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LHC Project Report 30

POWER TEST RESULTS OF THE FIRST LHC SECOND GENERATION SUPERCONDUCTING SINGLE APERTURE 1 M LONG DIPOLE MODELS

G. Kirby, J. Ostler, D. Perini, N. Siegel, A. Siemko, D. Tommasini and L. Walckiers

Abstract

Within the LHC magnet research and development programme, a series of single aperture 1m long models of second generation are presently being built and tested at CERN. The main features of these magnets are: five-block, two layer coils wound from 15mm wide graded NbTi cables, enlarged 56mm aperture and all-polyimide insulation. This paper reviews the power test data of magnets tested to date in both supercritical and superfluid helium. The results of the quench training, the initial location and propagation of quenches and their sensitivity to energy extraction are presented and discussed in terms of the design parameters and the aims of this short dipole model test program.

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Power Test Results of the First LHC Second Generation Superconducting Single Aperture 1m Long Dipole Models

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Within the LHC magnet research and development programme, a series of single aperture 1m long models of second generation are presently being built and tested at CERN. The main features of these magnets are: five-block, two layer coils wound from 15mm wide graded NbTi cables, enlarged 56mm aperture and all-polyimide insulation. This paper reviews the power test data of magnets tested to date in both supercritical and superfluid helium. The results of the quench training, the initial location and propagation of quenches and their sensitivity to energy extraction are presented and discussed in terms of the design parameters and the aims of this short dipole model test program.

INTRODUCTION

The Large Hadron Collider (LHC) project [1], approved by the CERN Council in December 1994, will enable protons and heavier particles to collide at higher energies than ever before achieved. For proton-proton collisions it will provide a centre of mass energy of 14 TeV and at an unprecedented luminosity of 10^{34} $cm^{-2}s^{-1}$. The LHC is based on a ring of high field, twin aperture superconducting dipole and quadrupole magnets, accompanied by numerous correction elements, all operating in a pressurised Helium II bath.

During the last few years, as a result of the research and development programme and cost optimisation studies, the design of the main magnets evolved considerably (c.f. [2],[3]). In 1995, the revised conceptual design of the machine [4] was established with the new parameters for the second generation of magnets being decided.

Since then, the design and fabrication of a new series of short (1.3 m long) single aperture (MBSMS) and twin aperture (MBSMT) dipole models has started at CERN. This paper describes the main results of the power tests for the first three single aperture magnets in this series.

MAGNET DESIGN AND FABRICATION VARIANTS

The MBSMS magnet series are aimed to study specific items in a well reproducible structure, following the same main design. Since June 1995 when the winding of the first coil started, five magnets denoted by the nomenclature MBSMS1 to MBSMS5 have been manufactured and three of them already tested. Following the tests results, two of them have been reworked into new versions.

A cross-sectional view of the cold mass is shown in Fig. 1. The yoke is split into two halves, each composed of three blocks. The central blocks are made of 5.8 mm thick ferromagnetic sheets, the lateral blocks are made of 2 mm thick stainless steel laminations to decrease the magnetic field in the ends and in part of the layer jump region.

Table 1 Main parameters of the MBSMS magnets

Central field at cable short sample limit	9.6 T @ 1.9K and 13240 A
Nominal current @ 8.3 T	11460 A
Peak field/central field ratio at nominal current	1.022 for inner layer, 0.85 for outer layer
Overall coil length	1080 mm
Magnetic steel length	560 mm
Total inductance (measured @ 20 Hz after assembly)	3.2 mH
Resulting magnetic forces per quadrant @ Inom	Sum Fx= 1650 N/mm, Sum Fy= -820 N/mm
Total axial force @ Inom	19.1 Tons
Design azimuthal stress in the shrinking cylinder	150 MPa after assembly
Shrinking cylinder thickness	12 mm
Vertical yoke gap	0.44 mm
Coil diameter	56 mm internal, 118.6 external
Overall outer diameter	536 mm
Overall length	1318 mm

