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MECHANICAL BEHAVIOUR DURING EXCITATION OF THE FIRST CERN 10 T DIPOLE MODEL MAGNET FOR LHC

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Abstract

In the frame of its current Superconducting Magnet R & D Program for the LHC collider, CERN has recently assembled and tested a 1 m long twin aperture model dipole in superfluid Helium, up to a record field of 10.5 T.

The magnet had been fully instrumented with mechanical force transducers, calibrated at 1.9 K, to measure azimuthal coil pre-stresses and magnet end-forces during assembly, cooldown and excitation. After a review of the mechanical design principles of the magnet, the transducers based on strain gauges are briefly described, and the results of the measurements taken during the various assembly phases and magnet excitations are presented.

1. INTRODUCTION

As part of the R & D effort for LHC [1], CERN has undertaken in 1992 the construction of 1 m long, full transverse scale, twin aperture models of different mechanical structures and cables.

The first model assembled at CERN, called MTACERN, followed a series of four models built in Industry (MTA) [2]. It used Industry-made identical coils wound with a 17 mm high cable of slightly improved critical current density, and with somewhat better end compacting. If the previous twin aperture models had common collars, the MTACERN follows the recommendations of the 1991 External Review Committee and investigates the design of separate collared coils in a common yoke. The magnet was fully instrumented with mechanical transducers ("beam" and "bullet" type gauges) and strain gauges, calibrated at superfluid helium temperature, in order to follow up its mechanical behaviour from assembly (collaring and skinning), cooldown to 1.9 K, and under the action of Lorentz forces. This magnet reached 8.1 T at 4.2 K without any training. It reached 10 T at 1.9 K after 6 quenches and 10.5 T after 15 quenches. After a thermal cycle, the first quench was at 9.7 T [3]. All quenches originated in coil end parts and layer jumps.

2. MAGNET MECHANICAL DESIGN AND INSTRUMENTATION

Figure 1 shows the cross section of the twin aperture dipole.

The two layer coils of 50 mm aperture are collared in separate stainless steel collars (O.D. 185 mm, I.D.120 mm) and are located 200 mm apart in the yoke. The room temperature (RT) pre-stress is 90-100 MPa for the inner coil, 70-80 MPa for the outer one. The stainless steel is a cold worked AISI 316LN having a $\sigma_{0.2}$ = 450 MPa at RT. Tapered lateral keys were used in the collaring and the overall stress on the coil during collaring was minimised by using both vertical and horizontal force when inserting the keys. The two collared coils are mounted in an O.D. 580 mm yoke, built in 3 parts. An horizontal interference of 0.4 mm per magnet at RT is included in the relative dimensions of the collar O.D. and yoke I.D. This interference, reduced to 0.2 mm after cooldown aimed at ensuring a very tight horizontal line to line fit between collars and yoke at 1.9 K. The yoke gaps are kept closed at RT by the high tension (200 MPa) of the stainless steel outer shell (316 LN, 10 mm thick), welded from two parts closed by a special press. A slot in the polar nose of the collars is provided to limit the inner coil pre-stress within acceptable values after closing the yoke. End plates of 50 mm thickness are designed to sustain the axial forces of 770 kN.

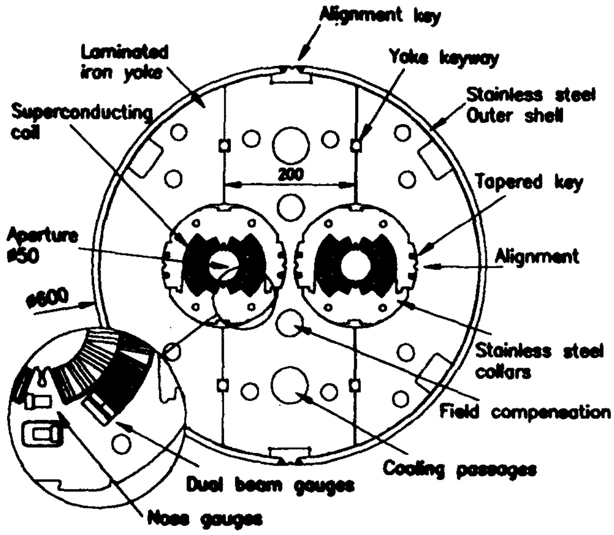

Figure 1. Cross-section of the MTACERN model magnet

The magnet was equipped with two special collar packs (one per aperture), each comprising four dual beam transducers to measure pole-outer coil pressure and its radial gradient, and two central nose gauges to measure the inner coil-pole pressure. Special bolts ("bullets") equipped with strain gauges were mounted against the end coils (4 per coil) in the 50 mm end plate, to measure axial Lorentz forces. MM.WK.09.250 BG.350 gauges were used. Gauges and transducers were calibrated at 300,77,4.2 and 1.9 K on a special machine [4]. They were mounted in the magnet with compensation gauges, used to correct for parasitic temperature and magneto-resistance effects. A four wire, quarter bridge measurement technique was used.

