Design and Fabrication of a 1 m Model of the 70 mm Bore Twin Aperture Superconducting Quadrupole for the LHC Insertions

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Abstract—**For reasons of geometrical acceptance, 70 mm bore twin aperture quadrupoles are required in the LHC insertions. For an operating gradient of 160 T/m at 4.5 K, a design based on a four layer coil wound from two graded 8.2 mm NbTi conductors has been developed. Three 1 m single aperture quadrupoles of this design have been built and successfully tested. Thereafter, the magnets have been disassembled and the coils re-collared using self-supporting collars. In this paper, we describe the design features of the twin aperture quadrupole, and report on the initial collaring tests and procedures for collaring and final assembly of the 1 m magnet.**

I. Introduction

The LHC insertion quadrupole program was started in the early 1990's, with the initial goal of developing a 70 mm aperture high gradient quadrupole operating at 200 T/m in superfluid helium for the LHC low-β triplets [1]. The quadrupole is based on a four layer coil wound from two graded 8.2 mm NbTi conductors, and has also been designed for a twin aperture configuration with a nominal operating gradient of 160 T/m at 4.5 K [2]. About 20 of these magnets will be installed in the LHC experimental and dump insertions, notably in the regions of the injection and dump kickers, and in all other areas where the 56 mm coil aperture of the LHC insertion quadrupoles may give rise to aperture limitation. The experience gained with the 8.2 mm cables was also essential for the development of the low current insertion quadrupoles, which will be installed as individually powered magnets in the LHC dispersion suppressors and matching sections [3].

In collaboration with Oxford Instruments, CERN has built and tested three 1 m single aperture quadrupoles with a 70 mm bore [4]. Thereafter, the last two magnets have been disassembled, and the coils refurbished and prepared for assembly using self-supporting collars. We recall in this paper the main design features of the twin aperture quadrupole, and describe in detail the initial collaring tests and assembly procedures developed for collaring and yoking of the 1 m twin aperture quadrupole. The magnet has been recently completed and is ready for testing.

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II. Design Features

Details of the conductor parameters and coil construction have been described elsewhere [1]. To summarise, the coil has four layers made of two 8.2 mm NbTi graded conductors, with the transition between the cables in the middle of the second innermost layer. The nominal gradient of the quadrupole is 205 T/m (1.9 K) and 160 T/m (4.5 K), and two magnets have been trained in a single aperture configuration up to the conductor limit of 260 T/m (1.9 K) and 200 T/m (4.5 K) [4].

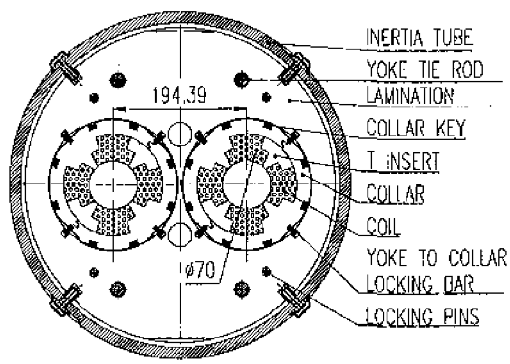

Fig. 1. Transverse cross section of the quadrupole

In contrast with the single aperture configurations, where narrow, spacer-like collars were used, a self-supporting collar system is proposed for the twin aperture quadrupole, Fig. 1. The system consists of two 22 mm wide collars covering 180 degrees, and of two inserts, located in the poles not covered by the collars. The collars are mounted by turning each successive set by 90 degrees. In the end regions, round 180 degree collars are used. The collar assembly is locked using eight full length tapered keys, which are finally fixed to the collar end plates. The pole leads are connected in the connection box which is mounted on the lead end plate, so that each collared coil can be handled as an independent unit.

For the 1 m model, the collared apertures are assembled in a twin aperture magnet using single piece yoke laminations. The mechanical link between the collared aperture and the yoke is made by four long keys at the poles, which centre the collar assemblies once the laminations are in place and locked with dowel pins. The rigidity of the yoke assembly is provided by the inertia tube, to which the laminations are locked in several positions, similar to the LHC arc quadrupole [5]. The main parameters of the quadrupole are given in Table I.

