Performance of the First CERN-INFN 10 m Long Superconducting Dipole Prototype for the LHC

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Abstract

A number of 10 m long twin-aperture superconducting dipole prototypes have been manufactured or are under construction by European industry within the R&D program for LHC magnets. The first dipole was completed in January 1994 and tested in superfluid helium. The dipole surpassed 8.65 T, the nominal operational field of the LHC main dipoles, without quench. No retraining was observed after a thermal cycle to room temperature. After a brief recall of the main features of this magnet, the paper reports the main results of a completed measuring campaign. Quench behaviour and field quality are remarkably good.

1. INTRODUCTION

The experimental program on 10 m long LHC dipoles started in 1989-90. Thanks to a long term collaboration between CERN and INFN (the Italian Institute for Nuclear Physics), the CERN program was anticipated by 8 months in spring 1990 with the order of two dipoles financed by INFN to Italian industry including superconducting cables and 1.8 K cryostats [1]. The first dipole was delivered to CERN in January 1994 and the second in May 1994. Five other 10 m long dipoles will be delivered by other European manufacturers in the course of the year.

It is worth recalling that the design was not completed when the first dipoles were ordered. The only available experimental results were from the two 1m-long single aperture models manufactured with cable made with HERA type strands [2]. The first series of twin aperture 1 m long model were still under development, while the construction of the TAP magnet was not yet completed [3]. The construction of the cold mass of the first dipole was therefore also an R&D program carried out directly in industry. Some initial concepts had to be revised and a number of modifications were fostered by the results coming from the 1 m long models to arrive at the final design [4]. Perhaps more expensive and time consuming for a first prototype, this route largely avoids the phase of technology transfer to industry needed in case of in-house development as usually done in the past.

2. FROM DESIGN TO FABRICATION

The design principle has been described in [1,4,5]. Detailed analysis showed that very tight tolerances were required, both in the fabrication of the coils and of other critical components as collars and yoke laminations. Typical tolerances for these main parts range in the order of few tens of microns. The common collars made of Al alloy and the yoke laminations were obtained by precision punching.

The clamping of the coils in their Al collars required development work performed on 0.4 m long dummy coil-collar assemblies. The dummy coils were made with copper cables. They had the same geometry and rigidity at compression as the superconducting ones, permitting elastic modulus measurements and optimisation of coil winding and curing.

Magnet collaring was carried out under a press at loads between 6 to 10 MN per meter of press length. The average compressive azimuthal stresses in the coils at room temperature after collaring amount to 80 MPa in the inner layers and 55 MPa in the outer layers. The insertion of the collar locking rods was made with a clearance of only few tens of microns.

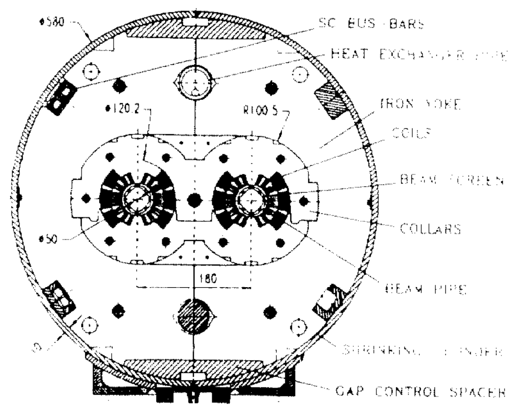

Fig. 1 Cross-section of the first full scale prototype (CERN-INFN 1)

3. BEHAVIOUR DURING THERMAL CYCLES

The magnet was thermally cycled three times from ambient to cryogenic temperature to help release the stresses locked by friction. Potentiometric displacement sensors indicated a symmetric and reproducible closure of the iron yoke gap between 150 K and 200K. The total stroke to close the gap amounts to 0.25 mm.

The thermal cycles were all performed with a conservative cooling/warming rate of about 15 K/h restricting the inhomogeneities of temperature in the transverse direction to below 10 K. As expected, strain gauges have measured a steadily increasing stress of the external shrinking cylinder during cool down. The total tensile stress increases by 140 MPa. The negligible variation (about 10 MPa) of the longitudinal stress correlates well with measurements performed on some 1 m long model magnets indicating that the longitudinal contractions and expansions of the structure are dominated by the shrinking cylinder.