3. MAGNET BEHAVIOUR DURING ASSEMBLY AND COOLDOWN

The force transducers were used to monitor the coils-pole contact forces (or coil pre-stresses) during the collaring phase, yoke assembly, welding of the magnet shell and cooldown. In addition some data was taken to assess the coil pre-stress relaxation at RT as a function of time. Figure 2 shows a typical coil pre-stress history during the various assembly phases.

The pre-stress loss after releasing the press is on average 27%; this springback loss could have been further reduced by applying more horizontal force during keying. Relaxation of pre-stress after collaring due to insulation and cable strand creep is noticeable during the first 24 hours and amounts to between 3 and 5% [4].

The stress increase generated by the yoke assembly process, during which the collared coils are deformed due to the designed horizontal interference, varies between 4 and 15% for the outer coils depending on the magnets. The change is larger for the magnet with less initial pre-stress; yoking re-equilibrates the pre-stress, which for the outer coil is consistently higher on its inner radius due to the horizontal line to line fit. After cooldown the pre-stress loss of the outer coils is 30-40 MPa (~ 30%). At RT, the Young's Moduli of the coils are around 28 GPa. Measured with nose gauges (uncalibrated), the behaviour of the inner coils is similar to outer coils, but with much smaller stress variations (15% after collaring, 10% after cooldown). This is due to the loaded-spring behaviour of the slotted nose of the inner poles : its springback potential is large enough to maintain high coil-pole pre-stress, in a very beneficial way, despite the large difference in stainless steel and coil thermal contraction coefficients.

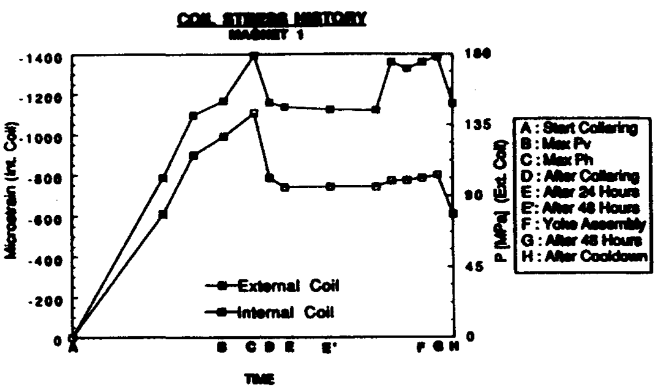

Figure 2. Typical coil pre-stress history during the various assembly phases

4. MAGNET BEHAVIOUR DURING EXCITATION

During its testing campaign (training, rate dependence measurements, energy extraction studies, etc.), the magnet experienced 65 quenches in two cooldowns. Figure 3 shows the evolution of the average initial pre-stresses before excitation (I=0) for the inner and outer transducers of the outer coil of one magnet as a function of the quench number. Quenches 1, 2, 8, 9, 42, 43, 45 occurred at short sample limit at 4.5 K. Between quenches 9 and 10, the magnet was warmed up at RT to tighten the end "bullet" gauges. Training resumed at quench 10 and at 1.8 K.

A few observations can be made from figure 2. After the first quench following a magnet warm up, the pre-stress loss is ~ 10 MPa on the outer transducer of the outer coil and 5 to 6 MPa on the inner transducer. An apparent difference of 3 to 4 MPa in pre-stress between 4.2 and 1.9 K can be inferred from the gauges signals. From compensation gauges readings at 4.2 and 1.9 K, half of this value can be attributed to a yet unexplained behaviour of the gauge. The rest of the loss in pre-stress (~ 2 MPa) between 4.2 K and 1.9 K seems to be real (the gauges relative accuracy being better than 1 MPa). During subsequent training at 1.8 K with increasing quench field, the pre-stress continues to decrease in small erratic steps. This behaviour could perhaps be due to an hysteresis in the coil motion under Lorentz Forces due to friction; under excitation the coil could move towards the mid plane causing loss of pre-stress and friction on the collaring shoe could prevent it from springing back to its original position after quench. The same cause could explain the large initial drop in pre-stress after the first quench following a warm up.

Similar observations can be done of the pre-stress at different current levels in the magnet [5].

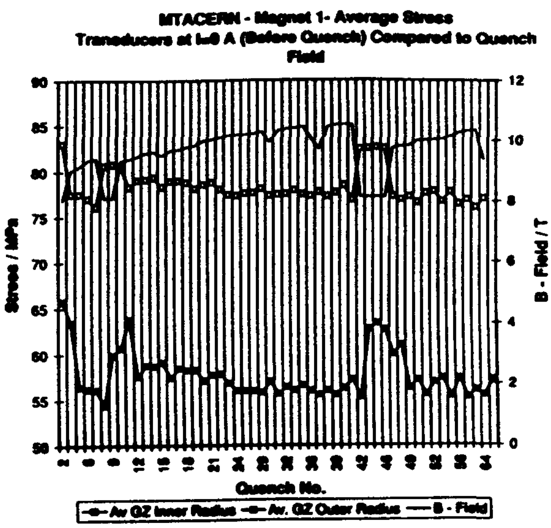

Figure 3. Initial pre-stress loss with quenches

5. COIL UNLOADING WITH EXCITATION

The beam transducers show that the outer coils unload in a uniform manner, in which pre-stress relaxation is proportional to I^2 (i.e. the Lorentz Force). From the unloading characteristics, it is clear that collars and yoke maintain contact at all field levels. However for some outer coil transducers the unloading gradients vary after quenches (figure 4), and thermal cycles. Some show very small gradients, i.e. almost negligible unloading.

