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Superconducting Dipole Model Magnet for LHC**

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Abstract

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FABRICATION AND TEST RESULTS OF A TWIN-APERTURE SUPERCONDUCTING DIPOLE MODEL MAGNET FOR LHC

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Abstract--In the research and development program for the LHC project at CERN the construction of superconducting dipole magnets with a twin aperture plays an important role. The design value of the magnetic field produced by these magnets is 10 tesla at superfluid helium temperatures below 2 K. One of the 1 meter long model magnets in the program for LHC has been built by HOLEC. The behaviour of this magnet under cryogenic conditions has been investigated twice: first, after the collaring of the superconducting coils had been completed and second, after the completion of the magnet (i.e. after assembling the iron yoke and aluminium shrinking cylinder). This procedure has enabled a study of the influence of the iron yoke and shrinking cylinder on the training behaviour of the magnet. The test results of this model magnet show that the design value of the magnetic field is feasible and that the mechanical structure is able to withstand the forces.

I. INTRODUCTION

CERN is preparing the construction of the Large Hadron Collider, which will consist of a double ring of high-field superconducting magnets [1]. The main dipoles of LHC are based on the two-in-one concept, i.e. two magnets sharing the magnetic circuit. Four model magnets of these twin-aperture dipoles have been ordered by CERN to four different companies, among which HOLEC is one [2]. Figure 1 shows a cross section of the model magnet which has been fabricated by HOLEC and tested under cryogenic conditions by CERN. The main design parameters of the dipole are given in Table 1. The main goals for the model magnet have been the demonstration of the feasibility of the design field and the acquisition of technical information concerning the fabrication of the final 10 T magnet with a length of approximately 9.5 m long. Meanwhile CERN has ordered 8 prototype magnets for a full cell evaluation. In collaboration with ELIN one of these magnets is currently under construction and will be finished in 1993.

II. FABRICATION OF THE MODEL MAGNET

The fabrication process of the model magnet consists of several stages, including winding, collaring and yoke assembly. These stages (except for the yoke assembly) have been described elsewhere [3,4]. After successfully finishing

Fig. 1 Cross section of HOLEC model magnet: 1. Coils, 2. Aluminium collars, 3. Yoke, 4. Iron inserts, 5. Clamp, 6. Gap, 7. Outer shrinking cylinder.

Table 1. Main design characteristics of Holec model magnet

Nominal field B_0 (2 K)	10 T
Operation current	15000 A
Turns per beam channel	1st layer 2x13 2nd layer 2x24
Coil inner diameter	50 mm
Coil outer diameter	120.2 mm
Length of the straight part	648 mm
Overall length of the coils	1080 mm
Distance between aperture axes	180 mm
Collars outer dimension (horizontal)	380 mm
Iron outer diameter	540 mm
Overall mass	2000 kg
Stored energy for both channels combined	684 kJ/m
Longitudinal magnetic forces for both channels combined	700 kN
<u>Resultant of magnetic forces per meter length in the first coil quadrant</u>	
F_x (horizontal)	2276 kN/m
F_y , 1st layer (vertical)	-234 kN/m
F_y , 2nd layer (vertical)	-980 kN/m

the collaring of the coils, it was decided to perform an interim cryogenic testing of the collared coils. Therefore, the end plates of the magnet were assembled, with interim stainless steel tie rods placed between them in order to support the longitudinal forces when exciting the magnet. Also the electrical connections were finished. The coils were not preloaded longitudinally. Care was only taken that there was direct contact between the collared coils and the end plates. Before the cryogenic test the assembly was mechanically measured and electrically tested. From the dimensions of the collared coils, which were measured at various locations on the assembly, the obtained pre-stress in the coils can be deduced. Figure 2 shows the differences between the measured dimensions and the design values of the straight part of the magnet. From the figure it can be concluded that the obtained pre-stress in the straight part is a little larger than the required 45 N/mm^2 . A homogeneous distribution in the coil ends was not fully achieved. After the first cryogenic test no significant deviations of the previous dimensions were measured, although the Lorentz load had amounted to approximately 80% of the design values of the completed magnet. Therefore, it can be concluded that the collar assembly is capable to withstand at least this percentage of the forces without any permanent deformation.

After these intermediate tests the magnet was transported to Holec to be completed with the yoke and

Fig.2 Differences between the dimensions of the collared coils from the design value for the straight section of the coils. The locations of the dimensions are indicated in the cross section.

shrinking cylinder. The two yoke halves are composed of punched 5 mm thick low carbon steel laminations. At the coil head regions a non-magnetic spacer was introduced to decrease the local high magnetic fields. On the model magnet, manufactured by HOLEC, shims have been added between collars and yoke to obtain a permanent gap on the yoke mating surfaces. Thus the shrinking force of the aluminium cylinder acts entirely on the collared coils [5]. Care was taken to avoid vertical preload on the collared coils. During assembly under the press, the gap was adjusted by dove-tail shaped clamps in combination with beryllium copper shims between collared coils and yoke at the horizontal and vertical plane. The gap was increased by shims to obtain 0.9 mm under a compression load of 800 N/mm . This resulted in an ovalized outer circumference of the magnet. After assembly of the iron yokes, a 25 mm thick aluminium cylinder (AL 5083) was shrink fitted with an average tangential prestress in the cylinder of 50 MPa. In longitudinal direction no preload was applied on the collared coils. Care was only taken that after cool down the longitudinal forces of the coils were transferred to the end plates which were locked by segments, fitting in a groove of the shrinking cylinder.