TABLE I
Main parameters of the 70 mm bore twin aperture quadrupole

Operating temperature	4.5 K
Nominal gradient	160 T/m
Nominal current	3600 A
Peak field in coil	6.16 T
Quench field	7.5 T
Percentage of the load line	82. %
Stored energy per aperture	141 kJ/m
Inductance per aperture	4.55 mH/m
Coil outer diameter (RT)	139.2 mm
Collar outer diameter (RT)	186 mm
Aperture separation (RT)	194.4 mm
Yoke inner diameter (RT)	188 mm
Yoke outer diameter (RT)	452 mm

III. Short Model Collaring Tests

A 120 mm section of the quadrupole, Fig. 2, was assembled to verify the collar design and to confirm the functionality of the tooling and collaring procedures. Certain design options, in particular the feasibility of collaring with bare keys as opposed to using interposed sliding sheets, also needed to be tested. Tests were also performed to assess whether the collar inserts could be removed from the design for ease of assembly.

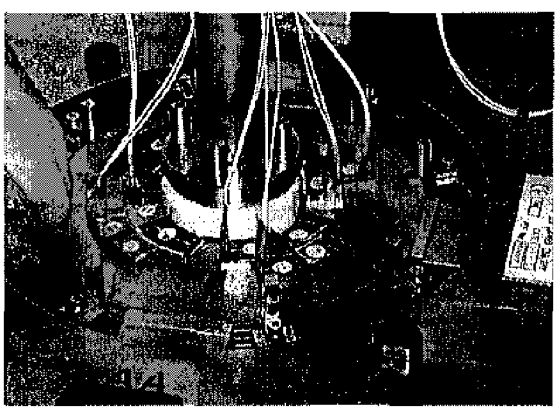

Fig. 2. Short model in the collaring press

An assembly mandrel made from a steel rod and four nylon pads which collapse when the rod is pulled out, was used for the central support. The coil was mounted around the mandrel with sections of quench heaters and ground insulation. Capacitance gauges for pressure measurement [6] were inserted in the shim grooves and positioned on the pole faces. Finally, the brass collaring shoes and the straight section collars were assembled.

The collaring press, also shown in Fig. 2, consisted of four quadrupole and eight keying rams, all rated at 10 tons. The basic idea was to use the quadrupole press to squeeze the collars to the point when the tapered keys enter the slots. The largest fraction of the coil pressure is then generated by pushing the keys fully in with the eight-way press. The exact sequence depends crucially on the compressive and frictional properties of the assembly.

In the first short model assembly full width keys were used. The coil pressures were lower than anticipated with a noticeable imbalance between the different layers (average pressure was 49, 16, 27, 30 MPa in layers 1-4, respectively). The keys could be removed easily and the model disassembled without any damage. After several rebuilds designed to shim layer 2, the average pressures increased to 59, 68, 51 and 61 MPa, respectively. However, the disassembly of the model became very difficult. In order to extract the keys, the four-way press had to be used at its maximum force and the keys hammered out. The keys and the collars were plastically deformed with fragments of keys cold welded to the key slots. It was also difficult to balance the pressures in the four layers, since adding shim to layer 2 transfered the load from adjacent layers, reducing their pressures. We found that the effective moduli of individual layers in the collared assembly behaved nonlinearly and were different than those measured in the arch tests.

In the second series of tests, the shims were sized with 80 MPa as target coil pressure. However, the 10-ton quadrupole press was not sufficient to get the keys started. A 1 mm chamfer was machined in the leading edge of the keys so that they could start with a smaller key slot, increasing the collar movement. A trial with full width keys showed, however, that the chamfer plastically deformed the collar slots and made deep dents in the keys.

The design of the collars and keys allowed for a reduction of key width by 2 mm and introduction of 1 mm thick sliding sheets on both sides of a key. The sheets provide a flat smooth surface, while spreading the internal forces. With this assembly, the keys were pushed in easily using only half the press force. On disassembly, we found no traces of cold welding. The key chamfer, however, reduced the area for transmitting the force, so that the sliding sheets showed signs of shearing. Also, some of the sliding sheets bent at the root of the key slots, preventing the keys to fully enter. An average pressure of 70 MPa was recorded with the keys in place. When the quadrupole press was released, the pressure dropped by 15 MPa, and due to creep after 16 hours, by another

10 MPa. After cooldown to 77 K, the average pressure reduced to 30 MPa. On a second thermal cycle, the pressures in the coil at room temperature and 77 K were reproduced within ±2 MPa.

