FERMILAB-CONF-05-399-TD

Production and Installation of the LHC low-β Triplets

S. Feher, R. Bossert, J. DiMarco, M. Karppinen, J. Kerby, N. Kimura, M. J. Lamm, T. Nakamoto, T. Nicol, A. Nobrega, T. Ogitsu, N. Ohuchi, R. Ostojic, T. Page, T. Peterson, R. Rabehl, P. Schlabach, T. Shintomi, J. Strait, C. Sylvester, M. Tartaglia, T. Taylor, K. Tsuchiya, W. Venturini Delsolaro, G. V. Velev, A. Yamamoto

***Abstract*—The LHC performance depends critically on the low-β triplets, located on either side of the four interaction points. Each triplet consists of four superconducting quadrupole magnets, which must operate reliably at up to 215 T/m, sustain extremely high heat loads and have an excellent field quality. A collaboration of CERN, Fermilab and KEK was formed in 1996 to design and build the triplet systems, and after nine years of joint effort the production has been completed in 2005. We retrace the main events of the project and present the design features and performance of the low-β quadrupoles, built by KEK and Fermilab, as well as of other vital elements of the triplet. The tunnel installation of the first triplet and plans for commissioning in the LHC are also presented. Apart from the excellent technical results, the construction of the LHC low-β triplets has been a highly enriching experience combining harmoniously the different competences and approaches to engineering in a style reminiscent of high energy physics experiment collaborations, and rarely before achieved in construction of an accelerator.**

***Index Terms*—Correctors, LHC, Quadrupole, Super-conducting magnets,**

I. Overview

IN preparing the approval of the LHC project in 1994, the CERN Council invited all interested countries to contribute to the LHC construction. The discussions between CERN, the US and Japanese accelerator communities, management and government authorities were concluded in 1996 with the agreement that the US and Japan would provide 16 low-β quadrupoles each, half of the number required for the LHC experimental insertions. In addition, the US agreed to provide the cryostat elements and assemble all triplet quadrupoles, and furnish the cryo-feedboxes, which link the triplet to the LHC cryogenic and power distribution systems. In early 1996, a collaboration was formed between teams from CERN, Fermilab and KEK, who were respectively charged to lead the effort from the US and Japan. The collaboration supervised all phases of triplet construction, starting from the initial magnet R&D, and up to the fabrication, testing and delivery to CERN of the 32 low-β quadrupoles. After nine years, the joint effort will be completed in 2005. In the following, we retrace the main phases of the project, present the performance of the low-β quadrupoles and report on the installation status of the first triplet at CERN.

Manuscript received September 20, 2005.

S. Feher, R. Bossert, J. DiMarco, J. Kerby, M. J. Lamm, T. Nicol, A. Nobrega, T. Page, T. Peterson, R. Rabehl, P. Schlabach, J. Strait, C. Sylvester, M. Tartaglia, and G. V. Velev are with the Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Il 60510, USA (phone: 630-840-2240; fax: 630-840-2393; e-mail: fehers@ fnal.gov).

M. Karppinen, R. Ostojic, T. Taylor and W. Venturini Delsolaro are with CERN, 1211 Geneva 23, Switzerland.

N. Kimura, T. Nakamoto, T. Ogitsu, N. Ohuchi, T. Shintomi, K. Tsuchuiya and A. Yamamoto are with KEK High Energy Accelerator Research Organization, Ibaraki 305-0801, Japan.

II. Triplet Design

The LHC low-β triplet layout is shown in Fig. 1. It is composed of four quadrupoles with a coil aperture of 70 mm [1]. The magnets are cooled with 1.9 K superfluid helium using an external heat exchanger system capable of extracting up to 10 W/m. Two types of quadrupoles are used in the triplet, 6.6 m long MQXA magnets designed and developed by KEK, and 5.7 m long MQXB magnets designed and built by Fermilab. The MQXA magnets are placed as Q1 and Q3 quadrupoles, while the two MQXB are located as the Q2 quadrupole. The Q1 magnet is placed at 23 m from the interaction point. Together with the orbit correctors MCBX, skew quadrupole MQSX and multipole correctors supplied by CERN, the low-β quadrupole cold masses are completed and cryostated by Fermilab.