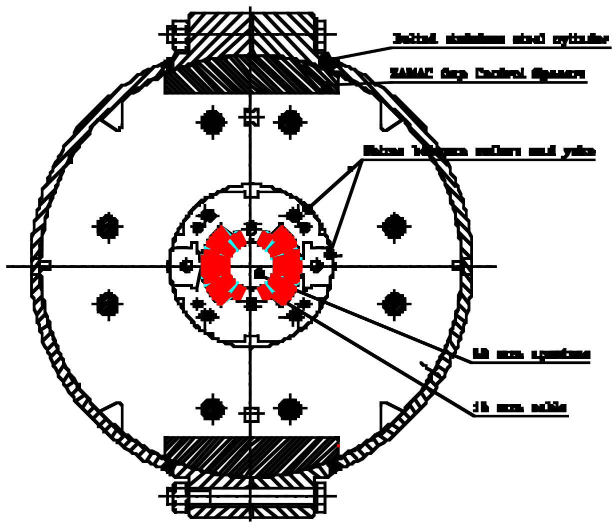

Figure 1 The cross-section of the MBSMS magnets

The transition between the stainless steel blocks and the ferromagnetic ones occurs in the ramp region. The coils are based on five blocks of 15mm cables insulated with polyimide tapes. To keep the yoke closed at the maximum field of 9.6 T the action of the stainless steel shrinking cylinder contrasts the horizontal resultant of the electromagnetic forces, i.e. about F_x=2.2 kN/mm per quadrant. The shims between the collars and the yoke are set so there is just contact in cold conditions. The gap control spacers are made of ZAMAC 27. The vertical yoke gap after assembly is equal to 0.4†mm.

Table 2 Main fabrication variants of the MBSMS magnets

Magnet	Inner Coil	Outer Coil	Collaring
MBSMS1.V1	cable : non coated end spacers : min deform- ation energy	cable : non coated end spacers : min defor- mation energy	end cage tightened
MBSMS2.V1	cable : non coated end spacers : isoperimetric machined	cable : non coated end spacers : isoperimetric machined	end cage tightened
MBSMS2.V2			end cage untightened
MBSMS3.V1	cable : non coated end spacers: isoperimetric moulded layer jump quality improved	cable : non coated end spacers: isoperimetric machined	end cage tightened
MBSMS1.V2	adjusted layer jump		end cage tightened
MBSMS4.V1	cable : tin coated end spacers : isoperimetric	cable : tin coated end spacers: isoperimetric	collaring under longitudinal tension small tightening of end cage
MBSMS5.V1	cable : tin coated end spacers : isoperimetric no mini-spacers in the coil ends - 150 mm layer jump	cable : tin coated end spacers : isoperimetric no mini-spacers in the coil ends	collaring under longitudinal tension small tightening of end cage

TRAINING BEHAVIOUR

The first three magnets have been successfully tested in vertical cryostats at CERN's short model test facility both in superfluid and 4.2 K Helium. At the beginning of each power test campaign, the so-called standard quench training at 1.8 K was performed. Magnets were energised by ramping up the current at a constant rate equal to 10 As^{-1} until the quench occurred. Once the quench was detected the power converter was shut off and after a predefined delay (10 ms for the majority of quenches) the external dump resistor was switched into the electrical circuit allowing the stored energy to be extracted. During the standard quench training program (generally consisting of up to 20 quenches) only about 15-17 % of stored energy was dissipated into the magnet structure. The training history is shown in Fig. 2.