4. POWER TESTS

To ensure proper protection of the magnet during quenches, the time interval between firing of the strip heaters and the transition of the outer layers of the coils was verified to be below 35 ms at 7 kA and 1.7 K. It was decided to further protect the magnet by performing the training quenches with energy extraction through a dump resistor of 40 mΩ. The 7 T/s decay obtained just after quench detection induces the transition in the inner layer in a similar time interval, helping even further an homogeneously distributed energy dissipation.

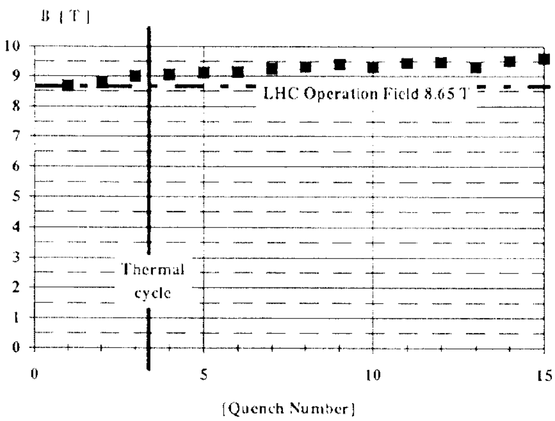

Fig. 2 Training curve at superfluid helium

The first quench occurred at a field of 8.67 T, slightly above the nominal field of the LHC. At the third quench the magnet reached 9 T. The magnet was then warmed-up to insert into the apertures the anti-cryostats needed for the magnetic measurements. Figure 2 gives the training curve including the quenches made after this thermal cycle, and shows that no retraining was observed. The training was stopped at 9.5 T.

These very encouraging results are comparable to the results obtained with the best performance of a 1m long model, illustrating that no additional difficulties arise when going from short model magnets to full length prototypes.

Quenches performed at 4.3 K give a conductor limit of 7.96 T. Scaling to 2 K places the conductor limit of the magnet at 10.3 T.

Together with the voltage taps at the connections between poles, a voltage tap was connected inside each pole on the inner layer conductor near the layer jump. They indicate that all the training quenches start in the splice region or in the outer layer. Preliminary analysis of the data obtained by the quench localisation coils [6] shows that most of the training quenches start in the layer jump/splice part although more refined data processing is needed. They nevertheless confirm the indication obtained with the 1 m long models that the layer jump-splice region needs improvement.

Quenches at the nominal field value of 8.65 T have been performed without energy extraction at the end of the test campaign, to ensure safe operation of this type of magnets when connected in series. The maximum value measured for the MIITS amounts to 34 MA^2s, giving a hot spot temperature of 225 K for the outer layer cable. The mid-point between the apertures rises to a maximum of 150 V with respect to magnet's terminals.

The average interstrand resistance of the inner layer cable is estimated by loss measurements to be about 1.4 μΩ. Although this value is comparable to that of one model magnet [7], the sensitivity to ramp rate of the 10 m long prototype is higher. The magnet quenches when going down from nominal field with a ramp rate of 0.1 T/s with a bath temperature of 1.95 K. Some margin is nevertheless available between a risk of quench and the decay rate needed to discharge in time a series of magnets when one of them quenches and is short circuited by diodes. A minimum decay rate (0.08 T/s) is necessary to avoid overheating of these bypass diodes.

5. FIELD QUALITY MEASUREMENTS

Differences in the field directions of both apertures would imply sorting the twin aperture magnets for installation in the accelerator or a more powerful scheme of correction dipoles. Although a global twist of 12 mrad had occurred during the assembly of the magnet over its length of 10 m (fig. 3), the measured average of the differences between the apertures is well below the present accuracy of 0.5 mrad of the magnetic measuring equipment.

