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Mechanical Behaviour of the Short Models of LHC Main Dipole Magnets

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Administrative Secretariat
LHC Division
CERN
CH –1211 Geneva 23
Switzerland

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CERN - European Organisation for Nuclear Research, CH-1211 Geneva 23, Switzerland

***Abstract*—A series of single and twin aperture 1 metre magnet models has been built and tested in the framework of the R&D program of main superconducting dipole magnets for the Large Hadron Collider project. These models, designed for a nominal field of 8.3 T at 1.8 K, have been constructed to test the performance of SC coils and to optimise various design options for the full length 15 metre long dipoles. The models have been extensively equipped with a specially developed mechanical instrumentation, enabling both a control of the assembly of magnets, and also the monitoring of magnet behaviour during cool down and excitation. The instrumentation used, mainly based on strain gauge transducers, is described and the results of measurements obtained during power tests of the magnet models are discussed and compared with the design predictions based on Finite Element calculations.**

I. INTRODUCTION

The Large Hadron Collider [1], to be built at CERN, will employ some 1200 high field double aperture main dipole magnets. Since 1995, the development of the full-scale 15 metre magnets has been accompanied by an intensive in-house program of fabrication and testing of short 1 metre dipole models. Their design is based on a 15 mm cable, 5-block coil geometry, and 56 mm inner coil bore diameter - as used at present for the fabrication of long dipole magnets in industry [2]. Similarly to the long magnets, the models have aluminium collars closed with locking rods, a vertically split magnetic yoke and a stainless steel shrinking cylinder. The short model program has been launched to test the performance of SC coils for various design and assembly options and has involved both single (MBSMS) and double aperture (MBSMT) magnets. Most of the tests has been done on single aperture models, treated as a convenient “coil test facility”. Up to now, 12 single and 2 double aperture models have been tested, some of them in several re-assembled versions, totalling to 23 different model variants tested so far. Companion papers to this conference describe in detail the design variants of the models and their performance during power tests [3], as well as magnetic measurements and field quality [4]. The present paper reviews the results of mechanical measurements of the models made during assembly, cool down and power tests.

II. INSTRUMENTATION

The magnets tested within the short model program have a standard mechanical instrumentation, based on specially developed strain gauge transducers, used to monitor azimuthal coil stresses, axial forces acting on magnet ends, and contact pressures between yoke halves. In some recently tested magnets special capacitive pressure transducers [5] have also been used for coil stress measurements.

The standard strain gauge transducer used to measure the azimuthal coil stresses consists of a strain-gauge collar pack, 90 mm long, in which two sections of collar laminations are equipped with special collars, shown in Fig. 1, with dual-grid rosette strain gauges glued in pairs on both sides of the collars and wired in a six-wire full-bridge configuration. This provides a self-compensation of bending effects and of the magnetic field. Slots are machined in the collars on both sides of the gauges to provide a quasi-unidirectional strain field in azimuthal direction. For the outer layer, HBM-XC11 dual grid gauges were used, while for the inner layer MM-WK-062TZ were employed. Temperature calibration of these gauges is performed at 77 K since the difference of apparent strain for the full-bridge gauges between 77 K and 1.8 K is small. A force calibration is made by applying a known press load via a coil on each separate layer. It is necessary to note that the gauges of the inner layer do not measure over the entire width of the cable, but rather on its outer half.

Four axial compression load cells (or 8 for the double aperture magnets), called “bullets”, are used to measure axial loads on the ends of the magnets (2 “bullets” per end). Each cell comprises two strain gauges wired in four-wire quarter-bridge configuration and undergoes force and temperature calibration. A compensation for magnetic field is made by using a dummy, strain-free gauge.