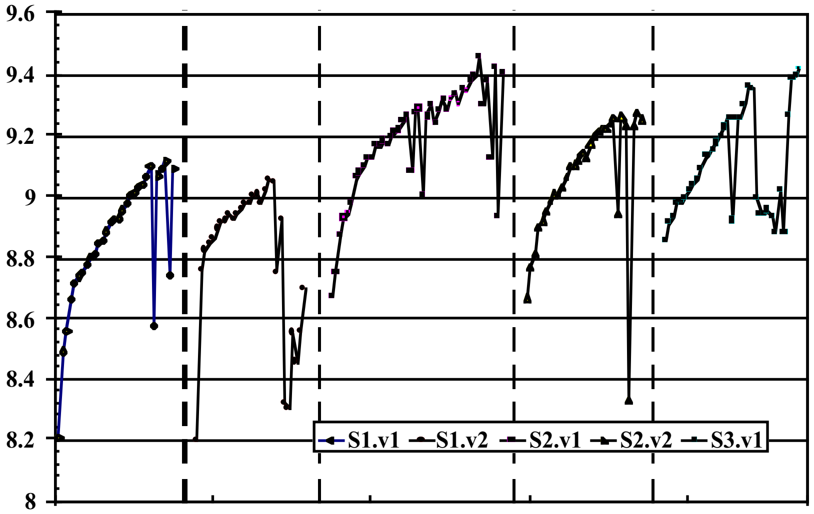

Figure 2 The training history of the MBSMS1 to MBSMS3 magnets

MBSMS1 Version 1 and Version 2

This was the first magnet tested in the series in which the minimum deformation energy concept for end design was implemented. The first quench occurred at 8.2 T i.e. just below LHC nominal field B_{nom}= 8.3 T (see Fig.3). Subsequent quenches appeared sufficiently above B_{nom}. However, a relatively long training period was observed and thus the magnet reached only 8.9 T in 16 quenches. After the modification (see Table 2) the MBSMS1.v2 model was re-tested and with the first quench 8.2 T was reached again. The quench training that followed was improved with respect to MBSMS1.v1, especially at the beginning of the training (see Fig. 3).

MBSMS2 Version 1 and Version 2

In this model the isoperimetric coil end design was adopted. The magnet quenched for the first time well above B_{nom} , at 8.67 T which corresponds to 9.7% less than the specified short sample limit for the superconducting cable (9.6 T at 1.9K) and about 12% less than the estimated, according to measurements at 4.2K, short sample limit. The subsequent training period, was similar to the MBSMS1 model, reaching 9.2 T after 16 quenches. The second version of MBSMS2 aimed to test the effect of the release of axial pre-stress in the end cage on the quench behaviour. As can be seen in Fig. 3 the general quench performance of MBSMS2.v2 is very similar to that of MBSMS2.v1.

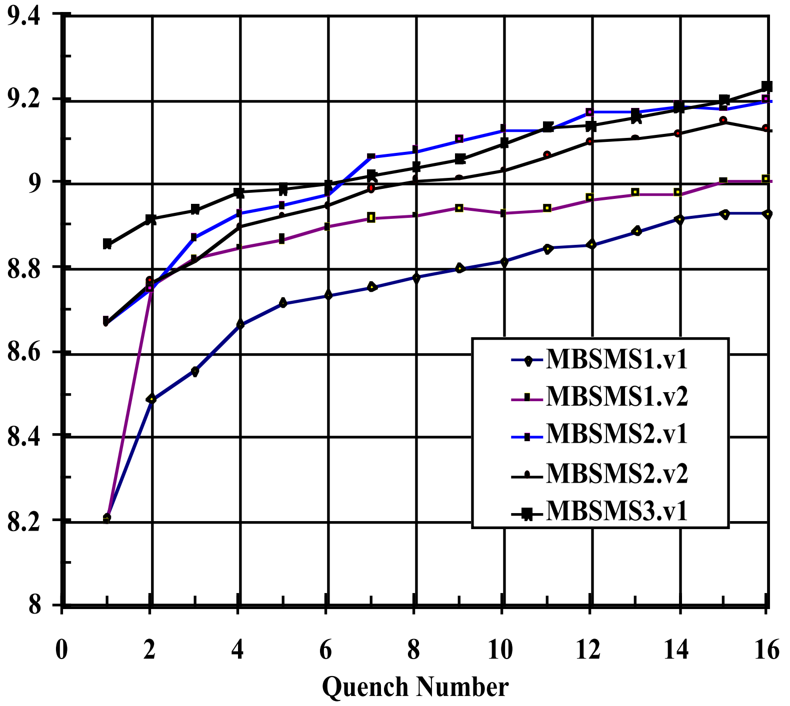

Figure 3 The first 16 quenches of the MBSMS1 to MBSMS3 magnets

MBSMS3 Version 1

The third model, MBSMS3, tested recently has shown the best quench performance for all five tests performed up until now. The first quench occurred at 8.86 T i.e. 7.7% less than the specified and 9% less than the estimated short sample limit for the cable. The training for 16 quenches ended at 9.23 T. After the thermal cycle 9.05 T and 9.5 T were observed respectively for the beginning and the end of the training.

