EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 272

Mechanical Design and Characteristics of a Superconducting Insertion Quadrupole Model Magnet for The Large Hadron Collider

*G. A. Kirby, R. Ostojic, T. M. Taylor, and I. Vanenkov
**T. Nakamoto, A. Terashima, N. Higashi, H. Higashi, H. Kawamata, T. Ogitsu, T. Shintomi, K. Tanaka, K. Tsuchiya and A.Yamamoto

Abstract

A superconducting insertion quadruple is being developed by KEK in collaboration with CERN for the Large Hadron Collider (LHC) project. The mechanical design of the magnet in which the pre-stress is applied to the coil through thin stainless steel collars inside the yoke, the two halves of which are held together by means of keys, has been validated experimentally by measurements on a short model. The 140 mm long model was assembled from real magnet components in order to simulate the magnet assembly and to evaluate the change in coil pre-stress during assembly and cool-down. A new technique using capacitance pressure transducers was used, which has enabled measurements of the stress distributions in the coil with high accuracy. This paper describes the mechanical design of the quadrupole magnet and results obtained from the short mechanical model.

* CERN, Geneva, Switzerland ** KEK, Tsukuba, Japan

Presented at the 15th International Conference on Magnet Technology
Beijing, China, 20-24 October 1997

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 10 February 1999

Mechanical Design and Characteristics of a Superconducting Insertion Quadrupole Model Magnet for The Large Hadron Collider

G. A. Kirby, R. Ostojic, T. M. Taylor, and I. Vanenkov
European Laboratory for Particle Physics (CERN), 23 Geneve, CH-1211, Switzerland

T. Nakamoto, A. Terashima, N. Higashi, H. Higashi, H. Kawamata, T. Ogitsu, T. Shintomi, K. Tanaka,
K. Tsuchiya and A.Yamamoto
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, 305, Japan

Abstract ---A superconducting insertion quadruple is being developed by KEK in collaboration with CERN for the Large Hadron Collider (LHC) project. The mechanical design of the magnet in which the pre-stress is applied to the coil through thin stainless steel collars inside the yoke, the two halves of which are held together by means of keys, has been validated experimentally by measurements on a short model. The 140 mm long model was assembled from real magnet components in order to simulate the magnet assembly and to evaluate the change in coil pre-stress during assembly and cool-down. A new technique using capacitance pressure transducers was used, which has enabled measurements of the stress distributions in the coil with high accuracy. This paper describes the mechanical design of the quadrupole magnet and results obtained from the short mechanical model.

I. INTRODUCTION

A cooperative program to develop the low-β quadrupole magnets has been established between KEK and CERN as part of the Japanese contribution to the LHC accelerator project which is being built at CERN [1-5]. KEK will provide half of the 32 quadrupole magnets required for the inner triplets. These quadrupoles are key components that are necessary for strong focusing of the high energy proton beams and high luminosity collisions in the physics experiments. The main design goal for the magnet is to provide a field gradient of 240 T/m in a coil aperture of 70 mm, corresponding to a nominal operational field gradient of 200 to 205 T/m at 1.9 K with a superconductor load line ratio of not more than 80 %. The lost particle showers from the colliding beams will deposit a power of several watts per meter into the coil windings, and this has to be allowed by the coil design. The design optimization has been based on the use of NbTi superconductor cooled with pressurized superfluid helium at 1.9 K.

In this paper, we discuss the reasons for building and testing of a140 mm thick “slice” of the straight part of the quadrupole, shown in Fig. 1, and describe the assembly of the mechanical short model.. The “slice” was built using real magnet components, and was instrumented with capacitance pressure transducers [6]. The model was assembled and cooled to liquid nitrogen temperature. The internal coil pressures were measured and the results compared with the design values [3]. Finally, we compare two techniques of coil modulus measurements, and comment on the choice of the material for the yoke, which has to provide support for the assembly and magnetic forces.