The magnetic yoke of the LHC dipoles and of the tested models is split vertically into two halves which must be open at RT and closed at cold, under compression of the shrinking cylinder. A bolted cylinder is used in the models for easy assembly. Closing of the yoke gap is monitored by contact gauges (“gap controllers” in Fig.2) consisting of strain gauges directly glued on two yoke laminations placed in the

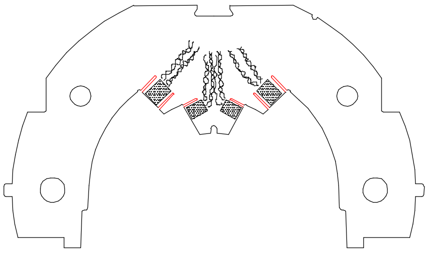

Fig. 1. Special coil clamping collar equipped with strain gauges

middle of the magnet, with the arrangement of gauges and unloading slots identical to the one used for the strain-gauge collar pack. These gauges, calibrated for low temperatures, merely register local contact deformations of the yoke, amplified by special grooves in the laminations and are not calibrated to deduce the contact forces between the yoke halves. The hoop stress in the outer shrinking cylinder is only controlled at RT, during magnet assembly, both by measuring the elongation of the fastening bolts and by the strain gauges on the cylinder. This equipment is, however, not calibrated for the use at cryogenic temperatures.

III. MEASUREMENTS – DISCUSSION OF RESULTS

For the sake of discussion of the results, the magnet models tested so far [3] are divided into four groups: 1). Single aperture models with aluminium coil clamping collars and "standard coil pre-stress" (18 models/variants tested, 16 analysed – magnets MBSMS1 to S12). 2). As above, but with deliberately low coil pre-stress (2 magnets - MBSMS9.V1 and V2). 3). As above, but with stainless steel collars (1 magnet – MBSMS3.V4). 4). Double aperture models with common aluminium collars, corresponding to the full-scale dipole magnets (2 magnets - MBSMT1.V1 and T2.V1). The discussion will be concentrated on the average mechanical performance of the first group, basic for the present testing program and providing a certain statistics of measured results; the differences observed for the three other groups will be pointed out.

A. *Closing of the yoke*

A complete closing of the yoke halves upon cool down depends on the yoke gap after assembly and on the force developed by the bolted outer cylinder. While the predicted design parameters providing closing of the yoke halves - gap equal to 0.2÷03 mm, cylinder hoop stress around 150 MPa for the standard single magnets - have been found correct, they were fully achieved only in recently tested magnets, equipped with strengthened cylinder bolts.

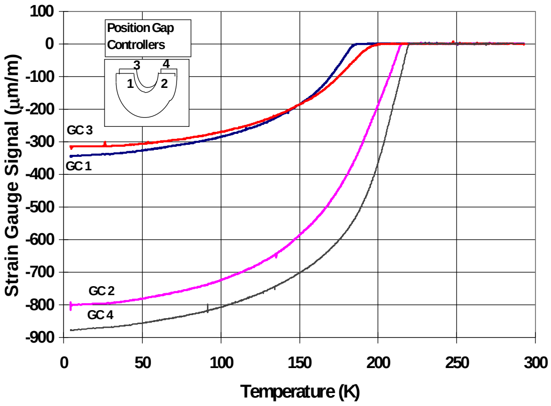

Fig.2 Yoke gap closing during cool down (MBSMS11.V1). The differences in strain gauge signals GC1/3 and GC2/4 may indicate a non-uniform closing of opposite yoke sides

For the magnets reported as having a "firmly closed gap", the gap was closing during cool down in the range of temperatures from 220 to 150 K, as indicated by negative signals of the "gap controllers", Fig. 2. For such magnets the yoke halves stayed closed under current excitation up to the maximum fields reached, showing only partial release of the mating force. On the contrary, in the earlier magnets with partially or weakly closed gap, there was a tendency of opening the yoke halves under electromagnetic forces at different field levels. Such magnets exhibit smaller horizontal rigidity, however their training behaviour was quite similar to those with a well closed gap.

B. *Coil pre-stress during collaring and assembly*

In general, the magnets tested had after assembly a "standard coil pre-stress" maintained in the range of 48 to 76 MPa for both coil layers, both for single and double aperture models. Two magnets have been assembled with a deliberately low coil pre-stress, in order to check whether such a decrease of coil pre-stress results in any change of the training performance of the magnets.