QUENCH LOCATION

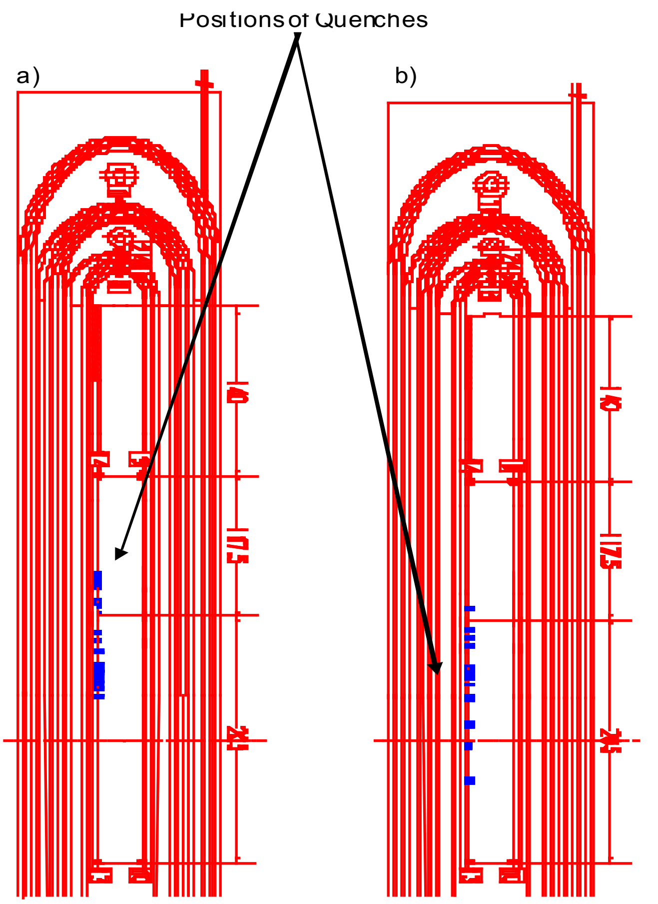

Figure 4 The distribution of quench locations in the inner layer for a) MBSMS2.v1 b) MBSMS2.v2

The technique applied to finding the location of the quench origins was the combined voltage taps and quench location coils method previously described in [6] and [7]. This method allowed positions within individual turns and in the axial direction to be ascertained to an accuracy of about 1 cm in most typical cases. Detailed studies have shown that the quench location map is very similar for all five tests performed. An example of the distribution of the quench locations in this region obtained for the MBSMS2.v1 and MBSMS2.v2 models is shown in Fig. 4.

It was found that the main weak region of the magnet structure is a particular conductor length of the pole turn in the inner layer. This conductor length is known to have been treated in a special way. During the magnet assembly process, in order to form the layer jump (ramp and splice), a part of the pole turn in the inner layer and similarly in the outer layer needed to be temporarily detached. After the layer jump is formed and the two layers are assembled the coil is subjected to the reconditioning process, aiming to re-fix the previously detached turns. Such a procedure seems to degrade the mechanical stability of this particular region and as a result is a source of mechanical motions leading to the frictional heating of the conductor.

