EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN AT/95-17 (MA)
LHC Note 329

Mechanical Performance of a Twin-Aperture 56 mm bore 1 m Long Dipole Model Made with SSC Type Cables

J. Buckley, M. Karppinen, G. Kirby, T. Kurtyka, D. Perini, A. Poncet,
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A twin-aperture dipole model made with standard SSC cables was launched to initiate studies of lower field magnets for a 7 TeV collider machine. This model, which was entirely constructed at CERN, reached at 1.8 K a peak field of 9.7 T. Short mechanical models, made to check the assembly parameters, as well as the final model magnet were instrumented with mechanical force transducers based on strain gauges to monitor azimuthal stresses and axial forces in the coils during assembly, cooldown and excitation. Dynamic measurements of forces and temperatures during magnet quenching were also performed with a high sampling rate acquisition system. This paper reviews the magnet mechanical design principles, describes the design, fabrication and the calibration of the force transducers and presents the main results of the measurements.

Magnet Technology Conference (MT14), 11-16 June 1995, Tampere, Finland

Geneva, Switzerland
3 November 1995

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J. Buckley, M. Karppinen, G. Kirby, T. Kurtyka, D. Perini, A. Poncet, T. Siambanis, N. Siegel, I. Vanenkov
CERN, CH-1211 Geneva 23

***Abstract*—A twin-aperture dipole model made with standard SSC type cables was launched to initiate studies of lower field magnets for a 7 TeV collider machine. This model, which was entirely constructed at CERN, reached at 1.8K a peak field of 9.7 T. Short mechanical models, made to check the assembly parameters, as well as the final model magnet were instrumented with mechanical force transducers based on strain gauges to monitor azimuthal stresses and axial forces in the coils during assembly, cooldown and excitation. Dynamic measurements of forces and temperatures during magnet quenching were also performed with a high sampling rate acquisition system. This paper reviews the magnet mechanical design principles, describes the design, fabrication and the calibration of the force transducers and presents the main results of the measurements.**

I. Introduction

The LHC, a 7 TeV proton collider machine, will consist of high field superconducting magnets installed in the existing LEP tunnel at CERN. Several short and long dipole model magnets with 50 mm aperture and 17 mm wide cable have been made in industry and tested at CERN [1]. The construction of a double aperture dipole model with a 56 mm aperture, made with SSC type cables was launched to initiate studies of lower field and wider aperture dipole magnets using smaller size cables. The coils are made in two layers, assembled in separate non-magnetic austenic steel collars, placed in a yoke which is split along the horizontal symmetry plane and held together by a bolted outer stainless steel shell. The design and construction of this model, so-called MBTRA, is reported in detail in a companion paper in this conference [2]. The mechanical calculations are discussed in [3].

This paper is concerned with the mechanical behaviour of this 1 m long model during assembly and cold tests. It describes also the collaring tests done with short mechanical models to determine the assembly parameters.

The azimuthal coil stresses were measured with special instrumented collars chosen in view of their reduced interference with the mechanics of the magnet. The design, fabrication and calibration of these instrumented collars are described below. The axial load in the coil ends, the closing of the midplane gap, and the shell tension were also measured with strain gauges. The cold test results are mainly based on the static measurements, but the dynamic response of the instrumentation is also briefly discussed.

Manuscript received June 12, 1995

II. Instrumentation

The instrumented collars which were developed for this application are shown in Fig. 1. Both apertures of the magnet were equipped with four instrumented collar packs, one placed in the standard straight section using collar type A and others in the jump/splice-section and in the coil ends using collar type B. A standard measuring pack consists of four instrumented collar laminations of type A with a pair of strain gauges glued next to the pole edge of each layer. On the outer coil layer a dual-grid rosette (HBM XC11-3/120) was mounted on each side of the collar lamination and wired in a six-wire full-bridge configuration. This provides an automatic temperature and magnetic field compensation. To give a uniform azimuthal stress distribution, 10 mm long slots were machined on both sides of the measuring bridge. On the inner layer a slot in the collar 'nose' acts as a spring giving a principle stress component in the radial direction. In this location two single-grid gauges (HBM LC11-3/350) were mounted and connected using four-wire quarter-bridge technique. Due to the limited number of connections available in the test cryostat the two inner gauges were connected in series. The gauges for compensating the magnetic field were mounted on a 0.7 mm thick "floating" steel plate placed in a 1 mm deep groove made in the facing collars.

