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**Assessment of the tests results of the two CERN-INFN 10 m long
superconducting dipole prototypes for the LHC**

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In the first phase of the R&D programme for LHC dipoles, seven 10-m-long, 50-mm-aperture prototypes have been manufactured by European Industries. The first two prototypes, fabricated under a CERN-INFN Collaboration, were successfully tested in 1994. This paper provides a first assessment of the main test results of these two magnets, in particular for what concerns kinematics and evolution of the stress distribution in the magnet during cooldown, energization and warmup. The influence of some adopted technological solutions is also discussed. Based on test results, some design corrections are proposed for adoption in the design of the future 15-m-long LHC dipole prototype.

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Assessment of the Tests Results of the Two CERN-INFN 10 m Long Superconducting Dipole Prototypes for the LHC

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Abstract—In the first phase of the R&D programme for LHC dipoles, seven 10-m-long, 50-mm-aperture prototypes have been manufactured by European Industries. The first two prototypes, fabricated under a CERN-INFN Collaboration, were successfully tested in 1994. This paper provides a first assessment of the main test results of these two magnets, in particular for what concerns kinematics and evolution of the stress distribution in the magnet during cooldown, energization and warmup. The influence of some adopted technological solutions is also discussed. Based on test results, some design corrections are proposed for adoption in the design of the future 15-m-long LHC dipole prototype.

I. INTRODUCTION

An important phase of the R&D programme for LHC superconducting dipoles has been achieved with the reception and testing at CERN of the first two 10-m-long, 50-mm-aperture, prototypes. These two magnets were fabricated by the firm Ansaldo, under CERN design and technical responsibility, thanks to a collaboration between CERN and INFN. The latter, in addition to funding the magnets, was responsible of the procurement of the superconducting cables.

Each magnet was tested separately, prototype 1 in Spring 1994, prototype 2 in Summer 1994. The test results were excellent, proving that the design of these dipole magnets satisfies the LHC machine requirements. Before the end of 1994 the two magnets were installed into an LHC half-cell test string and tested in such a configuration. In December 1994 the CERN Council approved the LHC Project.

Results of testing of prototypes 1 and 2, as well as the half-cell string, are extensively described elsewhere [1], [2]. Only test results useful to assess the actual behaviour of the magnet with respect to its design are considered in this paper. In the next chapters a description will be given of the differences existing between these two prototypes, followed by an account of their behaviour during thermal cycling and energization. Finally an overall assessment will be given, together with some indications of the modifications proposed for the next, full length, LHC prototypes.

II. MAIN FABRICATION CHARACTERISTICS OF THE TWO PROTOTYPES

Prototype 1 required several modifications to its original design and took a long time to be developed and fabricated [3]. Nevertheless such a long development permitted to detect elements on which improvements could be made on prototype 2. That is why prototypes 1 and 2 have not been fabricated exactly using the same components and the same techniques. Table I lists some characteristics of the two magnets to allow a comparative assessment. It should be

however recalled that the design was the same for both prototypes, as well as the fabrication parameters, unless differently specified.

III. FIELD QUALITY

Measurements have been carried out on geometrical alignment and on field errors both at room temperature and at 1.8 K. Parallelism between the field vectors in the two apertures was excellent, with an error smaller than 0.2 mrad, i.e. at the limit of sensitivity of the measurement device [8]. The torsion (~10 mrad) present in prototype 1 was corrected and practically no torsion was observed in prototype 2.

In terms of field quality both prototypes showed multipole harmonics close to the design values in both apertures [8]. Better results have been achieved in this respect with prototype 2 in which improvements were implemented thanks to the experience made on prototype 1. The third prototype fabricated by Ansaldo (prototype 3 of this series) has shown even better results, with all harmonics within the specified errors [7] (except the dodecapole component) as shown in Fig. 1 for the first components. The obtained results and the clear trend of the "learning curve" indicate that the know-how exists to ensure the required field quality for the LHC dipoles.