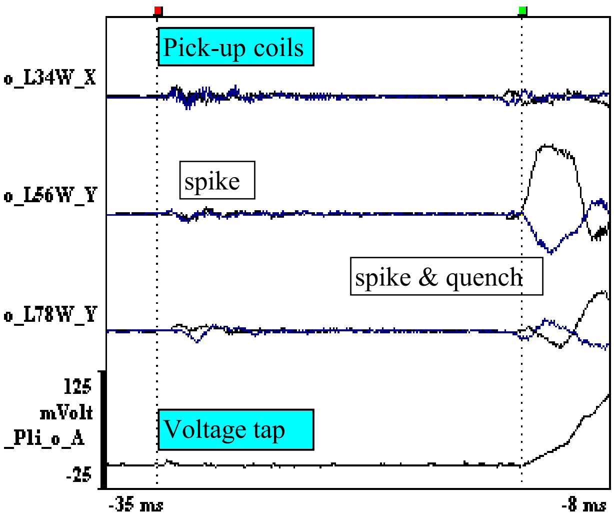

Figure 5 An example of transient spikes before one of the quench of the MBSMS3.v1 magnet

In Fig 5, signatures of such motions, as observed for one of the quenches in MBSMS3.v1, can be seen. It is possible to notice two of these oscillations, first c. 20 ms prior to the quench and the other just before the quench origin. It is worth noting that the observed "spikes" and oscillations, concerning their start position, are phenomena usually well localized in space. They propagate along the magnet with characteristic velocity, typically in the range of 1500 to 2000 ms^{-1}.This corresponds to the velocity of sound at low temperatures in composite materials like superconducting cable of the Rutheford type. It was also observed experimentally that the oscillation or spike origin and the quench origin are not always identical (see also [7]).

The analysis indicated that the transition between the straight and bending part in the second block of the inner layer, for both ends of the coil, is the second most common and important weak point in the first three magnets.

INFLUENCE OF THE ENERGY DEPOSIT ON TRAINING BEHAVIOUR

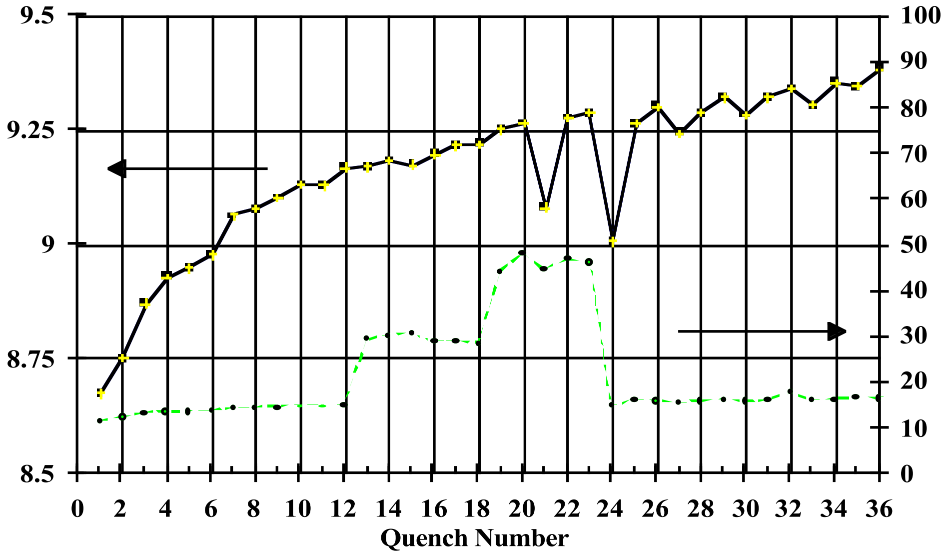

Figure 6 Effect of gradually increasing the deposited energy on the quench behaviour of MBSMS2.v1

The power test programme adopted for the first MBSMS models also included a short series of tests to see how the amount of energy dissipated into the magnet affected the quench behaviour. This effect was not investigated for the first generation of magnets in a systematic way. In Fig 6, the curve representing the percentage of the energy deposited into the magnet structure is shown beside the training curve for the MBSMS2.v1 magnet. Starting with a deposition of about 45 to 50% of the stored energy, the first signs of unstable quench behaviour were observed. When the amount of energy deposited was decreased the "normal" quench training reappeared again indicating a thermo-mechanical origin of the effect.

