

# Progress in the Construction and Testing of the 70 mm Aperture Quadrupole for the LHC Low- $\beta$ Insertions

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## Abstract

This paper reviews the current status and development of the one meter model of the 70 mm aperture quadrupole for the LHC low- $\beta$  insertions. We describe the problems that were encountered in insulating the cable with an all Kapton system, the manufacture of the shaped end spacers, and coil winding and curing. We also present results of the short mechanical model of the magnet straight section which confirmed the soundness of the structural design and proved the tooling for the final magnet assembly.

## 1. INTRODUCTION

As part of the magnet development programme for the Large Hadron Collider (LHC), proposed as a future extension of the CERN accelerator complex [1], a 1 m model of the 250 T/m low- $\beta$  quadrupole is presently being built by Oxford Instruments. This is a special magnet designed to achieve high magnetic field purity and 250 T/m at 1.9 K in an aperture of 70 mm. The magnet features a four layer coil, Figure 1, wound from two 8.2 mm wide NbTi keystone cables, graded in current density by a factor of 1.5. Its mechanical structure is based on the collar-spacer concept, where a thin stainless steel collar serves for coil assembly and transfer of compressive forces. The iron yoke has both important magnetic and structural functions, as the magnetic forces are taken by the rigidity of the iron lamination pack held together by aluminium ring-and-collet assembly. The gaps between the four-fold symmetric yoke packs are chosen such that nominal stress conditions in the coils are achieved at room temperature, while on cool down to 2 K the contact forces in the closed gaps are sufficiently large to keep the yoke closed under all magnetic loading conditions. The design principles and the magnetic performance of the quadrupole have been presented in ref. [2].

In this report we review the current status of the construction of the magnet. In particular, we describe the results of the test winds, the problems encountered in working with the all Kapton insulation, and the design and tests performed on the accuracy of the end spacers. Finally, we present the results of the mechanical model of the quadrupole straight section, as proof of the structural design of the magnet and of the assembly tooling.

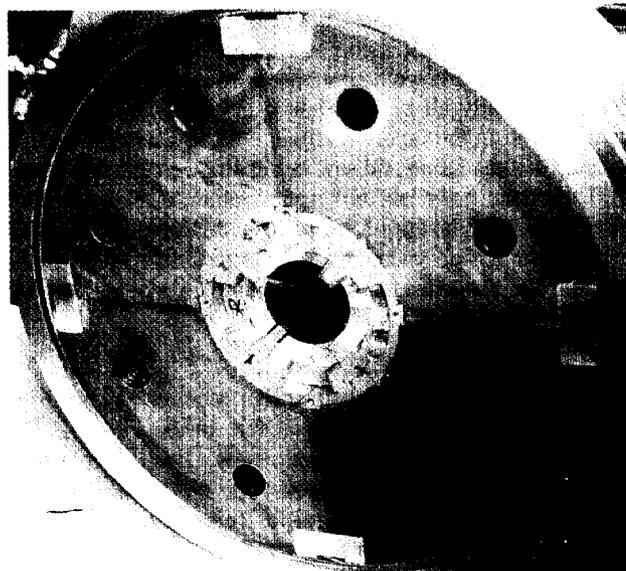


Figure 1: The cross-section of the 70 mm LHC low- $\beta$  quadrupole model

## 2. COIL WINDING

### 2.1 Cables and Insulating System

The two 8.2 mm wide NbTi cables have respectively 22 and 34 strands (0.74 mm and 0.48 mm diameter), and keystone angles of 2.2 and 1.1 degrees. The superconducting cables, as well as the dummy cables (with a slightly different filament diameter and superconductor volume) were supplied by Outokumpu Superconductors, Finland. The cables are mechanically stable and easy to wind. The critical currents achieved at 4.2 K are 8530 A at 6.5 T for the 22 strand cable, and 8150 A at 5 T for the 34 strand cable.

A number of different all Kapton cable insulation systems were considered, and a three layer, butt wound system was selected. The first two layers of 6 mm wide, 25  $\mu$ m thick 100HN Kapton tape are counter wrapped onto the cable. The third layer of 6 mm, 20  $\mu$ m thick Kapton tape has a 5  $\mu$ m thick layer of un-cured XCI Polyimide on one side, which cures at 190°C.

The 6 mm tape width design was the result of trials focused on reducing the wrinkle in the insulation when the cable is bent and twisted around the tight radius of the inner pole turn. The Polyimide bonding system will only bond to other Polyimide surfaces, therefore it is important that the sides of each cable lie flat against each other to form a strong bond. This configuration of wrapped tape insulation gives a porous structure allowing superfluid helium easy access to the strands in the cable, which is important since the quadrupole will need a high degree of cooling. Voltage testing on this insulation gave values  $> 2$  kV turn -to-turn.

