EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC PROJECT REPORT 177

Present state of the single and twin aperture short dipole model program for the LHC

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Abstract

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LHC Division

Presented at the 15th International Conference on Magnet Technology (MT15), Beijing, China, October 1997

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Geneva, 14 May 1998

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Abstract - **The LHC model program for main dipoles is based on the design, fabrication and testing at CERN of a number of single aperture and twin aperture 1 m long magnets. So far, a number of single aperture models, each with specific characteristics, were tested at 2 K at a rate of about one per month. These magnets are the main tool used to check coil performance as a function of design and assembly options in view of optimising and finalising choices of components and procedures. Initial quenching field levels of 8.8 T were obtained and the short sample limit of the cable at 1.9 K was reached corresponding to a central bore field of 10 T. Two twin aperture dipole models were also built and tested, using the same structural components as for the long magnets which are now being built in industry. The paper discusses the main characteristics of the models built so far, the instrumentation developed to date and the experience obtained. Finally it describes the plans aimed at continuing a vigorous program to provide input to the long magnet program in industry.**

I. INTRODUCTION

Following the approval of the Large Hadron Collider (LHC) [1] by the CERN Council in December 1994, it was decided to launch an intensive in-house program for the fabrication and testing of short dipole models. Their design is based on a 15 mm wide cable, 5-block coil geometry and 56 mm inner bore coil diameter, as used at present for the fabrication of long LHC dipole magnets in industry [2]. Both single and twin aperture models are built, with emphasis on single aperture ones. In fact, test results have shown that such short models exhibit similar performance and training behaviour as long magnets [3]. They represent therefore a convenient tool to study improvements, different design options and alternative production and assembly techniques at a faster turn around rate than otherwise possible. New models can be made at a rate of up to one per month and often already tested models are re-worked and re-assembled with modified parameters. First results of cold tests at 2 K and also design and fabrication of such models have been presented in previous conference papers in 1996 [4], [5]. The present paper describes the models tested so far, the experience gained in their fabrication and gives an update on power test results at cold. Companion papers at this conference describe mechanical instrumentation and behaviour [6], magnetic measurements and field quality [7], and quench propagation velocities [8], of the models.

II. STATUS OF THE SHORT MODEL PROGRAM

Since mid-1995, when the present regular short model program was launched, 12 single aperture and 2 double aperture models have been made and tested. Several models have been re-worked into new variants summing up to a total of more than 20 different models tested so far.

III. REFERENCE DESIGN

The basic design concept of the MBSMS models [5] is to allow reproducible coil testing conditions, with Al-alloy collars of a rigidity close to that of the double aperture magnet collars, within a bolted structure for easy assembly and re-use of yoke parts. Transverse and longitudinal sections of the MBSMS models are shown in Fig. 1 and 2 respectively and design and cable parameters are given in Table I below.

Some common features to most models are outlined hereafter. The coils are made in two layers. The conductors, insulated with an all polyimide system, are disposed in a 5-block geometry. Most models have end spacers with shapes of constant perimeter design, assuming cables constrained in the ends on the inner radius of the coil. Over the coil ends and part of the layer jump the yoke is made of non-magnetic steel laminations to reduce the field and increase the margin in these critical regions. The yoke, which has an open gap at room temperature controlled by Zn/Al alloy spacers which shrink away at cold, is held together by a bolted stainless-steel skin 12 mm thick pre- stressed to 150 MPa at RT.

At cold and nominal conditions, the collars are just in contact with the yoke and the yoke gap should remain firmly closed up to fields of 9.7T. In order to be able to apply longitudinal pre-stress in the coil heads, so-called end-cages were designed: four tie rods, connecting a glued collar pack in contact with the coil innermost end spacers to a flange at the coil ends, allow axial pre-loading of the ends up to 8 tons.