Together with the LHC main dipoles, the high-gradient wide-aperture low-β quadrupoles are the most demanding magnets in the LHC. They must operate reliably at 215 T/m,

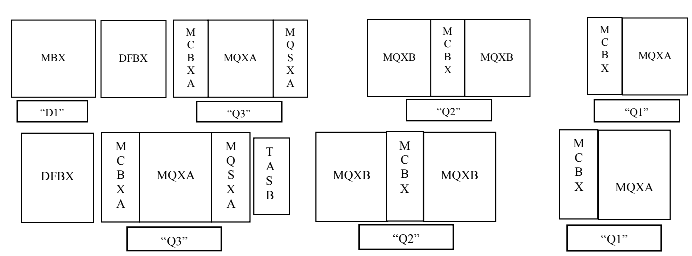

Fig. 1. Superconducting magnets and related components for the LHC interaction region for the low luminosity interaction points (top) and the high luminosity interaction point (bottom).

have a very good field quality, and sustain high heat loads generated by secondaries emanating from beam collisions. Initially, each triplet consisted of one type of quadrupole so that Fermilab and KEK could choose a magnet design best suited to their own experience and engineering style. In order to validate their design choices, Fermilab and KEK launched comprehensive R&D programmes comprising a number of short model magnets. Both programmes were successful in fulfilling the design goals and demonstrating the LHC operational requirements.

As a result of better understanding of the magnets, the initial layout of the triplet was modified on several occasions. The most important decision was to "mix" the triplet, i.e. incorporate KEK and Fermilab magnets in a single string. This decision was taken in order to improve the performance of the triplets and to reduce the costs of building magnets of different length by each laboratory. Another important modification was the reduction of the number and strength of the multipole correctors, which was the result of a better field quality of the quadrupoles than initially anticipated.

III. Low-β Quadrupoles

The design of the MQXA quadrupole is based on a four-layer coil using two 11 mm wide Rutherford-type graded NbTi cables [2]. The coils are wound and cured in two separate double layers and are assembled using spacer-type collars. The pre-stress in the coils and their rigidity is provided by the yoke structure, which consists of horizontally split laminations keyed at the mid-plane.

Five 1 m long model magnets were built and tested at KEK from 1998 to 2000. The measurements of the first two model magnets revealed that the value of the b_{10} harmonic term in the initial design had to be reduced, as indicated by beam dynamics studies made in the meantime. The b_{10} term was successfully corrected by making a minor adjustment to the coil and to the shims and collars. This strategy also allowed

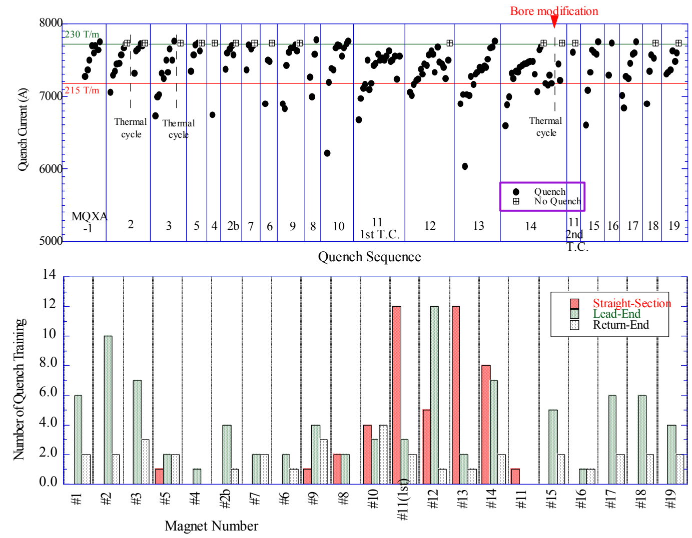

Fig. 2. Training history of the MQXA quadrupoles.

the simultaneous reduction of the b_6 term. The modifications were tested in the remaining model magnets and two full-length prototypes and applied in all series magnets.