A more pronounced effect due to the higher amount of energy deposited into the MBSMS3.v1 magnet is shown in Fig. 7. The first detraining was observed after the so-called protection tests; quenches provoked at B_{nom} by firing the spot heater. With subsequent quenches, the switching on of the external dump resistor to the electrical circuit was gradually delayed until nearly all the stored energy was

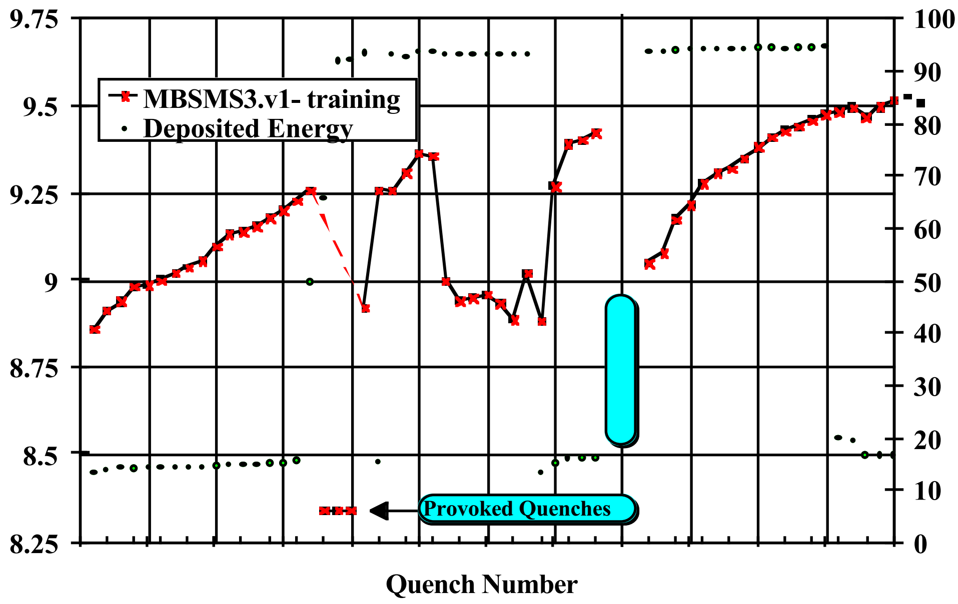

Figure 7 Effect of gradually increasing the deposited energy on the quench MBSMS3.v1

dissipated into the magnet. Afterwards the quench training was performed with no energy extraction and after a few quenches the strong detraining appeared. When energy was extracted again the quenching field was observed to recover after a very short retraining period. The quench location analysis has shown that all the “normal” training occurred in the inner layer whereas all the “detraining” quenches were found in the detached pole turn of the outer layer.

The MBSMS3.v1 magnet, without any modifications, was cycled thermally to room temperature and re-tested, from the outset, without energy extraction. As can be seen in Fig. 7 this time only the “normal” training appeared and quenches were located in the inner layer. Further tests on a virgin magnet are foreseen in order to understand the observed effect more.

CONCLUSIONS

The recent test results of the first MBSMS single aperture short models of the second generation have confirmed the validity of their design and fabrication. The improving construction quality of the subsequent models has been reflected in a gradual increase in the field level of the virgin quench.

The analyses performed have shown that the first three magnets behaved in the same way with respect to their training. Their quench performance was limited by quenches occurring in distinctive locations. It was found that the main weak region of the magnet coil is a particular conductor length, adjacent to the ramp-splice, in the pole turn of the inner layer and its counterpart in the outer layer. This region is known to have been treated in a special way during the coil assembly process. The analysis indicated as well that the transition between the straight and bending part in the second block of the inner layer, for both ends of the coil, is the second most common and important weak spot.

One of the aims of the tests on the first three magnets was to select the best design of the coil ends and end spacers. It was found that there is no experimental evidence that any of the different coil end designs is better than the others. This is due to the fact, as it is believed, that the real behaviour of the ends was kept in the background of the more pronounced weak spots described above. Nevertheless all tested variants of the coil end design seem to be at least satisfactory with respect to the MBSMS magnets quench performances.

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