Due to its flexibility the cable was difficult to insulate. As the Kapton tape rotated around the cable, the cable would move so displacing the insulation. A solution was found by increasing the cable tension and reducing the tape tension. The 34 strand cable would collapse with only light tension in the tape. Finally all of the cable was insulated with a very light tension in the tape. We found that it was very easy to damage the insulation and several repairs were made.

The main body of the ground plain insulation (GPI) consists of four layers of 125  $\mu\text{m}$  thick Kapton sheet, pre-formed in a heated vacuum mould to exactly fit the surface of the coil. The insulation at the ends is provided by the GRP end spacers.

## 2.2 Cable Joint

The four layer graded coil design requires a joint to be made between the two types of cable inside the coil. The insulation is cured at approximately 200°C, at which temperature soft solder will melt. On the other hand, the superconductor will be damaged if its temperature exceeds 300°C. A eutectic lead-tin solder with a melt temperature of 255°C and a re-melt at 290°C enables the joint to be made and the coil cured at approximately 200°C without damaging the joint or conductor.

The two ends of cable are tinned with the eutectic high temperature solder and all flux is then removed. The joint temperature is controlled during soldering. A jig is used to position the two cable ends accurately together. A solder inhibitor is used to stop solder running along the cable beyond the end of the joint, this leaves the cable flexible either side of the joint. The mechanical and electrical performance of the joint has been successfully tested.

## 2.3 End Spacers

The positioning of the end turns are described in [2]. We will now describe the detail design and manufacturing sequence for end spacers. The complex minimum strain end shapes were generated using the software program "BEND" [3]. There are a number of solutions to the problem and the final shapes chosen were slightly elliptical with the major axis of the ellipse aligned with the magnet bore. The ellipse orientation was chosen because the radius of the cable is increasing as it approaches the straight section, which minimises the problems encountered during winding the ends. A second program converted the surfaces into the chosen five axis milling machining operating language, and

added the facility to choose the number of machining passes taken by the cutting tool. A complete set of aluminium spacers were machined to test the tooling used during machining of the components. A trial coil was then wound using the aluminium spacers. This proved that, for layers 1 and 2, the CNC machined surfaces of the spacers mate well enough with the coil block surfaces to support the cables.

A full length, 1.3 m long, dummy coil was wound with end spacers machined from RLG3 (equivalent to G11, a high glass content GRP). These showed that spacers for layers 3 and 4 required modification. Although there was a perfect line to line fit between the spacer and the coil on the upper edge of the cable, (see Figure 2) there was a small gap of approximately 1 mm at the apex of the end at the inner edge of the layer. This was measured and the misplaced surfaces have been modified to produce matching coil to spacer surfaces.

The individual turns lie flat against each other within the cable blocks, this is important as the Polyimide bonding system requires that the surfaces butt together so that a strong bond is made. This bond is only needed to support the coil when it is being handled during assembly.

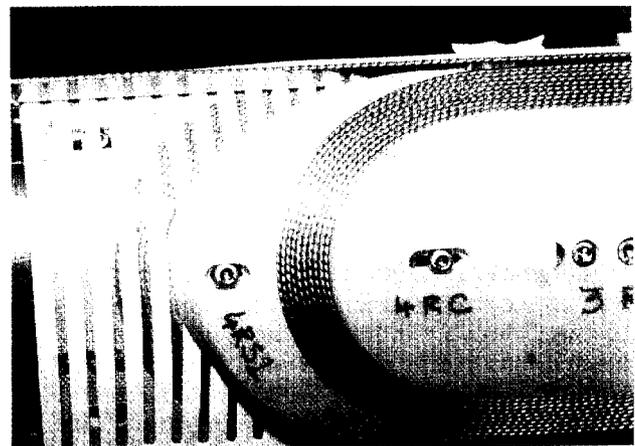


Figure 2: Winding the coil ends - layers 3 and 4

## 2.4 Test Winding and Curing

A simple 1.5 m long winding machine has been built to wind the model quadrupole coils, wound as two double layers. Sufficient cable to wind two layers is part wound onto two spools, one of the spools is fixed to the winding mandrel while the other is mounted on the tensioner. The first layer is then wound, the spool that was mounted onto the mandrel is then moved to the tensioner and the second layer wound. In this way, the coil start and lead ends are on the outside of the coil, which simplifies the cable runs in the magnet.

The all Kapton bonding system requires both temperature and pressure to cure the coil. Each of the two double layers is mounted in a simple mould, which is then placed into an oven. The mould design uses differential thermal expansion

to provide the curing pressure, which is continually measured. Initial trials on a short model mould achieved good bonding and dimensional accuracy.