TABLE I
SOME CHARACTERISTICS OF PROTOTYPES 1 AND 2

	Prototype 1	Prototype 2
Coils		
- Cable Insulation	kapton 25 μm " " 12.5 μm prepreg 0.125 mm	kapton 25 μm " " 12.5 μm prepreg 0.125 mm
- Coil ends filled with injection of charged resin	yes	yes
- Young's modulus (max + min) (N/mm^2)		
Inner layer	30250 + 32220	32540 + 33500
Outer layer	22730 + 28250	24150 + 27500
Collaring		
- Collaring rods		
Lateral rods	13.95 mm	13.95 mm
Central rod	21.90 mm	21.95 mm
- Stress in coils after collaring		
Inner layers	~ 80 N/mm^2	~ 80 - 85 N/mm^2
Outer layers	~ 55 N/mm^2	~ 55 - 60 N/mm^2
Final assembly		
- Gap control spacer (Al alloy)	yes	yes
- Welding method	TIG, manual	TIG, automatic
- Yoke gap after welding (average)	~ 0.3 mm	~ 0.3 + 0.35 mm
- Stress in shrinking cylinder (average)	~ 190 N/mm^2	~ 170 N/mm^2

Fig.1. Measured field harmonics vs longitudinal position of prototype 3 at 0.6 T (dBn/Bo*10⁻⁴ at 10 mm, 11 adjacent integrals over 0.75 m). Dashed are the specified errors [7] (systematic + 1 σ random).

IV. THERMAL CYCLING OF THE PROTOTYPES

A. The thermal cycles

Powering of each of the prototypes was preceded by two thermal cycles [1]. The cool-down and warm-up phases were carried out according to the following sequence: 300 K - 80 K - 260 K - 10 K - 260 K - 1.8 K.

The prototypes were cycled because non-uniform friction between the different parts of the magnet at mounting affects the kinematic behaviour of the structure. It was demonstrated on models fabricated during the development of these prototypes [3] that such a cycling has beneficial effects on the uniformity of the stress distribution in the structure and hence on kinematics of the magnet. An additional reason to carry out these thermal tests was to verify that the actual behaviour of the structure was as expected.

B. Gap closure during cool-down

At different positions in the straight part of the prototypes, gap closure transducers were placed. Two transducers were mounted at each position, as shown in Fig. 2. Due to the combined translational-rotational kinematics of the magnet cross-section, as well as to the presence of gap control spacers, the gap closure with temperature is not linear. The measured displacements at the "inner" location showed that the gap, the value of which was about 0.3 mm at room temperature, was completely closed at a temperature of about 150 K and remained close between 150 K and 1.8 K. The obtained displacement vs temperature curve was reproducible with thermal cycling. On the contrary much smaller displacements were detected by the "outer" gap closure transducers, generally less than 0.05 mm. This is not unexpected. The gap control spacers, in fact, are well compressed at room temperature due to the stresses in the shrinking cylinder (Table I) which were intentionally left higher than the nominal value of 110 N/mm² (value determined in a simulation with zero friction [4]). Due to this additional compression and to the bending of the iron yoke halves, the gap control spacers act as "pivots" to the yoke laminations, imposing a relative displacement between the two halves which is governed by the actual deformation of the gap control spacers. Consequently at 1.8 K, with the gap closed at the innermost position, the gap control spacers can

remain still under compression; such a compression plays the same role as the mating force between the two yoke halves.

It should be reminded that the gap control spacers were introduced in these prototypes because the manufacturer had difficulties in mastering the weld shrinkage without such spacers, and that the same collars and yoke laminations of the original design without spacers were used (actually the yoke laminations were machined to house the spacers). It was therefore not possible to optimize the kinematics. Moreover, the stress in the shrinking cylinder is difficult to control both in terms of average value as well as in terms of azimuthal distribution. The gap control spacer allowed to accept such imprecision, which would not be tolerated in a magnet without gap control spacers.

C. Stress increase in the shrinking cylinder during cool-down

The increase of stress in the shrinking cylinder during cool-down was as expected, resulting in ~ 140 N/mm² for prototype 1 and ~ 120 N/mm² for prototype 2. The curve stress vs temperature was stable, after the first cycle, on cycling the temperature. Practically no difference has been seen between cylinders fabricated according to different techniques. Shells used in prototype 1 were submitted to a direct machining of the inner surface, resulting in a reduced roughness. No machining of the inner surface of the shells was made for the cylinder of prototype 2. Treating the inner surface with molybdenum bisulphide ensured the expected relative azimuthal displacements regardless of the manufacturing technique. Moreover, joining several short shell pieces to obtain a long one (prototype 2) resulted neither in worse alignment tolerances nor in a reduction of the global helium tightness of the finished cylinder. The choice of the technique to be adopted for the mass production can therefore be based largely on economical considerations.