Table 1 shows a comparison of the coil pre-stress for the four groups of magnets, where for the first group average values for 16 models are given. For this group the efficiency of collaring, defined as a ratio of the remaining stress after collaring to the maximum stress under collaring press, is around 50 % for both layers. Finite Element calculations [6], predict here the values of 55/65% (inner/outer layer) as an upper estimation, made for nominal dimensions of assembled pieces and assuming that no overload is applied during collaring. The lower practical efficiency may be also explained by creep of the coils, slight but observed in some magnets, with the relaxation of coil pre-stress by some MPa, mainly just after the collaring. For the double aperture magnets this efficiency is much higher (60-72%), due to a special two-step collaring procedure. It is also higher (63%)

TABLE 1

Magnet Group	Coil Layer	Under Press	After Collaring	After Assembly	At 1.8 K	Unloading Rate
		MPa	MPa	MPa	MPa	MPa/kA^2
1 (16mod.)	inner	116	57	62	49.5	-0.20
	outer	119	63	65	48	-0.11
2 (S9.V1)	inner	61	31	35	19	-0.31
	outer	93	55	55	38	-0.11
(S9.V2)	inner	79	39	45	32	-0.32
	outer	93	49	53	36	-0.14
3 (S3.V4)	inner	170	108	109	42	-0.20
	outer	206	130	133	60	-0.12
4 (T1.V1)	inner	112	68	73	57	-0.23/-0.34
	inner	84	54	51	38	-0.12/-0.15
(T2.V2)	inner	106	75	78	60	-0.24/-0.33
	outer	86	62	60	47	-0.12/-0.15

for the magnet with stainless steel collars, more rigid and therefore ensuring a smaller spring-back. During yoking and final assembly of the outer cylinder the pre-stress in the coils increases for all the types of magnets, as a rule by some 7 MPa (and exceptionally more), usually slightly more for the inner layer.

C. Coil pre-stress upon cool down

At 1.8 K the measured coil pre-stresses decrease for all the magnets tested. The loss of pre-stress is higher than predicted ([6,7]), and may be due to a high thermal contraction of the tested coils, greater than assumed on the basis of preliminary tests. More systematic tests are being performed now to verify these results, also by cross-checking the relative precision of the coil pre-stress measurements under cool down conditions. For the magnet with steel collars the measured loss of pre-stress is particularly high (67/73 MPa for inner/outer layer), due to a low thermal contraction of the collar material (high-manganese steel).

D. Coil stress during current excitation

Under electromagnetic forces the coil-collar clamping pressure, referred here as "coil stress', decreases, unloading the collar. For most of the magnets tested this unloading was approximately linear with current squared. Complete unloading was observed for the inner coil layers of the two magnets with deliberately low initial pre-stress, but tendency toward such an unloading was also visible for some magnets with the low "standard" coil pre-stress.

The observed unloading rates for the four groups of tested magnets are given in Table 1. In general, the unloading rates for the inner layer are approximately twice that for the outer layer. FE calculations [6,7] predict here nearly equal rates for both layers (of the order of –0.17/-0.20 MP/kA^2 for the single/double aperture magnets with Al collars). Lower observed rates for the outer layer may be explained by frictional effects influencing the displacements of the layer, neglected in the FE analysis. Further, the observed unloading rates are higher for the magnets with lower pre-stress at cold. This is visible for the "low pre-stress magnets", but also for some recently tested standard magnets which have the unloading rates close to –0.26/-0.13 MP/kA^2, as presented in Fig. 3 for the magnet MBSMS11.V1, where under high currents the inner layer is close to the unloading. Such a complete unloading at a current of 10.5 kA (7.7 T) is clearly visible in Fig. 4 for the low pre-stress magnet MBSMS9V.2. It is worth pointing out that, in spite of the complete unloading of the inner layer at low currents, both low pre-stress magnets showed correct performance and quenched only at much higher fields. The unloading rates of the double aperture magnets are also relatively high and the coil halves unload in an asymmetric way within each aperture; the side halves of the coils have much higher unloading rates, up to –0.34 MPa/ kA^2 , than the central ones, Fig. 5.