The load calibration of the standard instrumented half collar packs was carried out on a small collaring press

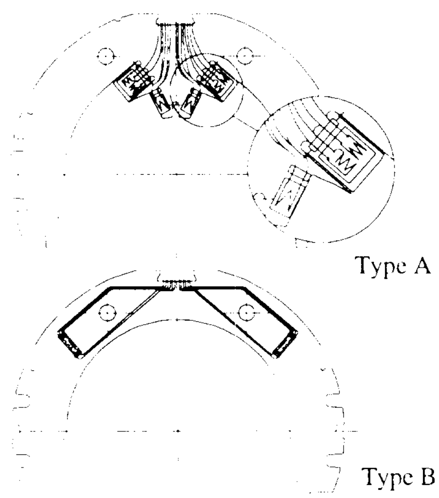

Fig. 1 Standard (Type A) and round (Type B) instrumented collars

simulating the real cross-section of the magnet using 100 mm long coils. Pressure was applied separately on each coil layer and a fourth order polynomial was then fitted on the loading and unloading curves.

Each instrumented standard collar pack had two carbon-resistors for temperature measurement. The collar packs were cycled 4-5 times to liquid helium temperature and then slowly cooled down to 1.6 K recording the apparent strain of the strain gauges and the signal from the carbon-resistors. A least square polynomial fit was applied to the measured data. This was then used to compensate for the temperature variations.

The round instrumented collars in the jump/splice-section and in the coil-heads had four small strain gauges (HBM KY41-2/120) on each side, wired in quarter-bridge configuration to measure azimuthal and radial stresses in the collar legs. Due to the grid material (Konstantan) they were used only at room temperature.

Eight axial compression load cells (so-called bullet-gauges) were mounted to measure axial loads on the ends of the magnet. Each cell comprises two active and two compensating gauges in serial four-wire quarter-bridge configuration. The closing of the midplane gap was monitored with two displacement transducers placed in a groove between the yoke halves. Strain gauges (HBM DB1-150 and LC11-6/350) were also used to measure the azimuthal strain in the outer cylinder.

III. Collaring Tests on Short Mechanical Models

A number of 90 mm long instrumented collar assemblies were made to define the assembly parameters and to study the elastic relaxation of prestress after the collaring and after cooldown to 77K. The first pack had four instrumented collar laminations whereas in the second and third pack pre-calibrated beam transducers were used to cross-calibrate the standard instrumented laminations and to verify the loss of pre-stress at liquid nitrogen temperature. The fourth pack was an asymmetric combination of standard (A-type) and round (B-type) half packs. The latter was used to calibrate round measuring collars for the 1m model and to determine the pole shims for the jump/splice-section of the magnet.

These tests showed that the loss of prestress after collaring was 20-25/23-27% (Inner/Outer) and after cooldown to 77 K the prestress was further decreased by 25-34/28-35 MPa (Inner/Outer).

IV. Mechanical Measurements During Assembly

Throughout the assembly of the magnet mechanical measurements were made. The typical coil stress history for both apertures is presented in Fig. 2 and 3.

A. Collaring

The collars were loaded with a vertical pressure until the key ways were aligned. The tapered keys could then be partially inserted. A set of horizontal hydraulic cylinders then pushed the keys firmly into position. This resulted in a small increase in the coil prestress. The pole shims were adjusted as a result of the first collaring trials and then both magnets were successfully collared. The significant steps for both apertures are compared in Table I. The values for the jump/splice-section and for the coil ends are average values for both coil layers. During collaring inner and outer layers were compressed to 146 MPa and 104 MPa respectively. The loss of azimuthal stress due to spring back was 54-58 MPa for the inner layer and 30-35 MPa for the outer layer. There was a further relaxation of the coil prestress between collaring and yoke assembly. Roughly 50% of loss in prestress occured already during the first 24 hours after collaring. From then on the relaxation rate was much smaller and continuously decreasing. The prestress lost was about 12-17 MPa (-15 %) and 7-8 MPa (-11 %) in the inner and outer layer respectively. This can be assigned to the flow of the insulation material from the higher compressed regions [4].