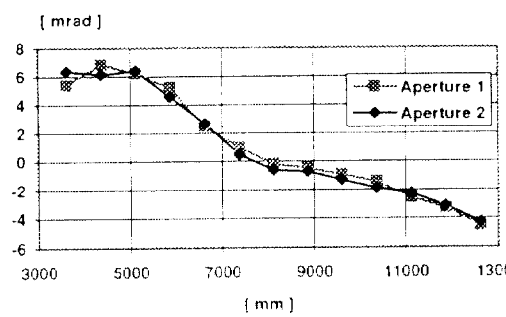

Fig. 3. Dipole field direction vs longitudinal position in both apertures at injection field level

The integrated dipole fields of both apertures are equal to better than 0.1 % (80.04 and 80.10 T*m at 12808 A or 8.65 T central field). Figure 4 presents in both apertures a weak but similar oscillatory behaviour with respect to longitudinal position.

Except for the skew quadrupole term, the variation of the field harmonics over the length and between apertures is within the specifications [8]. In fig. 5 the field errors are given up to the decapole term in 11 adjacent positions of both apertures. Figure 6 gives the sextupole term as a function of field level. The residual high field value is due to slightly larger thickness of the insulated cables than assumed in the design computations. The shimming of the coils-collars interfaces was optimised to ensure proper prestress disregarding the field quality for this first 10 m prototype.

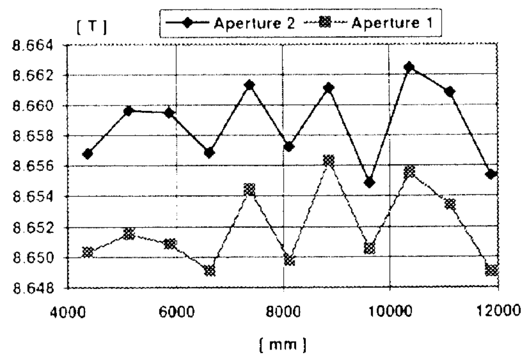

Fig. 4. Dipole field value vs longitudinal position in both apertures at 8.65 T

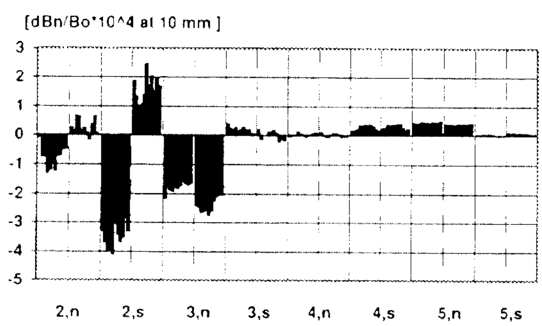

Fig. 5 Relative field errors for 11 adjacent 0.75 m long integrals in the straight part of both apertures at 8.65 T. The harmonics go from normal quadrupole (2,n)to skew decapole (5,s)

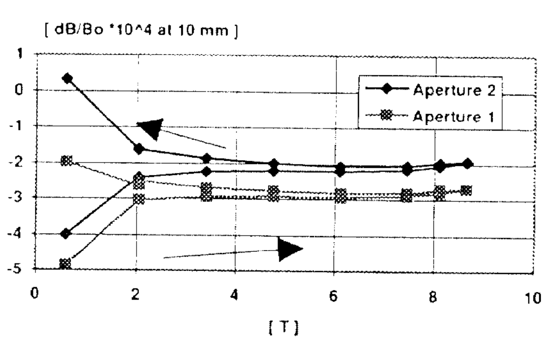

Fig. 6 Normal sextupole harmonic integrated over 0.75 m in both apertures as a function of field

6. CONCLUSIONS

The first LHC 10 m long prototype dipole magnet has been submitted to thorough tests concerning performances, protection, thermal aspects, and to accurate magnetic measurements. Some known weak points in the splice-layer jump region did not prevent the magnet to surpass the nominal field at the first quench. Field quality measurements indicate that this design with twin apertures and common collars meets the stringent specifications required by the LHC collider.

7. ACKNOWLEDGEMENTS

This test program has been efficiently and rapidly performed on a completely new test station. The invaluable competence and help of both the Cryogenic teams (AT-CR) and the Control Group (AT-IC) deserve our thanks. The continuous devotion from numerous members of the CERN Magnet group and help from INFN-Milan technicians allowed to meet the tight schedule.

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