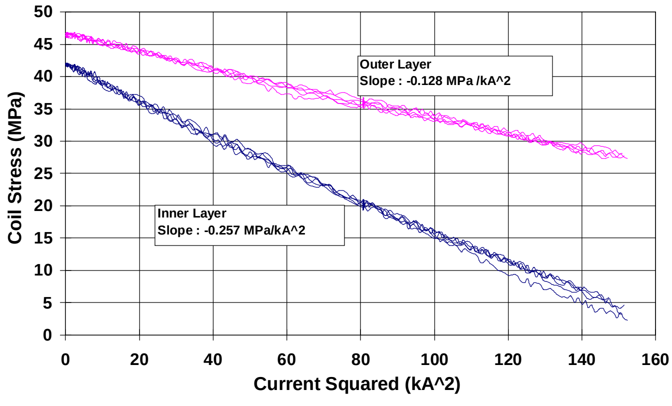

Fig. 3 Coil stress during excitation – magnet MBSMS11.V1

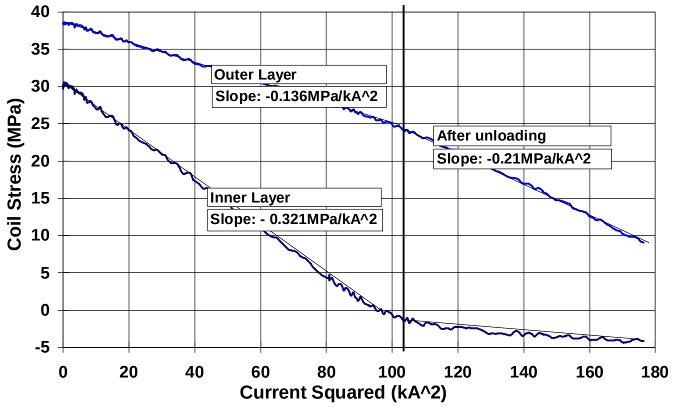

Fig. 4 Coil stress during excitation - low pre-stress magnet MBSMS9.V2

E. Evolution of coil pre-stress during training

Fig. 6 shows a rather typical evolution of the average coil pre-stress measured throughout the magnet training at zero current after each quench. Usually, the changes in the coil pre-stress are small, however, with a visible tendency toward gradual increase of the outer coil stress, at the expense of the slightly decreasing stress of the inner layer, the tendency confirmed by re-distributed stress values after warm-up of the magnet. This re-distribution is probably caused by an

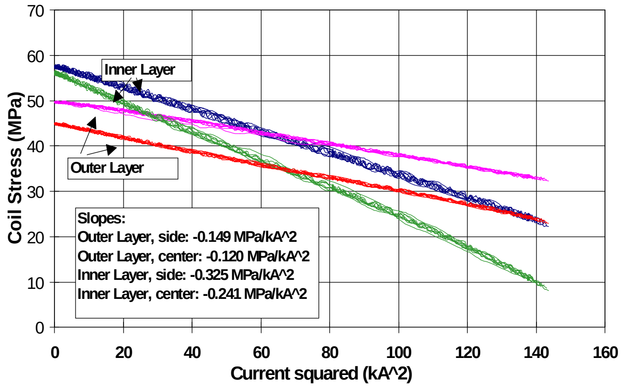

Fig. 5 Coil stress during excitation – double aperture magnet MBSMT2.V1

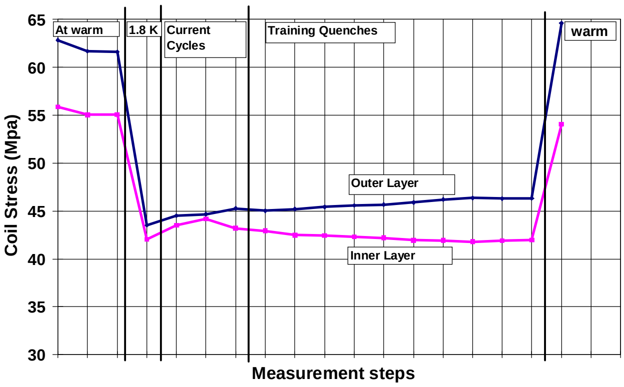

Fig. 6 History of coil pre-stress at zero current – magnet MBSMS11V.1

outward radial “settling-down” of the coil. This has been tentatively confirmed by recent measurements of the radial pressure between the inner layer and the collar part adjacent to the second layer. Gradual increase of the radial pressure was observed after each current ramping or quench, up to a certain saturation level. Such measurements will be continued for subsequent magnets.

