temperature and at 1.9 K.

All models have quench heater strips placed between the outer layer and the ground insulation, to rapidly heat up the conductors in case of a quench. The calculated hot spot temperature assuming full energy dissipation in the coils and triggering of the heaters is around 240 K.

### 3.4 Fabrication and description of variants

Coil winding of MBSMS1 started in June 1995 and since then seven models have been manufactured and some reworked (see Table 2). The cable insulation is all in polyimide and composed typically of two layers of 25μm thick tapes each overlapped by 48%, and a third 70μm thick adhesive-coated layer, spaced by 2 mm to provide channels for helium penetration inside the coils. After winding, each layer is heated in a mould to 185°C for 30 minutes gluing turns firmly together. The coil heads are then impregnated with a heavily charged resin and the layers assembled with a grooved G11 sheet placed in-between them. The inside cable ends are joined with an AgSn alloy, reinsulated and glued back onto the coil blocks in an operation referred to as reconditioning . The size and modulus of each layer are then measured to define pole and coil head shimming for collaring. Different collaring variants have been tried. Typically the coils are compressed to about 120-130 MPa, the collaring rods are inserted and the external pressure released. The residual coil pre-stress is about 50-60 MPa on both layers. The end cages have been tightened generally after collaring. For models 4 and 5 the coils have been stretched during collaring with an internal mandrel reacting against the innermost coil end spacers and the cages pre-tightened at an intermediate stage to better distribute the longitudinal stresses inside the coil heads. An example of such a collaring is shown in Fig. 3.

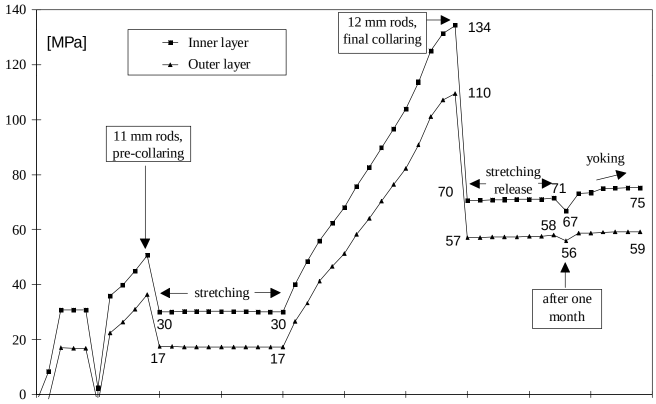

Figure 3. Collaring procedure for magnet MBSMS5

The main fabrication variants are shown in Table 2.

Table 2:fabrication variants from MBSMS1 to MBSMS8

| *magnet* | *coils** | *assembly* |
|---|---|---|
| MBSMS1.V1 | non coated cable<br>type I end spacers | reconditioning @ 185°C<br>end cage tightened |
| MBSMS2.V1 | non coated cable<br>type II end spacers | reconditioning @ 100°C<br>end cage tightened |
| MBSMS2.V2 | | end cage untightened |
| MBSMS3.V1 | non coated cable<br>type II & IIa end spacers | reconditioning under pressure<br>end cage tightened |
| MBSMS1.V2 | | reconditioning under pressure |
| MBSMS4.V1 | tin coated strands cable<br>type II end spacers | reconditioning under pressure<br>end cage tightened<br>coil stretching |
| MBSMS5.V1 | tin coated strands cable<br>type II end spacers<br>no interturn spacers<br>150 mm layer jump | reconditioning under pressure<br>end cage tightened<br>collaring under stretching |
| MBSMS6.V1 | tin coated strands cable<br>type II end spacers<br>no interturn spacers<br>150 mm layer jump | reconditioning under pressure<br>end cage tightened<br>different collar material |
| MBSMS7.V1 | tin coated strands cable<br>type III end spacers<br>150 mm layer jump<br>coil end not impregnated | reconditioning under pressure<br>end cage not present |
| MBSMS8.V1 | tin coated strands cable<br>type II end spacers<br>no interturn spacers<br>150 mm layer jump<br>different cable insulation | reconditioning under pressure<br>end cage tightened |

*end spacers types, design principle and material:
type I : minimum deformation energy, G11; type II : isoperimetric, G11;
type IIa : isoperimetric, PEI; type III : Fermilab design with "shoes", G11;

## 4 TEST RESULTS

Cold tests have been made so far up to model 4. Power test results are reported in Ref. [5]. All models are cooled directly to 1.9 K, first training quenches were at 8.2, 8.65, 8.87, and 8.67 T for models 1, 2, 3, and 4 respectively, followed by slow training, occurring mainly in the first turn and in the transition between straight part and heads of the inner layer. Quenching with full energy deposition gives a hot spot temperature of 240 K and shows a safe magnet protection scheme. After a few such quenches, training switches to the first turn of the outer layer at a lowered unstable field level which remained however above 8.9 T for model 3. After a thermal cycle, this model retrained at 9.05 T, showing limited training memory, but no longer exhibited the unstable behaviour mentioned above and reached 9.5 T after 16 training quenches.

## 5 CONCLUSIONS

A full test and result analysis program is going on for these models. In parallel the fabrication of new models and relevant variants is underway. Results show that general improvements in the assembly have brought better training behaviour, model 3 reaching 92% of the calculated short sample limit on its first quench, proving the validity of the basic design. So far there are no clear indications of a significant advantage coming from a particular end spacer type or from a specific technique like end cage tightening or coil stretching. Known weak spots have been addressed in later models: e.g. increased length of layer jump region, suppression of interturn spacers in the coil ends, smoother transitions between straight part and coil ends. Important aspects of dipole performance like dynamic behaviour and field quality are also addressed by the model program and will steer specific design solutions and fabrication techniques.

## 6 ACKNOWLEDGEMENTS

The authors wish to thank L. Evans, J. P. Gourber, R. Perin and P. Sievers for their constant support, the teams responsible of model assembly and measurements for their excellent work, R. Bossert and J. S. Brandt from FNAL for the design and supply of the end spacers for model 7 and industry for the supply of material and components.

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