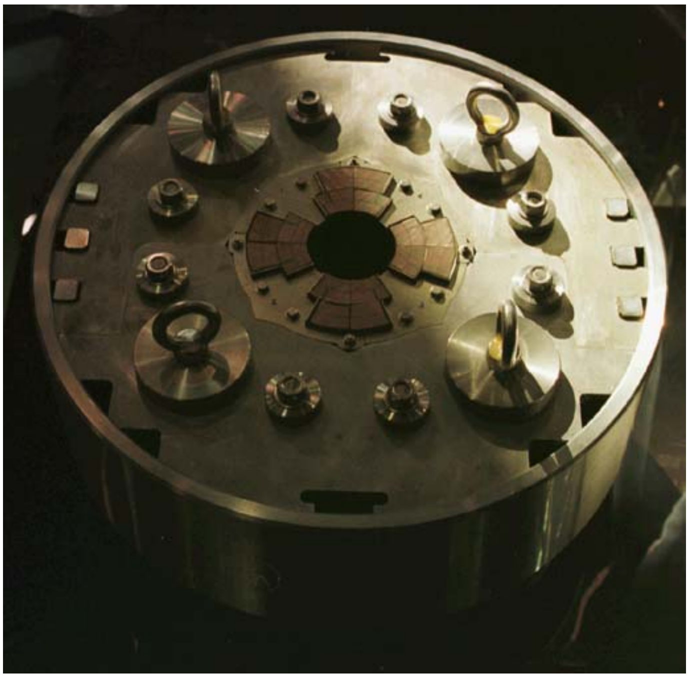

Fig. 1. Picture of mechanical short model

II. OBJECTIVES OF THE SHORT MODEL

Although it is possible to calculate with some accuracy static models, it is difficult to assess mechanical structures which involve friction. By assembling a short model we can check if the structure can be assembled as foreseen, and if the required internal pressures and component positioning are correct. Furthermore, the assembly of the model allows to check the functioning of the assembly tooling.

The mechanical design of the low-β quadrupole, Fig.2, is based on using thin stainless steel collars for pre-assembly of the four quadrupole coils, and a horizontally split yoke for coil compression. The yoke halves are held in place with keys and a shrink fit stainless steel ring. The structure relies on the yoke and collars sliding together to introduce a uniform pressure distribution between the coil packs. Furthermore, in order to obtain uniform pressure on all four magnet poles, it is necessary that the top and bottom yoke halves slide together. As in both cases friction may modify the behavior of the structure, it was very important to check its performance in advance of the full magnet assembly.

Manuscript received on October 20, 1997
Glyn Kirby +41 22 767 82 33 E-Mail: Glyn.Kirby@cern.ch

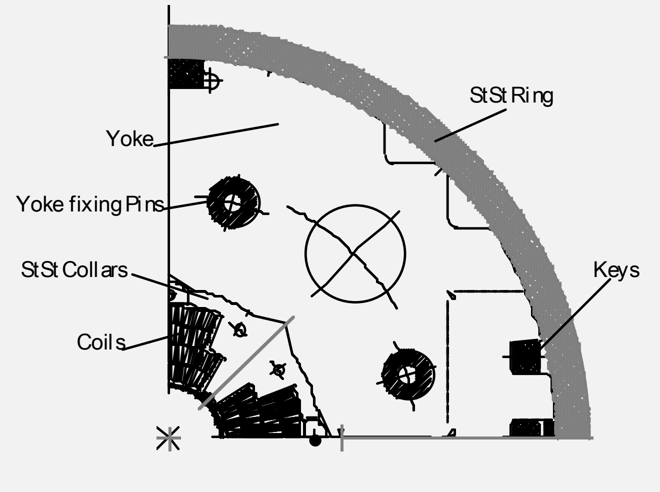

Fig. 2. Cross section of the low-β quadrupole

III. MECHANICAL ASSEMBLY OF MODEL

The 140 mm long “slice” of the quadrupole straight section was assembled using real magnet components and assembly tooling. One complete pole comprising two double layer coils was wound using NbTi superconductor. The coils were cured in the curing molds and cut to produce the four poles needed for the short model. The “slice” was assembled using sheets of Upilex ground plane insulation (GPI), while the quench protection heaters were simulated with stainless steel ribbons of the correct width and thickness, wrapped with Upilex. The collaring shoes were made of three layers of 0.15 mm and one layer of 0.25 mm thick stainless steel sheets. To facilitate assembly the sheets were pre-rolled to approximate the outer radius of the coil, and held together by a small spot weld at the center.

The nominal 1 mm thick coil shims are approximately 22.5 mm wide and cover two layers. The shims were accurately machined with two pockets to take the capacitance gauges, and were glued to the collar packs using super-glue. With the coils, quench heaters and GPI assembled around a mandrel, the collars were positioned and held in place with two fabric straps, and the capacitance gauges slipped down into the machined pockets in the shims. Each coil layer was separately monitored, for a total of 32 capacitance gauges. The calibration of the gauges used a third order polynomial fit giving an accuracy of the order of 1 MPa throughout the full range of pressure measurements.