III. CRYOGENIC TESTS OF THE MODEL MAGNET

As mentioned above, the behaviour of the HOLEC model magnet under cryogenic circumstances has been investigated at two stages of its fabrication. First, after the collaring of the coils and second, after the completion of the magnet. During the measurements of the magnet in its collared state, the magnet was surrounded by a magnetic shield in order to reduce the stray fields. The presence of this shield and the absence of the iron yoke give a relation between the maximum magnetic field in the coils and the current which is different from the one for the completed magnet. Without the iron yoke the maximum achievable field is lower, while the current is higher. Therefore, both measurements should not be evaluated by comparing only the quench currents or quench fields.

The magnet has been tested in a vertical position with the current connections on top [6]. For investigation purposes pick-up coils have been inserted into the bores of the magnet. These coils divide the longitudinal direction of the magnet into three sections: the straight part and the two heads. Careful analysis of the voltages from these coils at the moment of the quench enables to locate the origin of the quench in one of these sections [7]. At the moment of the quench the ramp rate of the current was 4 A/s or less. The cryogenic tests of the magnet in the collared state and of the completed magnet have each been performed in two runs. In both cases the magnet was first cooled down to liquid helium temperatures of 4.3 and 1.8 K. After investigation of the quench behaviour the entire magnet was subsequently warmed up to approximately 200 K. Finally, a second run

Fig.3 Quench performance of the HOLEC model magnet in the collared state. The short-sample limits (SSL) are indicated for 4.3 and 1.8 K.

of measurements was performed at superfluid helium temperature of 1.8 K to investigate whether the previous training had any permanent effects on the performance of the magnet after a thermal cycle.

A. Cryogenic testing of the collared magnet

Figure 3 shows the training behaviour of the HOLEC model magnet in the collared state. In the second attempt at 4.3 K the magnet quenched at approximately 90% of the short-sample limit. After a further cool down the behaviour of the magnet improved quite strongly during the first quenches. Later on the magnet still continued to reach higher quench currents, but the rate of improvement was less strong. The measurements were stopped at a field of about 92% of the short-sample limit. In the second run a large part of the training behaviour had to be repeated. The magnet started at about 88% of the short-sample limit, but improved a little faster than in the first run. The final quench at 4.3 K turned out to be very close to the short-sample limit. The origins of the training quenches could be located in the ends of the coils (with the exception of some for which no signals were available). In the first quenches of each run one of the four poles turned out to be the main originator of the quenches. Later on, the causes of the quenches could be found in the ends of all four poles.

B. Cryogenic testing of the completed magnet

After the completion of the magnet, the final cryogenic testing of the HOLEC model magnet was performed. The results are shown in figure 4. Initially, the quench behaviour was similar to the results of the collared magnet, starting a little under the short-sample limit at 4.3 K, but rapidly improving at 1.8 K. However, the rate of improvement made with each training quench gradually de-

Fig.4 Quench performance of the completed HOLEC model magnet. The short-sample limits (SSL) are indicated for 4.3 and 1.8 K.

creased, but small increases in the field continued to be made. This resulted in a maximum quench field of 9.8 T after approximately 30 quenches, which is 98% of the short-sample limit. During the second run the quenches started again quite low, but in only a few quenches a significant progress was recorded. The quench of the sixth attempt was already 9.6 T. In the two final measurements at 4.3 K the magnet reached its short-sample limit in both cases. The training quenches could again be found to start in the ends of the coils.

IV. DISCUSSION

On the basis of the magnet performance relative to the short-sample limits, it can be concluded that the presence of the iron yoke has a positive effect on the magnet performance. Another method of evaluating the two cryogenic tests is the comparison of the product of quench current and field which is a measure of the maximum Lorentz force acting on the cable. Figure 5 shows the training behaviour expressed in terms of this force per unit length of the cable. Note that a higher field at 1.8 K implies a significant increase of the acting forces. It is clear that the maximum achieved forces were significantly higher in the completed magnet.

It should be noted, however, that in figure 5 the Lorentz forces have been calculated on the basis of the peak field and that the location of this field is different for the two measurements. The improvements of the magnet behaviour can be partly accounted for by the fact that the iron yoke transfers the peak magnetic field from the ends towards the central part of the coils. This leads to relatively lower forces in the ends of the coils, which are known to be the most delicate parts of the magnet. Although the quenches are still originating mainly in the ends of the coils, this

Fig.5 Maximum Lorentz force on the cable during the quenches. Temperatures during the measurements (4.3 K or less than 2 K) are indicated in the figure.

now happens at a higher level of overall magnet performance. A second cause for the better performance can be the fact that the mechanical confinement in the horizontal plane of the magnet is much better, as the collared coils are supported by the iron yoke in the horizontal plane. This will lead to a smaller horizontal displacement of the coils, which ensures a better support for the windings of the magnet.

V. CONCLUSION

The goals that were set for the fabrication of the model magnet have been achieved. The design field has almost been achieved and valuable technical information concerning the production of twin aperture magnets has been acquired. From the cryogenic measurements it can be concluded that the magnet, being a model, performed satisfactorily. From the mechanical measurements that were made on the collared coil assembly before and after the first cryogenic test, no significant deformations could be observed. Therefore, the assembly is perfectly capable to withstand the forces during excitation. In both the collared and the final state of the magnet the maximum fields that were obtained at 4.3 K were equal to the short-sample limits

of the cable. At temperatures below 2 K the maximum achieved field was 9.8 T. As the magnet needed a large number of training quenches to achieve the maximum field, the measurements were stopped at this point. Thermal cycling showed that parts of the training memory was lost. Modifications in the design and manufacturing for the prototype LHC magnet have been carried out to improve the magnet behaviour.

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