Twin aperture models are built using the same structural elements, as those used for the long magnets, i.e. same collars, yoke laminations and shrinking cylinder. For diagnostic

TABLE I
MAIN MBSMS PARAMETERS

Coil inner diameter	56 mm
Number of turns: inner layer/outer layer	15 / 26
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 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

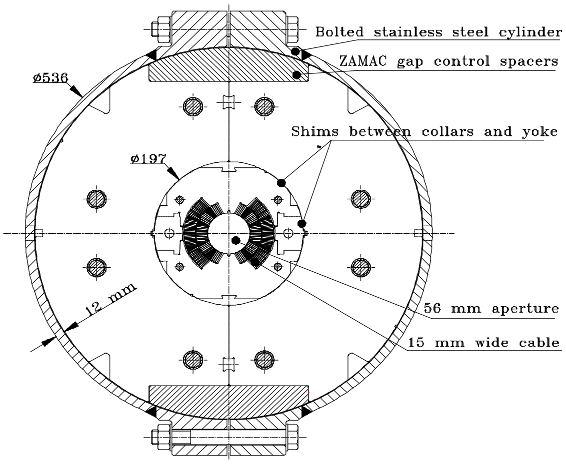

Fig. 1. Schematic cross section of MBSMS models.

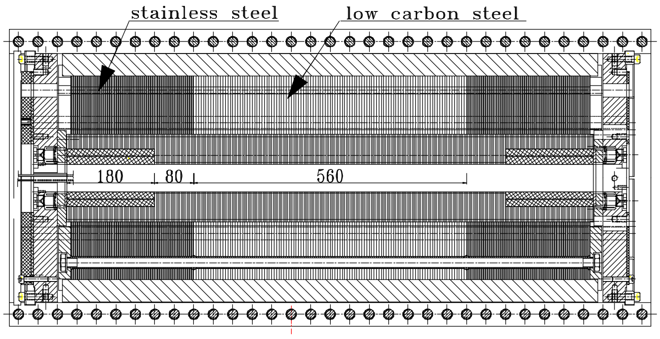

Fig. 2. Schematic longitudinal section of MBSMS models

purposes a comprehensive set of instrumentation is implemented in each magnet [5], including recently developed capacitive gauges, allowing in specific cases a finer resolution of stress measurement [9]. All models have heater strips to rapidly heat up the conductors and spread the quench when a transition is detected.

IV. FABRICATION AND DESCRIPTION OF VARIANTS

Basically the models follow the reference design but incorporate a number of specific features detailed in Table II. The cables, insulated on line, are wound on a rotating mandrel, which can swivel horizontally to adjust to the turn inclination. Typical inner and outer layer cable tensions are 700 and 500 N respectively. The innermost end spacers for winding are in bronze and replaced during coil assembly by spacers made of glass-epoxy type G11 (ISO EPGC3). All coils have end spacers made of G11, except the inner layer of model 3 where they are made of ULTEM™ with good results. The coils are submitted to a heat-pressure cycle inside a mould of fixed cavity to glue the turns firmly together. After an initial heating to 130° C at low pressure, the mould is closed typically around 80, maximum 100 MPa. The coil is then heated to the bonding temperature. Although the nominal gluing temperature of the polyimide adhesive tape is 185° C to achieve maximum strength, recent models have been cured at 165° C, sufficient for 1 m coils, with the aim to preserve the cable inter-strand resistance. However experience has shown that full length coils of 15 m require gluing at 185° C to ensure integrity of the bonding during coil handling. The empty spaces around the coil blocks in the ends are filled with heavily charged resin, optimised to ensure crack-free performance at cryogenic temperatures. The layer jump is formed warm at about 200° C in a precision mould and doubled up to the splice with a Cu strip. Strip and splice are soft soldered with Sn/Ag5 alloy in precise moulds. For this, only a small part of