The production of 20 MQXA magnets, including four spares, was completed in 2004. The magnets were tested in the vertical testing facility in KEK. They were systematically trained to 230 T/m to guarantee safe operation in presence of high heat load. The acceptance criterion for both MQXA and MQXB quadrupoles was that following training and a full-energy dump, the magnets should be powered to 220 T/m without quench. All MQXA magnets satisfied this criterion. As shown in Fig. 2, the number of training quenches increased for magnets in the middle of the series, which was traced to the movement of the warm bore, installed to provide a suitable environment for field measurements. After improving the radial support of the tube, the number of training quenches returned to normal. All MQXA quadrupoles were systematically measured for static and dynamic field effects. The field quality of the production magnets is compared to

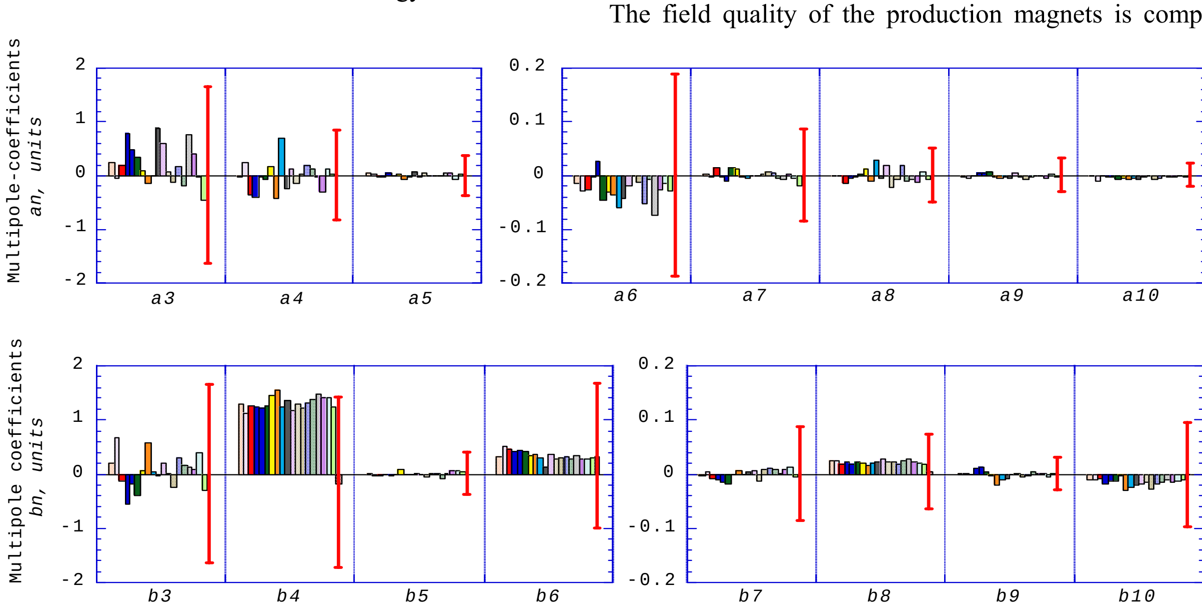

Fig. 3. Measured multipole components of the MQXA quadrupoles at 217 T/m in units of 10^{-4} at R_{ref} of 17 mm.

target values in Fig. 3.

Nineteen MQXA magnets were shipped from KEK to Fermilab for further assembly and cryostating. The remaining one will be delivered directly to CERN as an additional spare. As agreed by the collaboration, the first Q1 and Q3 quadrupoles were retested in Fermilab as completed cryo-magnets. As expected, the magnets reached nominal field gradient without quenching and the test also confirmed that the assembly operations performed by Fermilab is adequate.

The MQXB design features a two-layer coil, with each layer individually wound using a 15.4 mm wide Rutherford-type NbTi cable [3]. The coils are assembled using free-standing Stainless Steel collars, which provide the pre-stress and balance the magnetic forces. The collared assembly is aligned in the yoke structure with precision keys and the magnet is enclosed in a stainless steel helium vessel consisting of half-shells welded at the pole plane.