A quadrupole collaring press was used to push the four collar packs uniformly together so that the fixing pins could be inserted. The average pressure in the coils during collaring was 17 MPa. The size of the coil assembly as function of pressure was measured using the four gaps between the spacer collars and the holding collars, which are nominally 0.50 mm when the iron yoke is closed. Using the capacitance gauges to measure the pressure and the gap to measure the coil size, the effective coil modulus was obtained. The resulting shim thickness was found to be too small by 0.2 mm on all four layers. Furthermore, we observed that the pressure was higher in the inner layers than in the outer ones. In order not to over-compress and damage the coils we placed 0.1 mm shims in the outer two coil layers.

The collared coil assembly was mounted into the bottom yoke half. As the coil was not compressed at this point the diameter of the collared coil was larger than the hole in the yoke, and gaps appeared between the collars and the yoke, as shown in Fig. 3. Subsequently, the large vertical dipole type press was used to slowly push the top and bottom yoke halves together. A collapsible mandrel was used to keep the magnet bore round by pushing the coils into the collars. At approximately 25 % of the yoking force the mandrel was removed. The main design concern at this stage was whether friction would inhibit the movement of the top and bottom joints in the collars, resulting in higher pressure in the two horizontal coil packs. PTFE spray was used on the surface between the collar and the yoke. As the gap in the yoke closed, the distribution of pressure in the coil was measured and found to be uniform in both horizontal and vertical planes.

Mechanical stops limited over-compression of the assembly. With the press in contact with the stops, three keys were tapped into the yoke on both sides. With the keys in place and the press released, the gap between the top and bottom yoke halves was 0.02 mm on the right yoke half, while it was closed on the left. The loss in coil pressure due to “spring back” was low due to the stiffness of the yoke, approximately 10 MPa from a maximum of about 75 MPa. After yoking the outer yoke diameter was measured to be uniform around the circumference within ± 0.05 mm. The stainless steel shrinking ring was heated to 70°C and slipped over the yoke. After the ring had cooled to room temperature, the pressure in the coils had increased by about 10 MPa.

Fig. 3. The short model in the yoking press prior to final assembly with the gap between collar and yoke visible.

After assembly, the model was cooled to liquid nitrogen temperature. The pressure on all poles and layers was recorded at each step, and the mean values and deviations from mean plotted, as shown in Fig. 4. The loss in coil pressure of 10 to 16 MPa was less than expected, and was explained by the closing of the small remaining gap in the yoke. If the gap had closed at room temperature, the pressure loss would be 20 to 30 MPa, depending on the layer. The model was disassembled and the shim size increased by 0.2 mm in the mid plane of the two outer layers. After re-yoking the gain in pressure was only about 5 MPa. On cooling to liquid nitrogen temperature the coil pressure dropped by about 30 MPa as predicted, as shown in Fig. 5.

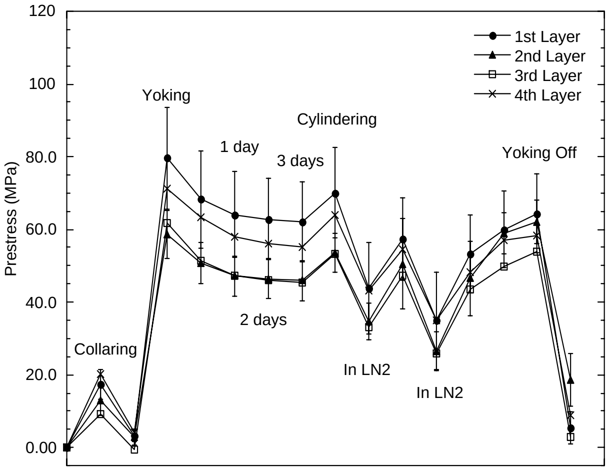

Fig. 4. Coil stress history of the first model assembly

After the second model assembly and a thermal cycle in liquid nitrogen, the coil stress was measured daily to assess any creep that may be present. As shown in Fig. 5, the coils have reached stable pressure, well balanced between different layers, after one day.