The assembly was subsequently re-collared without the 'T' shaped collar inserts. For identical shims sizes, the pressure in the coil decreased by about 10 MPa. Such a large reduction is explained by the fact that the small aspect ratio of the collar (width to inner radius), determined by the available spacing between the apertures, results in their considerable ovalisation at high pressures. The inserts tend to keep the collar assembly round, and thus enhance the prestress in the coils.

The short model tests clearly demonstrated that the collar inserts and sliding sheets are essential features of the keying system. We also observed that due to nonlinear behaviour of the assembly, larger collar movement than expected was required. We concluded that the necessary movement could not be achieved with chamfered keys, and that the 10-ton quadrupole press was insufficient. A 90-ton four-way press was built and the original eight-way keying press incorporated in the new frame. Its operation was verified on a new assembly of the short model.

IV. Coil Size Measurements And Shimming

The coil size was measured in four locations along the straight section of the coil. A fixed volume system, calibrated with a precision cut steel base, was used to measure the change in shim size required to achieve the design pressure in the coil. The measurements showed that the coils were undersized on the average by 0.27, 0.55, 0.32, and 0.31 mm for layers 1-4, respectively, with an rms variation of 0.04 mm. The average layer moduli were 9.9, 10.0, 10.9 and 8.4 GPa, respectively, with variations of 10 and 20 % for layers 1 and 2, and 5 % for layers 3 and 4. The coils were sorted according to the their size to help balance the pressures between the poles. For each layer, shims were calculated corresponding to the size of each pole and target prestress of 80 MPa after collaring, and the largest shim was manufactured and installed in all four poles. In this way we expect that none of the layers will be below 40 MPa after cooldown.

In order to shim the coil ends, the assembled four layer pole was placed in a measurement cavity of the nominal size, Fig 3. The cavity was closed and the pressures in the four layers measured using a set of four capacitance gauges. The pressure in each layer was iteratively adjusted by adding shims to the mid-plane. The final shim in the coil ends was divided into three sections. In the section covering the ramp box, a shim size corresponding to the pressure in the magnet straight section was used. In the region of the end turns, the shims were tapered from the ramp box size to zero. Finally, no shims were placed in the coil heads.

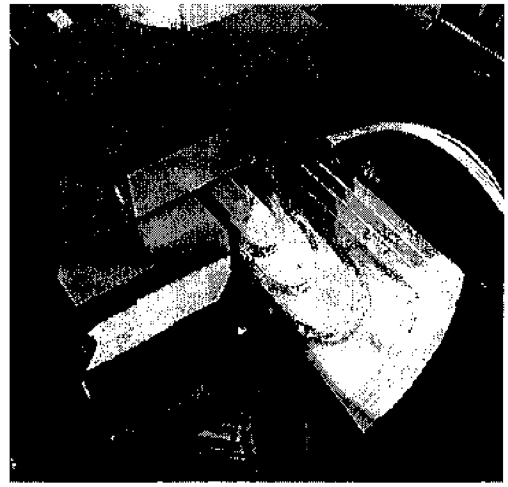

Fig. 3. Measurement of coil size in the ends

V. Magnet Assembly

It was foreseen that the collaring of the quadrupole apertures was to be done using full length keys. This aspect of the design could not be tested on the short model, and presented the greatest unknown in the assembly of the magnet. Furthermore, as the coil ends were found to be quite soft, the transition region between the straight section and the coil ends was expected to be particularly delicate.