Also, the inner part of the outer coils shows a consistently larger unloading gradient (0.09 MPa/KA^2) than the outer part of the same coils (0.05 MPa/kA^2).

These two observations are again consistent with a possible erratic frictional behaviour of the outer coil with the collaring shoe.

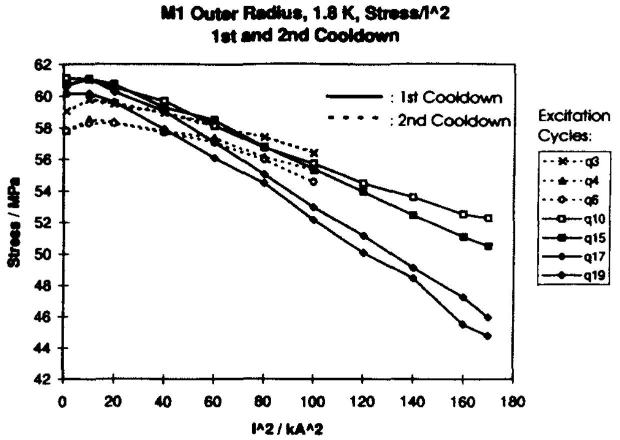

Figure 4. Outer coil typical unloading with excitation, for different training cycles and cooldowns

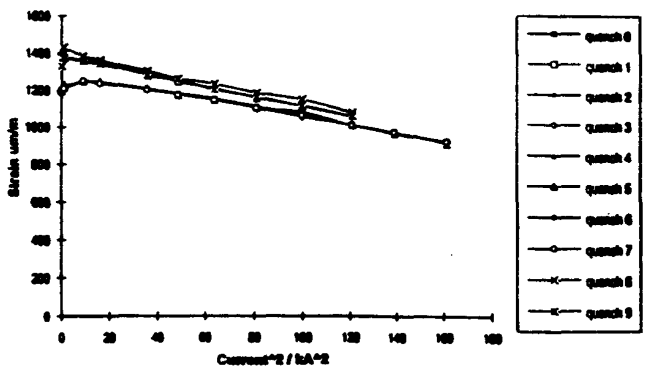

Figure 5. Inner coil typical unloading with excitation, for different training cycles

A similar behaviour is observed with the nose gauges reading the inner coil-pole pre-stress [4]. The inner coil unloading is only 20% of the full excitation range (0.09 MPa/MA^2). This weak unloading can also be attributed to the springback of the slotted nose.

6. MAGNET END FORCES DURING EXCITATION

During cooldown, the bullet gauges did not register any change of end forces. This is consistent with a magnet structure tightly constrained, not permitting differential coil-outer shell displacements. Figure 5 shows the response of the "bullet" gauges upon excitation of the magnet.

The registered force increase represents only 12% of the axial Lorentz force. There again, the very tight magnet structure explains the fact that axial forces are bypassed via collars and yoke to the outer shell.

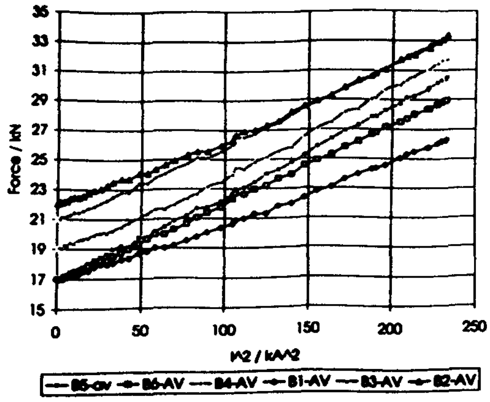

Figure 6. Axial Bullet gauge response with I^2

7. CONCLUSIONS

The mechanical force transducers developed for operation at 1.9 K, proved to be useful tools to understand the MTACERN magnet behaviour, both during assembly and excitation. They showed that high coil pre-stresses in a very tight and rigid magnet structure could be maintained reliably up to a record 10.5 T field. The rich harvest of measurements includes many interesting observations of possible coil motion during assembly, thermal and electrical cycling. In particular friction of the external coil on the collar structure could be a fundamental phenomena in explaining coil motion hysteresis, although this friction was not the direct cause of quenches (quenches originated only in the end parts of the coils).

Coil pre-stress unloading with increasing current was found very weak compared to SSC magnets [6]; this can be attributed to the high structural rigidity, high coil modulus and springback of the central polar nose.

8. REFERENCES

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