### 3. MECHANICAL SHORT MODEL

#### 3.1 Components and Assembly

A set of 180 mm long straight section coil packs were cured using a short test version of the curing press. The set of cured coil sections were assembled around a former. The GPI was positioned over the coils with the brass shim that protects the GPI and coils from the fine blanked edges of the collars. The collars were then positioned around the coil packs. A collaring press with four 20 tonne hydraulic rams compressed the assembly to permit the insertion of the four securing pins. The collars incorporate a set of load cells that have been calibrated at 1.9 K. Due to the size of the load cells it was only possible to monitor the pressure in the outer two layers, a separate experiment measured the pressure in all the layers at room temperature.

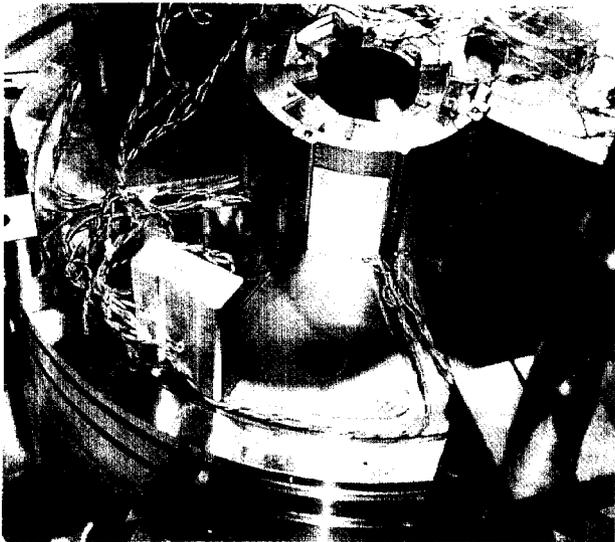


Figure 3: Short model during assembly

The glued yoke packs were positioned around the collared coil assembly. The wiring for the load cells are brought out of the assembly through passages in the yoke pack. The four aluminium spacing bars were fitted and the stainless steel tapered split ring positioned. We used the force ring press to pull the aluminium tapered ring over the stainless steel split tapered ring, this squeezes the yokes, collars and coil pack to the design room temperature pressure. The design relies on a balance of yoke gap at a set coil pressure. The tapered force ring design allowed several iterations of assembly to change spacer thickness, and so adjust the gap to coil pressure setting. All of the assembly and dismantling tooling worked well. To set the coil pressure in sections of the magnet that are not monitored by load cells, we plan to calibrate the change in circumference

of the aluminium force rings. The sensitivity of this method was tested in the short model and worked well.

#### 3.2 Test Results at 77 K

The model was placed in a nitrogen cryostat and slowly cooled. The temperature difference between all of the components did not exceed 3 K even with a high flow of LN<sub>2</sub> entering the cryostat. The pressure in the coils was continuously recorded. The measured pressures in layer 3 were: 53.4 MPa at room temperature, 109.2 MPa at 77 K then 58.2 MPa on returning to room temperature. Layer 4 showed values of 42.7, 96.8, and 46.0 MPa respectively. The ratios of pressure between the different layers had good correlation with the ANSYS finite element model. The pressure at 77 K was higher than expected, this was due to the room temperature pressure being set too high. This has now been corrected and a second set of tests are currently in progress.

### 4. 1.8 K TESTING STATION

A 1.8 K atmospheric pressure refrigerator has been designed and built to test the magnet. The refrigerator provides 1.5 m long, 50 cm diameter volume and supports a magnet weight of up to two tonnes, and supplies 10 W of cooling power, at 1.8 K. It is equipped with a pair of 6 kA current leads, 400 diagnostic leads and a rotating cold probe to plot the field.

### 5. CONCLUSIONS

The flexible 8.2 mm wide cable is easy to wind, follows the profile of the end spacers and sits flat against the mandrel with very little persuasion for all but the first few turns of layer 1. The all Kapton insulation is easy to cure in a simple mould but is delicate and will damage easily. The cross section structure works well. Using the aluminium force rings has proved very successful due to the ease of adjustment, simple tooling, and the ability to set the pressure along the full length of the magnet without relying on load cells.

Coil winding development is now complete and we are winding real magnet coils. Barring setbacks we will test the magnet in August and September 1994.

### 6. REFERENCES

- [1] The LHC Study Group, LHC, *The Large Hadron Collider Accelerator Project*, (CERN/AC/9303(LHC))
- [2] R. Ostojic, T. M. Taylor and G. A. Kirby, "Design and Construction of a One-Metre Model of the 70 mm Aperture Quadrupole for the LHC Low- $\beta$  Insertions", Proc. 13th Int. Conf. on Magnet Technology (MT13), Victoria, Canada, September 1993, LHC Note 245.
- [3] R K Puri, F Nobrega, "HEB Dipole BEND Analysis and End Part Design Report", SSC Lab Report, DSB-101 HEB Dipole.