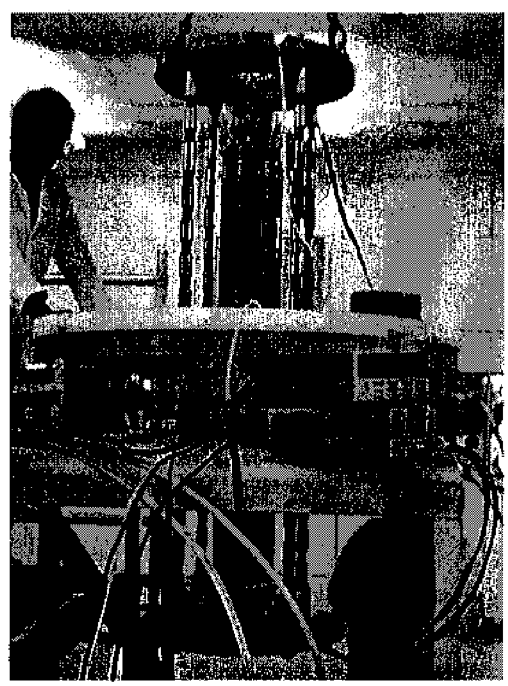

Fig. 4. Collaring of the quadrupole using full length keys

The four poles were assembled around a collapsible mandrel, and the assembly introduced in the collaring press, as shown in Fig. 4. In the first step, the coils were compressed over 100 mm with 50 ton force in the quadrupole press, and a set of four 100 mm full width keys were inserted without sliding sheets in every second slot. As the keys were pushed in successively over the whole length of the magnet, the adjacent slots opened sufficiently for inserting a set of 1.5 mm undersized short keys and full length sliding sheets. These were subsequently pushed in, and the previously filled slots opened for a set of still larger keys. At this stage, the mandrel was extracted. After three further steps, reaching an undersize of 0.25 mm, it was possible to introduce nominal full length keys in one of the quadrant slots. These were pushed 2/3 of the way, and the second set of full length keys introduced. In the final stage, all eight full length keys were pushed fully in and fixed to the end plates. The complete collaring operation required eight passes and five sets of 100 mm intermediate width keys. As shown in Fig. 5, the prestress in the coils progressively increased and after releasing the press averaged 100 MPa, with a minimum of 90 MPa in layer 3.

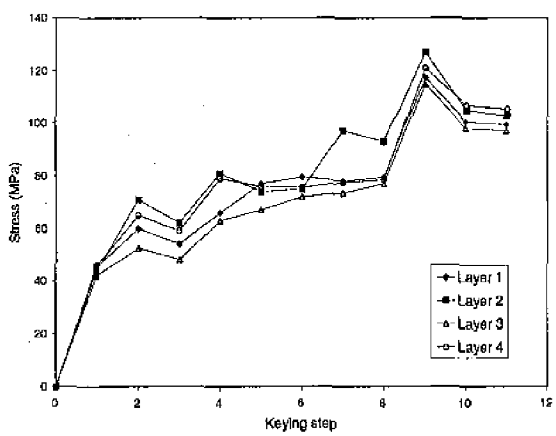

Fig. 5. Average prestress in the coil. Steps 1-7: progressive compression with 100 mm long undersized keys. Full length keys inserted in step 8 and pushed fully in (9). Collaring press released (10); relaxation after one day (11).

The assembly of the magnet proceeded with jointing of the poles and completing the instrumentation. In the last phase, the two collared apertures were placed vertically in the yoke end plate with the connection boxes at the bottom. Four full length centring keys were fitted into the slots in the collar poles, and yoke laminations lowered over the apertures one at a time. A small press was used to align a 5 cm pack of laminations, Fig. 6, which was locked with staggered dowel pins. The yoke was finally longitudinally secured with four tie rods, and the inertia tube fitted over the yoke.

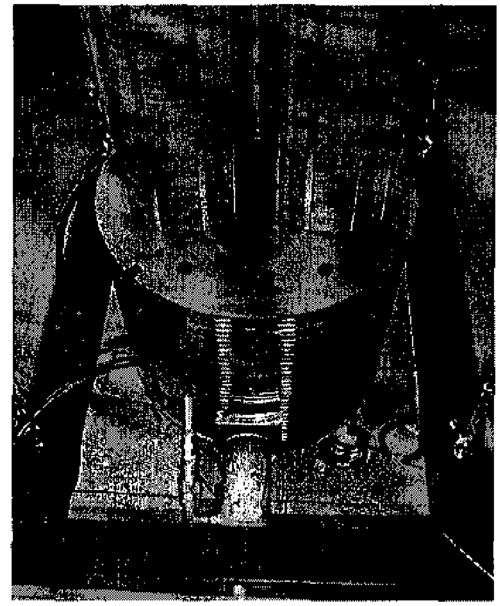

Fig. 6. Assembly of the collared apertures in the two-in-one yoke laminations.

VI. Conclusions

A 1 m model of the 70 mm bore twin aperture quadrupole for the LHC insertions has been designed and built. The four layer quadrupole coils, previously tested in single aperture configuration, were re-shimmed and assembled using self-supporting collars. Full length keys were used for locking the collars which were progressively compressed with undersized short keys. The collared apertures were assembled in the twin aperture quadrupole using single piece laminations and an inertia tube, and the magnet made ready for testing.

References

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