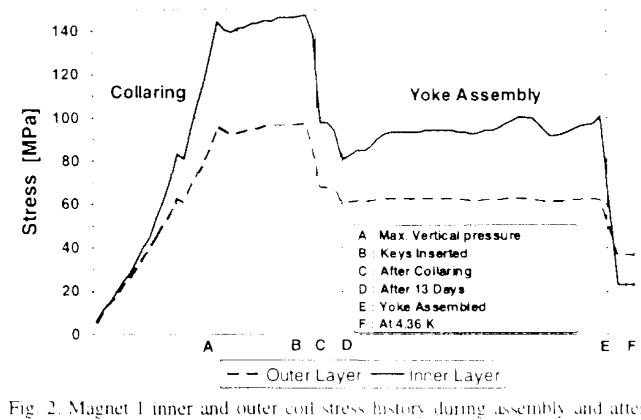

Fig. 2. Magnet 1 inner and outer coil stress history during assembly and after cooldown to 4.36 K.

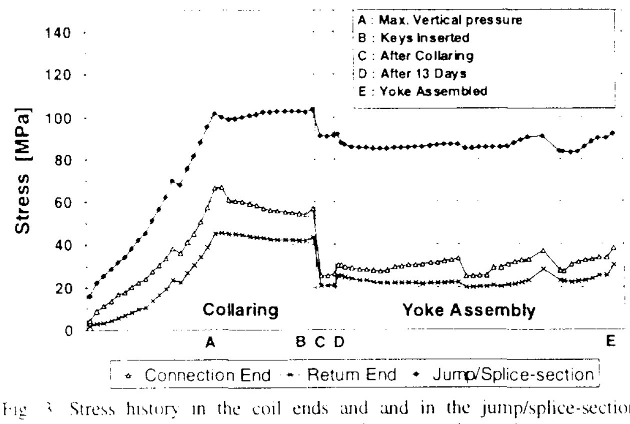

Fig. 3. Stress history in the coil ends and and in the jump/splice-section Vertical scale is average azimuthal stress in the inner and outer layers.

TABLE I
AZIMUTHAL COIL STRESS IN 1ST / 2ND APERTURE FOR SIGNIFICANT STEPS IN MPa

Step	Inner Layer	Outer Layer	Jump/ Splice	Connection End	Return End
Keys inserted	147/146	97/104	102/93	54/55	42/65
Vertical press released	98/88	67/69	91/86	25/31	31/35
Prior to yoke assembly	81/76	61/61	87/82	30/34	25/30
After yoke assembly	101/99	62/63	90/82	34/41	25/35
1st Cooldown 4.36K	(23/25)	37/39		-	-
1st Warm up (293K)	89/100	61/63		-	-
2nd Cooldown (1.72K)	(28/30)	35/38		-	-
2nd Warm up (293K)	91/98	62/64	-	-	-

B. Yoke Assembly And Cooldown To 4.3K

There is a radial-horizontal interference between the collars and yoke of about 0.10 mm, which extends over ±20° about the median plane. This ensures a rigid structure to support the horizontal electromagnetic forces. The bolted stainless steel shrinking cylinder was tightened up to give enough pre-compression to close the midplane gap at ambient temperature. After tightening of the bolts the shell tension was about 140 MPa.

The midplane gap remained slightly open in two positions where stainless steel keys were spot welded to align the collar-yoke shims during the assembly. After cooldown the gap was firmly closed along the whole length. During the yoke assembly the inner and outer layer prestress increased by 18% and 3% respectively. The prestress was then within the target range before the cooldown. Compressive axial preload of 20-22 kN/magnet was applied to the coil ends.