TABLE II

LIST OF VARIANTS OF SHORT MODEL DIPOLES

magnet	coils	cage	specific features
S1.V1	cable: non coated end spacer*: type I	yes	collared many times reconditioning@185°C
S1.V2	*Coils glued @ 185 °C* **	yes	poles re-assembled reconditioning as S3.V1
S2.V1	cable: non coated	yes	reconditioning@100°C
S2.V2	type II	no	cage untightened
S3.V1	cable: non coated type II & IIa	yes	PEI end spacers (inner layer) *reconditioning@110 °C under 30MPa***
S3.V2		yes	re-collared on cold tube
S3.V3		yes	shrinking cylinder tightened more
S3.V4		yes	re-collared on cold tube non- magnetic Mn steel collars
S3.V5		yes	no contact collars-yoke
S4.V1	cable: coated	yes	coil stretching
S4.V2	type II	yes	more rigid end plates
S4.V3		yes	collars welded after collaring
S5.V1	cable: coated type II, poor turn gluing	yes	coil stretching no inter-turn mini spacers in coil ends *150mm long layer jump (instead of 130)*
S6.V1	cable: coated type II	no	shimming of layer jump copper strip on first turn outer layer
S7.V1	cable:inner coated outer non coated	no	FNAL end spacers [5]
S7.V2	type III	no	collared coils annealed @ 120°C
S8.V1	cable: coated type II	no	*layer jump formed warm*
T1.V1	coated type II	no	double aperture, welded skin *layer jump stab. with cooling holes*
S9.V1	cable: coated type II	yes	inner layer 20 MPa at cold *layer jump box pinned*
S9.V2	*coils glued @ 165 °C*	yes	re-collared radial shims 1^{st} block inner layer inner layer 30MPa@cold
S10.V1	cable: coated type II	yes	cable of higher MQE [11] more rigid end plate fish-bones paint on both sides
S11.V1	cable: Ni-coated type II	yes	B.P. layer jump & splice nickel coated strands fish-bones painted both sides
S12.V1	cable:15.1 mm type II’	yes	new specification cable (15.1 mm wide) thinner collaring shoe (0.5 mm) fish-bones painted both sides
T2.V1	used existing coils 1xS5+1xS6+2xS8	no	fish-bones painted both sides radial shim 1^{st} block inner layer bolted skin

*end spacers types, design principle and material:
type I :minimum deformation energy, G11; type II : isoperimetric, G11
type II’: isoperimetric, G11 new shape iteration
type IIa: isoperimetric, PEI; type III:Fermilab design with “shoes”, G11
***italic: new technologies implemented in subsequent models*

the last turn of the outer layer must be detached from the coil. The conductors are then re-insulated and a thin layer of epoxy resin is applied to the detached turn and to the contact surfaces of the innermost spacer. After insertion of a grooved 0.5 mm thick G11 sheet in-between the coil layers, the completed coil assembly is placed in a mould, and heated to 110° C under a pressure of 30 MPa to cure the above mentioned resin. Size and elastic modulus are measured all along the assembled coils with a precision press, to define pole and coil end shims for the desired pre-stress distribution. The 3 mm thick Al-alloy fine-blanked collars supplied by Malvestiti (I) are pre-stacked with 0.1 mm separation, provided by small nipples, in 90 mm long packs assembled by stainless steel rods. During collaring, the coils are compressed between 100 to 120 MPa, which allows inserting the 1 m long locking rods. After removal of the external pressure the remaining pre-stress is typically 50% of the maximum coil compression (Fig. 3). End cages are usually tightened after the collaring operation, typically with a total force of 3 to 4 tons per end. Models 4 and 5 were collared while the coils were stretched axially applying force onto the innermost end spacers via the end cages, with the aim of improving distribution of longitudinal pre-loading in the ends when tightening the cages. The yoke laminations, fine blanked by Garconnet (F), are made of 5 mm thick low carbon steel from Cockerill (B) for the central part and of 2 mm thick non-magnetic Mn steel (0.00215 integrated thermal expansion coefficient) from Ugine (F) for the ends. The collared coil assemblies are shimmed along the median plane and at 50° such that at cold they are in contact with the yoke. For some magnets, a too large collar/yoke shimming prevented the closing of the yoke at cold and in others an insufficient tension in the skin caused the gap to open during excitation at cold. The force of the closing bolts, tightened now to 35 dNm, is taken at RT by the Al/Zn spacers and maintains at cold the yoke mating faces closed. In most of the models, the average coil pre-stress after yoking is in the range of 50 to 70 MPa. In the ends, the pre-stress decreases progressively from typically 50 to 20 MPa. Model 9 was assembled with a relatively low pre-stress in the inner layer of respectively 35 and 45 MPa for versions 1 and 2. Model 3 in its version 4 was assembled with collars made of non-magnetic 2 mm thick Mn-steel supplied by Sandvik (S) which has an integrated thermal expansion coefficient of 0.0027 from RT to 2 K.