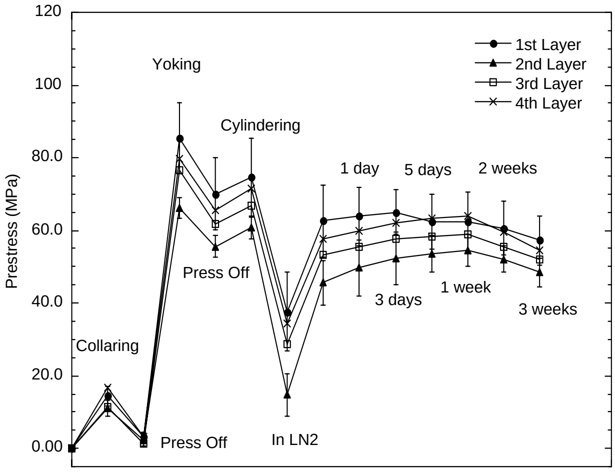

Fig. 5. Coil stress history of the second model assembly

IV. COMPARING TWO TYPES OF MODULUS MEASUREMENT.

At the initial magnet design stage we require information on the coil modulus and expected size. This is normally obtained by performing “10 stack tests” on a dummy superconducting conductor that has similar strand size but not necessarily the cross section of the final cable. The cable is assembled using the design insulation into a stack, alternate cables being reversed so that a straight stack can be cured, and the modulus of the assembly measured. This is a compromise as the final superconducting cable may have slightly different superconductor composition or size. Furthermore, the coil pack is in the form of an arch.

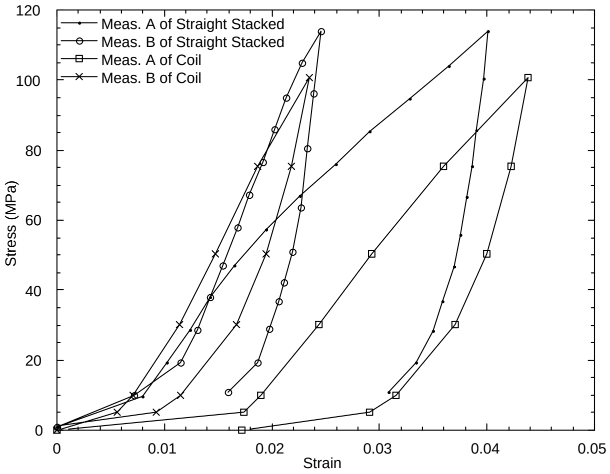

Fig. 6. Coil modulus measurements performed on the “10 stack” and arched coil packs. Measurements on the first load cycle (A), and on the tenth cycle (B) are shown.

In Fig. 6, the modulus obtained with the “10 stack “ is compared to the measurements on the arched coil packs, on the first and tenth load cycles. During the first cycle the assembly was still settling down, and by about fourth or fifth load cycles the curves were reproducible. We can see from the plots that the elastic modulus of the “10 stack” and the final coil are very close. The values obtained are compared in Table 1 with those of other components intervening in the magnet.

Table 1. Mechanical properties of the coil and other structural materials of the quadrupole

	Modulus (GN/m^{-2})	Yield stress (MN/m^{-2})
Coil azimuthal modulus	8	
Insulation material (Upilex)	8	70
Spacer collar High-Mn steel	207	305
Yoke Iron	170	280

Although the modulus of the coil can be anticipated by the measurements on the “10 stack”, it is difficult to forecast the coil size by this technique, and so eliminate shimming. Unfortunately, the shim size is a combination of the design of coil cross section and curing mold size, of the size of the void in the collars into which the coil is placed and of the modulus of the support structure, etc. It is therefore difficult to forecast exactly the required dimensions.

V. YOKE MATERIAL SELECTION

The low carbon steel which is commonly used for magnet yokes has a relatively low yield stress compared with other structural materials. As in our design the yoke must restrain the assembly and magnetic forces, a stronger material is required. A series of ANSYS calculations were performed to determine the detailed stress distribution in the fully loaded yoke lamination, and to reduce the excessive stress that occurs during yoking around the pressing points. Our final result is shown in Fig. 7. The yoke material finally chosen is a low carbon steel with a coercive force Hc 1.46-1.57 x 100 Oe, permeability (at 1 Oe) 1080-1240 G, and yield strength 264-280 MPa. This material is one of the strongest used for superconducting accelerator magnets [7], as shown in Fig. 8.