The loss of coil pressure due to cooling down to 4.3 K was 25 MPa in the outer layer. Inner layer gauges showed a much larger loss (75%) caused probably by the coil layers sticking together. This shifted the position of the resultant force against the pole radially outwards. The orientation of the inner layer gauges makes them very sensitive to bending, which may explain the large unloading. The average loss in end forces due to cooldown was 1.1 kN in the connection end and 2.7 kN in the return end.

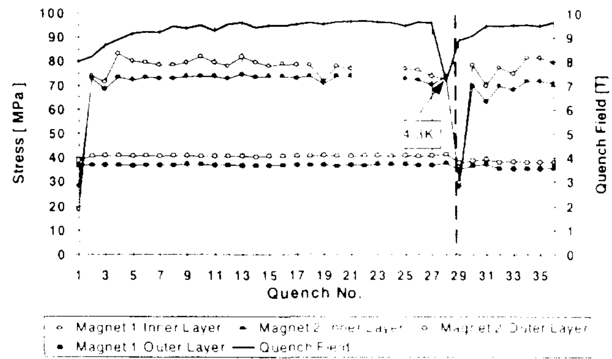

Fig. 4. Cooldowns 1 and 2, average coil stress before quench (I = 0 A) compared to quench field

V. MECHANICAL BEHAVIOUR DURING CURRENT EXCITATION

Coil pressures and end forces were measured during the excitation of the magnet. The collar strain gauges are submitted to large magnetic fields and the Kondo-effect of Karma-alloy [5] gauges are severely dependent on small changes of temperature below 4.3 K. Substantial noise was observed on signals from gauges connected in a quarter-bridge configuration. Inner layer gauges were the most affected since they are in the high field region and the compensating gauge is placed about 20 mm apart in slightly different orientation with respect to the field. The wire connecting the nose and bullet gauges in series provided a loop, ie. pick-up for a.c. noise. Therefore, for the inner layer gauges only the readings before current ramping gave useful information. The outer layer gauges performed considerably better since the noise is balanced out in the full-bridge configuration. The azimuthal stress history for both cooldowns is shown in Fig. 4 before the current excitation, and compared to the quench field. The signal from the displacement transducers between the yoke halves showed that the mid-plane gap remained closed during the excitation, which confirms the FE-calculations [3].

A. Outer Layer Gauges

Except for a small increase of 2-3 MPa after the first quench for both cooldowns there was no change in zero current prestress of the outer layer (Fig. 4). The prestress decreases during the ramping up of current. We observed a somewhat nonuniform unloading rate, above 5.5 kA (Fig. 5). This may be due to a local build up of elastic strain energy during cooldown, released after the first quench. It was not repeated after the thermal cycle.

The prestress loss was faster at higher currents before quenches 5 and 6, which could be attributed to "sticking" between inner and outer layer or outer layer and collars. The observed unloading rate (-0.35 / -0.39 MPa/kA^2, 1st / 2nd aperture) was higher than in the MTACERN model (-0.14 MPa/kA^2) [6] or SSC 17 m magnets (-0.23 MPa/kA^2) [7], but lower than in the SSC short 1.5 m models (-0.55 MPa/kA^2)[8]. The unloading of the outer layer illustrated in

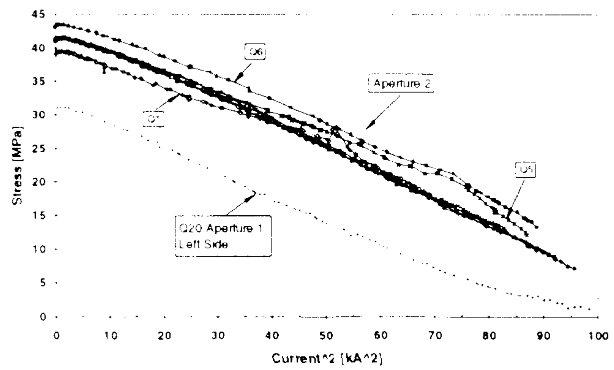

Fig. 5. Outer coil average stress in the second aperture vs. I^2 for some training quenches after the first cooldown. The lower curve for the left side of the first aperture shows the unloading above 9.7 kA.