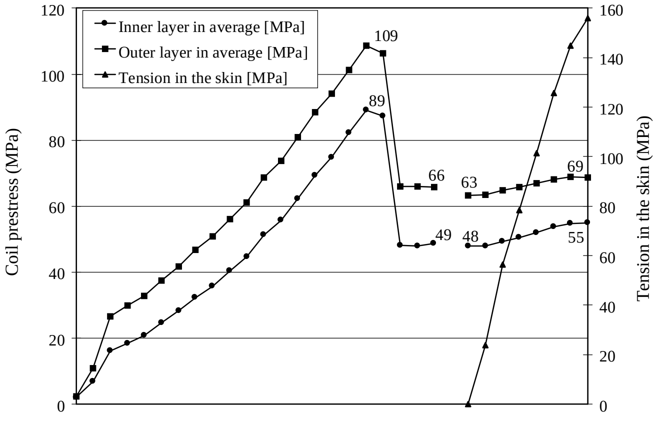

Fig. 3. Collaring and assembly history for MBSMS10.

V. TEST RESULTS

The models are tested in a vertical cryostat, immersed in a bath of superfluid He at atmospheric pressure. The usual test sequence is to start with a few current cycles up to 11 kA, followed by 16 training quenches, extracting about 80% of the stored energy. Quench origin can be accurately located by use of voltage taps and pick-up coils placed in the aperture [10]. The magnets are then tested for high ramp rate sensitivity, followed by loss measurements, protection studies and magnetic field measurements. After a number of training quenches without energy extraction, to investigate performance when reaching higher temperature gradients, the models are warmed to 4.4 K for checking short sample limit. Some models are re-tested after a thermal cycle to RT.

A. Training and quench locations

Typical training behaviour of the MBSMS series is shown in Fig.4. Fields between 8.6 to 8.8 T are reached with a few or no training quenches followed by gradual training around 20 to 30 mT/quench. The origin of most of these quenches is located in specific areas, mostly in the inner layer, although not all models present the same spectrum of occurrence. These areas are the innermost turn and block of the inner layer, the transition regions from straight to ends and the layer jump region. Lower field quenches before the start of gradual training are located more randomly in weak spots, which are mostly not recurrent. After a thermal cycle to RT, magnets usually retrain at the starting level of the gradual training, i.e. preserving only the training at "lower" field values. After a series of training quenches without energy extraction, some models "de-train", quenching at a lower field always on the 1st turn of the outer layer. This effect may be intermittent and disappears after quenching with energy extraction.