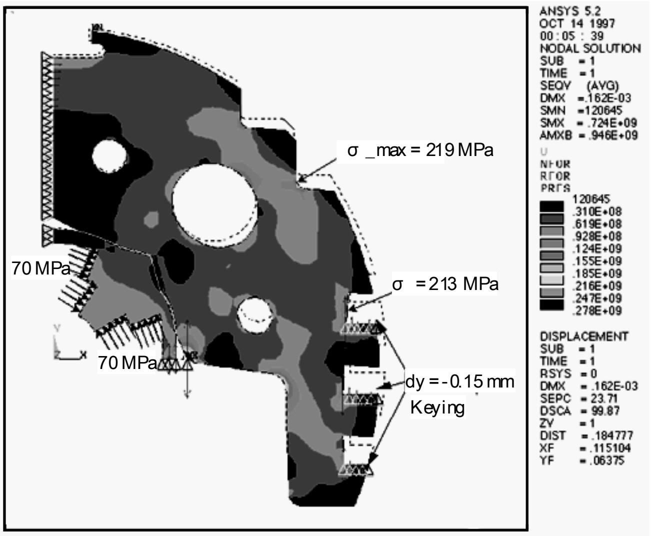

Fig. 7 ANSYS calculations of the stresses and deflections of the yoke

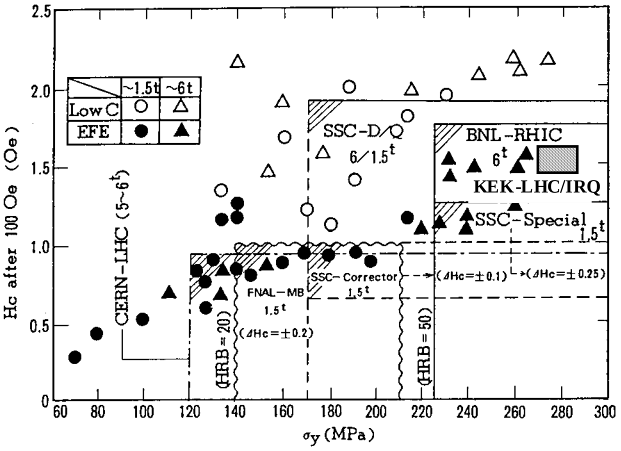

Fig. 8. Coercive force (Hc) vs. yield strength (YS) of low carbon steels used in superconducting accelerator magnets.

V. CONCLUSIONS

A 140 mm long mechanical model of the low-β quadrupole has been assembled and tested. The model confirmed the mechanical design of the magnet and the assembly techniques that will be used for a series of models. Capacitance pressure transducers were successfully used to accurately measure pressures distribution inside the coils packs during assembly and on cool-down to 77 K.

The elastic behavior of a simple stack of conductors and magnet coils have been compared, and a good correlation was observed.

A magnetic yoke material with higher strength has been successfully used in the short mechanical model.

The first 1 m quadrupole model is being assembled at this time and it is planned to test it before the end of 1997.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the professional support and cooperation of both the KEK workshop (mechanical engineering center) and cryogenics center, as well as the valuable help provided by all of the material and component suppliers.

REFERENCES

[1] A. Yamamoto et al., “Design Study of a Superconducting Insertion Quadrupole Magnet for the Large Hadron Collider”, ASC’96, Pittsburgh, USA., August 1996, IEEE Trans. Applied Superconductivity, **7**, No.2, p.747-150, 1997

[2] The Large Hadron Collider Conceptual Design Report, CERN/AC/95-05 (LHC), 1995.

[3] A. Yamamoto et al., “Development of a Superconducting Insertion Quadrupole Model for the Large Hadron Collider”, presented at this Conference (MT-15) (OA1-4).

[4] A. Greene et al., “The Magnet System of the Relativistic Heavy Ion Collider (RHIC)”, IEEE Trans. on Magnetics, 32, No. 4, p.2041-2046, 1996

[5] P. Wanderer et al., "Construction and Testing of Arc Dipoles and Quadrupoles for the Relativistic Heavy Ion Collider (RHIC) at BNL", Proc. of the 1995 Int. Conf. Particle Accelerators, Dallas, 1995.

[6] I. Vanenkov, “Using Capacitive Force Transducers for Measuring Stresses in Superconducting Magnet Coils”, LHC Internal Note 96-14, November 1996.

[7] K. Nohara, K. Okumura, and H. Sasaki, “Development of Non-Ferro-Magnetic Steel and their Applications to Accelerator Superconducting Magnets”, Presented at CEC/ICMC Conference, Columbus, Ohio, USA, June 17-21, 1995.