Fermilab built and tested nine 2 m long model magnets from 1997 to 2001. The first magnets showed poor quench training and several modifications in the coil design, the most important of which was the change of material for end parts, were introduced before satisfactory performance was obtained. All magnets showed very good field quality. One full-length prototype was also built and fully satisfied the operating requirements.

Fermilab has built 18 MQXB magnets and nine Q2 quadrupoles, including one spare, were tested as completed cryo-magnets. As shown in Fig. 4, most magnets reached 230 T/m after a few training quenches. Two magnets, however, trained to a plateau of 200 T/m, while another developed an open protection circuit. These magnets will be repaired and retested before shipping to CERN.

The integral field harmonics have been measured for all magnets at injection and collision energies. Measured harmonics are compared to target values in Fig. 5.

IV. Correctors

Each triplet is equipped with horizontal and vertical orbit

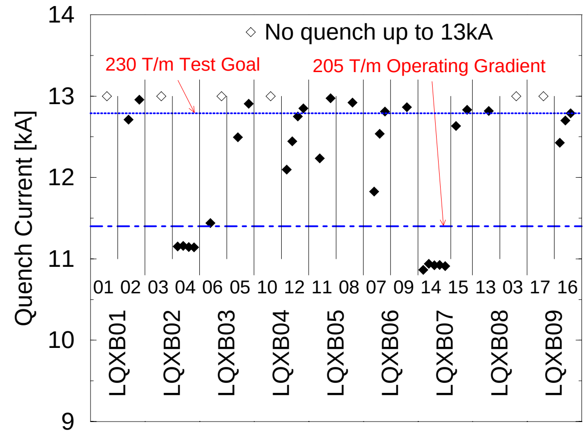

Fig. 4. Training history of MQXB quadrupoles.

correctors, a skew quadrupole and multipole correctors. The dipoles have nested coils with an inner bore of 90 mm, providing space for the multipole inserts, and are made by winding superconducting wires pre-assembled as a flat ribbon [1]. The coils are epoxy impregnated. The other correctors are made using a similar technique but with different wires.

All correctors were tested at CERN before delivery to Fermilab. These tests were necessary to guarantee the nominal current of impregnated coils in various field configurations that occur in nested layers. Indeed, the training of the pre-series orbit correctors proved lengthy, and the series magnets required on average about 10 quenches to reach nominal current.

V. Cryostats and Cooling System

Components for the inner triplet are either built at FNAL or shipped to FNAL for final assembly. The cooling system of the triplet consists of a linear heat exchanger which is modeled after the arc dipoles, i.e. a two phase helium volume