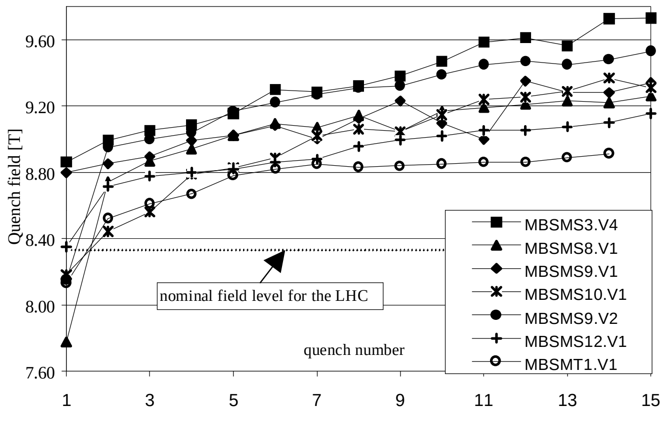

Fig. 4. First 15 training quenches of recent model magnets

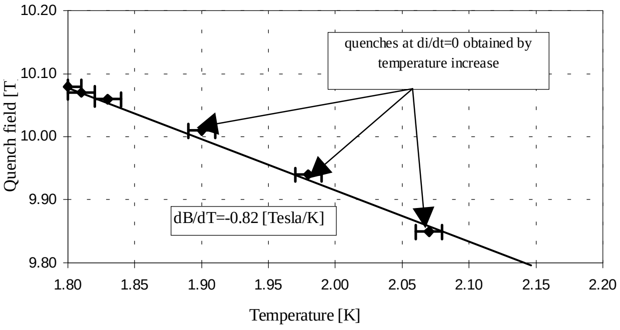

Fig. 5. Temperature dependence of quenching field at 2 K (MBSMS3.V4)

B. Short sample limit

Quenches at conductor limit are made for all models around 4.4 K and for S3.V4 around 2 K. The temperature dependence of quench field (Fig.5) agrees with that of cable critical current, showing that no training is involved for these quenches and that short sample limit is reached. These measurements also show that cable performance is not degraded by the model fabrication procedures.

C. Behaviour of recent models

MBSMS3: All versions had their first training quench around 8.8 T. Version 4, which was re-assembled with non-magnetic Mn steel collars, reached short sample limit at 2 K at a faster training rate. The inner coil unloaded at around 9.7 T and some unstable training occurred at these high field levels.

MBSMS4, 5: Both showed typical behaviour. Model 5 was quenched from the beginning without energy extraction and showed no "de-training".

MBSMS6: After a few "lower" field quenches in the layer jump, which in this model had not been shimmed adequately, the performance followed the typical behaviour. A thin 0.2 mm thick Cu strip was brazed to the first turn of the outer layer. Only some "de-training" was observed, however the field quality during current ramping was influenced.

MBSMS7: Made with FNAL end spacers [5], it has non-impregnated ends and shows some "lower" field quenches in the ends of the outer layer. Training then followed the typical pattern and no "de-training" occurred. For version 2 the collared coils were heated to 120° C for two hours. A similar training pattern was observed, improved by about 0.2 T.

MBSMS8: As from this model the layer jump is formed warm at about 200° C. In addition, the 1st Cu wedge of the inner layer is perforated, allowing He venting from in-between the coil layers. Apart one "lower" field quench in an outer layer pole turn around the end spacer, the behaviour is typical, with "de-training" observed.

MBSMS9.V1, 2: Both versions, collared with a lower pre-stress, have the usual training pattern, but at an initially faster rate, similar to the steel collared model 3 version 4. At higher fields V1 (lowest pre-stress) has unstable quench behaviour.

MBSMS10: An inner cable with a higher minimum quench energy (MQE) was used [11]. Training quenches started low,but eventually after 40 training quenches the magnet reached 9.8 T, the highest apart model 4 with steel collars. Atypical is the frequent training in the first turn of the outer layer. It also showed some "de-training".

MBSMS12: Built using new cable (15.1 mm wide) made of same strands as previous one, with more rounded corners and somewhat less compaction. After one "lower" training quench, the model followed the typical pattern with no "de-training".

MBSMT1: Due to horizontal collar oversize the gap of T1 did not close at cold. It had one "lower" field quench and then followed a typical behaviour. After two thermal cycles it re-trained around 9 T.

VI. Conclusions

Initial quench fields of 8.8 T were reached both with Al-alloy and steel collared models. Subsequent training is faster for the latter type, which reached short sample field at 2 K. Models assembled with lower pre-stress are promising showing good initial training, but some have unstable quench behaviour at higher fields. Model assembly and testing will continue at the best possible rate in order that solutions for the long magnet program can be tested and evaluated in time.

Acknowledgment

The authors wish to thank L. Evans, J.P. Gourber, C.Wyss and P. Sievers for their constant support, the teams making model assembly and measurements for their excellent work and industry for the supply of material and components.

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