C. End axial forces

The magnets were assembled with the initial compressive axial pre-loads in the range of 22 to 40 kN per aperture, typically close to 32 kN. The applied axial pre-loads, based on the experience with previous magnets, are small and should ensure a correct contact of the coil ends with the end magnet plates at cold. Upon cool down this pre-loads decrease, as a rule, by some 8 to 15 kN. During current ramping the axial electromagnetic forces transmitted to the end magnet plates, registered by “bullet” gauges, increase linearly with the current squared, Fig. 7. Typical increase at 12 kA (8.65 T) is of the order of 17 kN per bullet or 34 kN per aperture, i.e. about 17 % of the total axial electromagnetic force of 200 kN per one aperture. During the training the axial pre-loads registered by bullet gauges at zero current are, as a rule, changing only slightly, first gradually increasing, and then stabilising. This increase, signifying outward coil micro-movements (or “ratcheting”) against the clamping forces of the collars and friction, is sometimes interrupted by a backward “jump”, registered for example for the magnet MBSMS12V.1 and shown in Fig. 8.

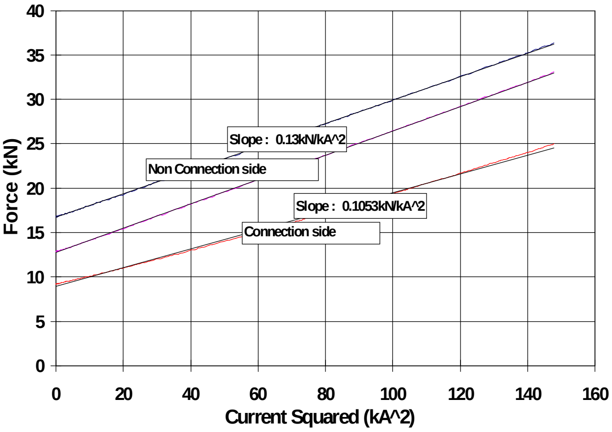

Fig. 7 Signals of axial load cells during excitation – magnet MBSMS12.V1

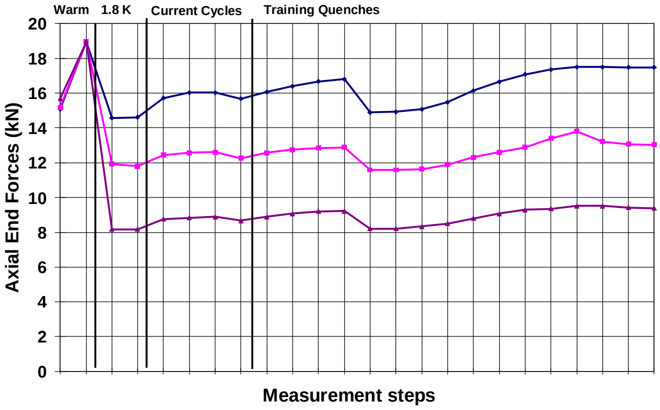

Fig. 8 History of axial load cells at zero current – magnet MBSMS12.V1

IV. CONCLUSIONS

The mechanical measurements of the short dipole models have been primarily introduced to control and optimise the assembly parameters of the magnets. As such, they have been found very useful, providing also a valuable insight into mechanical behaviour of the models during power tests. This behaviour is rather uniform for the whole series tested and consistent with the basic design predictions. The measurements also reveal some points where further analysis and tests are necessary to better understand the performance of the magnets; in particular, the loss of coil pre-stress at cold should be verified and the unloading rates of coil/collar pressures under electromagnetic forces, for some magnets higher than expected, should be further studied.

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