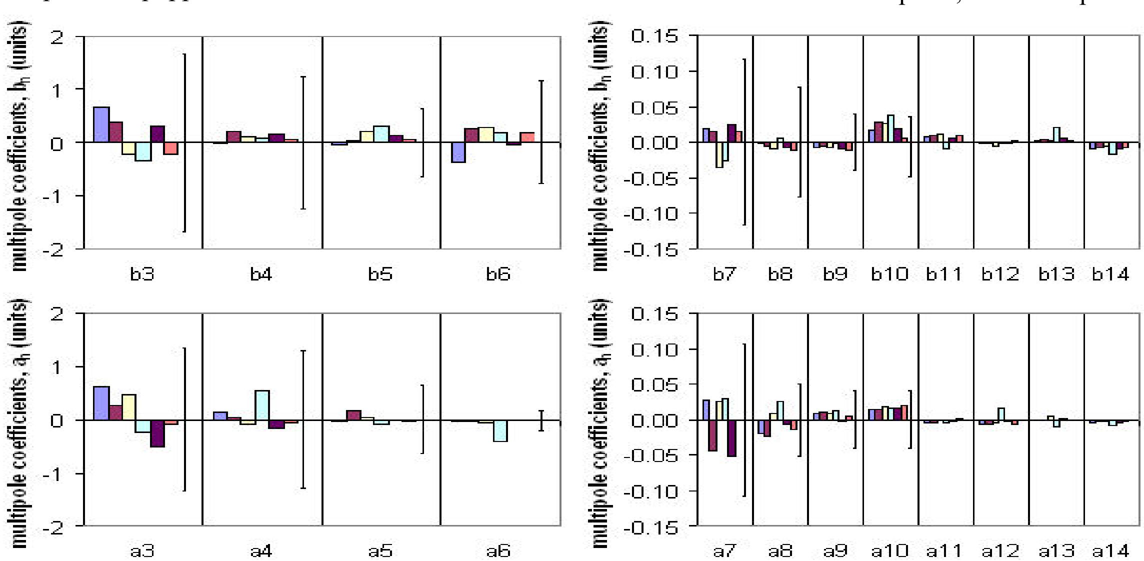

Fig. 5. Measured multipole components of the LQXB quadrupoles at collision energy in units of 10^{-4} at R_{ref} of 17 mm.

in a corrugated copper pipe, surrounded by the static single phase superfluid volume. Unlike the arc dipole and

Fig. 6. Heat Exchanger and supports for the inner triplet quadrupoles.

quadrupoles, the superfluid heat exchanger element, shown in Fig. 6, is located outside of the cold mass. It was determined during the design program and verified experimentally that a heater exchanger located inside the cold mass cooling channel would not allow for a copper heater exchange pipe large enough to accommodate the significant heat load which is expected to be 180 W at full operation luminosity.

The alignment stability of the quadrupoles is provided by a composite "spider" suspension system which supports the cold mass and internal piping similar to structures used in the cryogenic transfer lines. These structures are very strong and

Fig. 7. LHC Low-β triplet assembled at CERN before installation in the LHC tunnel.

stiff in the radial direction and make good use of radial space. They also should give small displacements of the geometric magnet axis. These elements do have higher heat loads than the more traditional post designs, but these loads are small compared to the expected 180W heat load on the whole system. To better distribute the axial loads to all the support spiders each pair of spiders has a set of axial tie-bars to tie them together. The tie-bars are made from Invar tube to minimize axial forces imposed on the supports during cool down. The supports are shown in Fig. 6. For alignment purposes, the position of the supports can be adjusted through vacuum ports in the cryostat vessel. Finally additional restraints are added prior to shipping to reduce the risk of support damage.

VI. Installation and Commissioning

The first completed low-β quadrupole arrived at CERN mid 2004, and to date a third of the quadrupoles have been delivered. Inspection at CERN revealed that the spider support in three quadrupoles suffered damage in shipment due to transport in violation of the shipping instructions and will need to be repaired. All remaining magnets will be shipped to CERN by early 2006.

The installation of the first low-β triplet is foreseen in October 2005. As the magnets were already available, the collaboration decided to proceed with the assembly of the triplet in an experimental hall in CERN. The triplet assembly, shown in Fig. 7, was completed in April 2005 and the insulation vacuum pumped down for the first time. The assembly was an extremely valuable exercise, in particular for checking the components, tooling and procedures for completing the interconnections between magnets, which were all supplied by Fermilab. Due to lack of cryogenic infrastructure it was not possible to cool down the string. This phase of hardware commissioning is foreseen in the LHC tunnel in early 2006 with participation of the members of the collaboration, whose experience in testing the magnets will be a further valuable contribution to the LHC.

VII. Conclusion

The construction of the low-β triplets for the LHC was carried out in the framework of a collaboration between CERN, Fermilab and KEK started in 1996. The successful production, testing and assembly of the quadrupole magnets and other elements of the triplet, in time and in budget, are a demonstration of the ability of accelerator laboratories to collaborate internationally in the supply of state-of-the-art equipment for large projects.

Acknowledgment

The authors would like to thank all the collaborators from BNL, CERN, FNAL, KEK and LBNL who participated in this successful LHC accelerator project, and also to acknowledge the management of each laboratory for their support.

References

[1] LHC Design Report, Vol.1, "The LHC Main Ring", CERN-2004-003.
[2] A. Yamamoto et al., "Production and Measurement of the MQXA Series of LHC Low-beta Insertion Quadrupoles", ASC 2004, Jacksonville, FL, October 2004.
[3] S. Feher et al., "Test Results of LHC Interaction Regions Quadrupoles Produced by Fermilab", ASC 2004, Jacksonville, FL, October 2004.