V. BEHAVIOUR OF THE MAGNET DURING POWERING

A. Quench localization

The detailed test performance of these prototypes have been described elsewhere [6]. Only those results which are of interest for a critical assessment of the design of the magnets will be recalled here.

Although different cables were used in the two prototypes, both magnets had similar training curves. Prototype 1 had its first quench at approximately 8.67 T which is well above the

Fig. 2. Positions of gap-closure transducers in the iron yoke (other transducers are placed symmetrically with respect to the horizontal axis of the magnet).

nominal field of the LHC machine of 8.4 T, while prototype 2 had its first quench at ~ 8.3 T. After four quenches both prototypes went beyond 9 T, reaching values of 9.59 T for prototype 1 and 9.33 T for prototype 2 [6]. Both magnets showed no retraining after thermal cycling. The majority of the quenches, for both prototypes, occurred in the "splice region" (Fig. 3), typically in the outer layer cable [6].

B. Coil ends and splice region

At the time when the design of these prototypes was made, no experimental confirmation existed about the behaviour of a two-in-one cross-section [5]. Only during the development of prototype 1 the 1 m long MTA1 models of similar design were tested. Training of these models indicated that the end parts of the coils and the splice region, where a change of stiffness exists, are the most critical parts. The only improvement that could be introduced in the 10-m-long prototypes consisted in a tighter control of the geometry of the splice region. Unfortunately also for these prototypes it was necessary to proceed with shimming of the coils to compensate for variations in thickness of the insulated cable under stress. As a result "kinks" of the cable when passing from the straight part to the end part of the coil could not be avoided, which made even more difficult to impart the correct azimuthal pre-stress to the coil in a region already affected by the above mentioned change of stiffness. An additional possible cause of the weakness of the splice region of prototypes 1 and 2 (as well as for prototype 3 fabricated by Ansaldo and presently under test at CERN), can be attributed to a specific design solution implemented into the special collars placed in the "layer jump and splice" region (Fig 4). The presence of the "tooth" might prevent a correct distribution of the azimuthal stress in the coil arc. The collaring shim is in fact contained into a "groove" and is not likely to transmit the prestress to the rest of the arc since the tooth is rigidly linked to the collar bulk. Incidentally it should be noted that prototypes 1 and 2 had their quenches preferably in the second or in a further turn of the outer layer, which would confirm the above given interpretation [6].

A different solution was implemented in prototypes of the same design fabricated after the ones in matter, by another manufacturer. In those prototypes the tooth is replaced by a piece filling the same volume made of glass-epoxy, which can "float" azimuthally allowing transmission of the azimuthal stress to the rest of the coils. The first of these prototypes did not show quenches in the splice region. Although quenches in the straight part of the magnet occurred at lower fields, which might have "hidden" a possible weakness of this design solution, it is felt that having a separate glass-epoxy piece is an improvement for the magnet design. This solution is therefore adopted for the first 15 m long dipole prototype presently under development.

Fig. 3. View of the "layer jump and splice" region.

Fig. 4. Special collars.

The other delicate area, the end part of the coils, behaved better than the splice area in terms of number of training quenches. In the ends of the coils of both prototypes 1 and 2 charged resin was injected, with the aim to fill all the voids existing between cables and between cable and spacer.

The choice of the resin/filler system was dictated by the need of finding out a sound solution to be implemented in a relatively short time. Probably the choice (resin CIBA AV138) was not the optimal one, since a certain brittleness at low temperature was expected. For the future prototype a better system will be introduced, based on developments made at CERN. Despite the fact that this technique was introduced as an "ad hoc" solution suggested by the indications coming from testing of model magnets, it can be said that it showed to be quite effective in ensuring an adequate structural support of the cable in the end parts. In fact the coil ends were not found to be the "weak point" of the magnets, limiting their performance.