Fig. 6 shows the curve flattening out, such as when prestress approaches zero. However, the magnet did not quench in these regions which indicates that clamping at high excitation levels was sufficient.

B. Inner Layer Gauges

Fig. 4 shows a marked redistribution in the coil stress after the first quench for both cooldowns. The initial prestress increased from 20/30 to about 70/80 Mpa, which could partly be explained by the characteristics of the instrumentation.

C. End Forces

Fig. 6 illustrates the evolution of axial forces in the return end before current excitation for both cooldowns. After each quench there was a gradual increase in the force measured on the bullet gauges at zero current as quench current increases. This suggests that due to a stick-slip motion the collar assembly moved longitudinally outwards during current excitation, but did not move back to exactly the same position after the quench ("ratcheting"). This phenomena was not observed in the MTACERN model where the axial loads did not change.

The compressive end force increased linearily with I^2. The loading rate in the connection end and in the return end were slightly different (0.15 kN/kA^2 connection end, 0.18 kN/kA^2 return end, 0.15 kN/kA^2 MTACERN, 0.30 kN/kA^2 SSC 17 m) [6],[7].

Table II compares the forces excerted on the end plates after the assembly and during the two thermal cycles. The loads increased by about 4 kN in each aperture during the first thermal cycle and remained almost unchanged after the second test campaign.

D. Dynamic Measurements

Four strain gauge bridges on the outer layer and one carbon gauge were connected to a fast (9600 meas/sec) acquisition system with a pre-trigger to measure stress and temperature on the collars during a quench. To reduce the electromagnetic noise (high dB/dt and dI/dt) induced in the

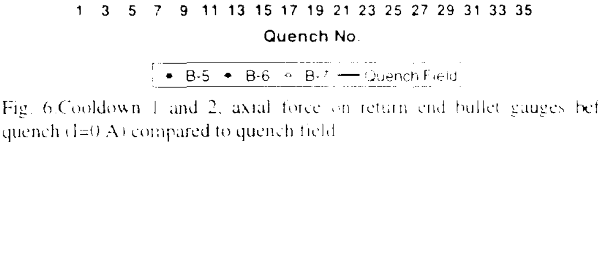

Fig. 6 Cooldown 1 and 2, axial force on return end bullet gauges before quench (I=0 A) compared to quench field

TABLE II
FORCE MEASURED WITH BULLET GAUGES IN kN IN CONNECTION (1-4) AND RETURN END (5-7)

Bullet	B1	B2	B3	B4	B5	B6	B7
Assembly (293K)	10.3	9.3	8.9	9.3	12.3	11.6	13.4
1st Cooldown (4.36K)	8.8	8.1	8.3	8.1	10.8	7.6	10.8
1st Warm up (293K)	12.9	11.7	10.7	11.3	14.7	13.8	15.2
2nd Cooldown (1.72K)	11.7	10.5	10.3	10.4	13.7	10.9	13.6
2nd Warm up (293K)	11.3	11.0	10.3	10.8	14.1	13.3	13.9

measuring circuits, an excitation level of 2.5V/4.8kHz was used for dynamic measurements while 0.5V/600Hz was used for the calibrations. Therefore only the relative behaviour was considered.

In training quench 33 located next to the jump/splice-section in the outer layer of the second aperture, mechanical vibrations were observed about 25 ms before the quench. After the energy extraction was initiated the change of coil prestress was linear with decaying I^2. The temperature on the collar 'nose' rose to about 20 K in 50 ms after the quench, then to recool below the lambda-point took some 30 seconds.

Mechanical impact tests at ambient temperature were made, but no correlation to quench induced frequencies could be found.

VI. CONCLUSIONS

The instrumentation developed for this model allowed optimization of: coil shims, assembly parameters of the magnet, and monitoring of stresses and forces during assembly and testing. Good results were obtained with the outer layer gauges, showing linear prestress loss with I^2, and partial coil unloading above 9.7 kA, which did not affect the quench performance. Due to limited space the signal of the first layer gauges was not reliable during current excitation, which is being improved for subsequent models. The ratcheting observed in the ends of the magnet did not have any adverse effect on the magnet operation.

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