C. Pre-stress in coils after collaring

Long discussions took place in the past concerning the effect on the behaviour of the magnet of the pre-stress imparted to the coil with the collaring operation. Test of prototypes 1 and 2 provided interesting elements for an assessment of this problem, since two (slightly) different levels of pre-stress were obtained. The central collaring rod of prototype 2 is in fact 0.05 mm larger in diameter than the one placed in prototype 1, which should correspond to an increase of average stress of about 5 N/mm².

However, it is worth mentioning that in order to account for friction and to have well clamped coils, it was decided to increase the pre-stress levels after collaring as follows:

- Inner layers ~ 80 N/mm².
- Outer layers ~ 55 N/mm².

Such average residual stresses were higher than the nominal design ones of 55 N/mm² and 35 N/mm², respectively [4]. This modification has required the application of very high forces to the coils when collaring [5]. Furthermore, collaring was even more complicated by the fact that the press available at the manufacturer could actually provide only 1000 ton/m, instead of the ideal ~ 1500 ton/m. Due to the high level of required stress and to the risk of damaging the coils, collaring of prototype 1 was not pushed as far as possible. Only on prototype 2 it was decided to insert a central locking rod 0.05 mm larger in diameter, which required a lot of additional work and operating at limit conditions with the tooling. Although the different cables used in prototypes 1 and 2 do not permit to make a direct comparison, it can be remarked that collaring with an higher pre-stress has not automatically led to better performance of

the magnet. Prototype 2 training curve was even a bit worse than that of prototype 1.

Reflections are therefore to be made on whether or not we should insist in trying to have an as high as possible residual pre-stress after collaring. It should also be kept in mind that the higher the residual pre-stress the higher the peak stress to which the coils are submitted during collaring. Also the value of the ratio actual pre-stress/nominally needed pre-stress should be critically assessed. In prototypes 1 and 2 this ratio was ~ 1.45 for inner layer coils and ~ 1.55 for outer layer coils. The feeling is that in the future magnets such a ratio should be kept lower than the value adopted for these 10-m-long-prototypes.

D. Deformations and stress evolution during magnet energization

Both prototypes 1 and 2 showed practically no deflection of the end plates with respect to the shrinking cylinder when increasing the test current. Beside this, an increase of longitudinal stress up to a value of $\sim 20 \text{ N/mm}^2$ at fields $> 9 \text{ T}$ in the shrinking cylinder was detected. These two facts indicate that neither the coils nor the coil/collar assembly slide with respect to the outermost part of the magnet, under the effect of the longitudinal component of the magnetic forces (~ 70 tons). The combined effects of high radial stresses and friction do therefore ensure a sound clamping to the structure. This fact will permit a reduction in thickness of the end plate for the LHC dipoles of final design.

A slight aperture of the gap (few hundreds of a millimetre) was measured at the innermost position and maximum field for both prototypes. This is an expected behaviour, already foreseen in the finite-element structural design [4]. Although the magnet can still work while having a small fraction of the internal part of its mating face open, the gap aperture should be limited as much as possible. Imposing a very strict quality control to the manufacture of the magnet components is therefore a must, since the behaviour of the magnet is very sensitive to tolerances of the components (collars, yoke laminations).

V. CONCLUSION

The paper exposed the main considerations that can be made, based on the test results, on the absolute and comparative behaviour of the first two 10 m long LHC dipole prototypes. The main assessments can be resumed as follows.

- Prototypes 1 and 2, although equipped with different cables, behaved in a similar manner reaching the LHC machine requirements both in the individual test and in the string test configuration.
- During the thermal cycles to which they have been submitted, the kinematics and the evolution of the stress distribution were as expected. The presence of the gap-control spacers has contributed to this result, even if the room temperature gap size and stress in the cylinder were different from the design values.

- The training quenches were predominantly located in the "layer jump and splice" region. A design weak point has probably been detected in the geometry of the special collars located in such region. This weak point will be corrected in the next LHC dipole models and prototypes.
- Injecting charged resin in the coil ends, although reducing the cooling efficiency, has had beneficial effects since the coil ends, unlike expected, have shown not to be the weak point with respect to quench.
- Increasing as much as possible the pre-stress in the coils does not improve the performance of the magnet.
- Slight aperture of the gap between yoke halves with current at its inner position has been eventually detected.
- The test results have shown that the high radial pre-stress and friction provide a strong longitudinal clamping of the coils, which allows to reduce the thickness of the end plates.

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