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Production of the Superconducting Matching Quadrupoles for the LHC Insertions

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***Abstract*— The LHC insertions are equipped with individually powered superconducting quadrupole assemblies comprising several quadrupole magnets and orbit correctors, and range in length from 5.3 m to 11.3 m. Following the initial experience in the assembly of the pre-series cold masses, the production has advanced well and about half of the total of 82 units has been produced at CERN. In this paper we present the experience gained in steering the cold mass production, in particular with respect to the alignment requirements. We also report on the field quality and other measurements made for assuring the quality of the quadrupoles.**

Index Terms— **LHC, insertions, superconducting, quadrupoles**

I. Introduction

THE LHC dispersion suppressors and matching sections contain individually powered quadrupoles, which provide the required tuning of the insertions [1]. These cryomagnets comprise several superconducting quadrupoles of the MQM or MQY types [2] arranged to give the necessary field strength. In the dispersion suppressors the quadrupoles are part of the continuous arc cryostat and are operated at 1.9 K. They are independently powered but provide identical cryogenic and powering interfaces to the adjacent main dipoles as in the regular arc cells. Most of the quadrupoles in the matching sections are stand-alone units and are cooled in a static helium bath at 4.5 K. Although in principle simpler, their cryogenic and powering interfaces are determined by the local conditions of each insertion (e.g. slope of the tunnel, interference with injection lines etc.). This customization leads to 31 types of cold masses arranged in 11 families with 6 different lengths from 5.35 up to 11.35 m, as shown in Fig. 1.

The insertion quadrupole cold masses are assembled in the LHC Magnet Assembly Facility at CERN. To date, 44 quadrupole assemblies, half of the total production, have been completed. Approximately twenty of them have been cryostated and cold tested. In this paper we present the experience in steering the cold mass production, in particular with respect to the alignment requirements.

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II. Magnet Performance tests

The MQM and MQY magnets are tested individually in the vertical test cryostat at CERN as part of the acceptance tests. To date, 29 MQM type magnets and 16 MQY magnets have been tested. As shown in Fig. 2, both MQM and MQY magnets exhibit a very fast training with an average of 0.26 and 0.31 quenches respectively to reach nominal current (corresponding to the 7 TeV LHC collision energy) and 1.03 and 2.34 quenches to reach ultimate current in the LHC (corresponding to 9 T in the LHC main dipoles). No detraining after provoked quenches or thermal cycles was observed.

The optics of the LHC insertions is such that most quadrupoles in the matching sections see transverse beam sizes which are significantly larger than in the arcs and dispersion suppressors. For this reason, and in view of improving the field quality of a subset of cold masses, the magnets are assigned to a particular cold mass on the basis of their field quality measured during production. Based on this data the magnets are combined in a given cold mass such that the resulting harmonics are minimized. The random field multipoles of the series MQM quadrupoles are shown in Fig. 3, where the full lines represent the acceptable limits [3]. Open points in the figure represent the random errors of the subset of the cold masses where magnets have been sorted.

III. Cold mass production

The design of the cold masses and the different stages of assembly are described in detail in [4]. As the assembly of the pre-series magnets confirmed all assembly steps, no major changes were made in the series built magnets. In the following, we summarize the status of the production.

A. Components

Most of the major components for assembly of the cold masses have been delivered, and the assembly schedule is now determined by the delivery and test rate of individual magnets. Detailed inspections are systematically carried out before and during assembly to handle the non-conformities as soon as possible. Regular contacts with the suppliers have considerably improved the quality of the components.

B. Assembly procedure

The cold mass assembly is made of five major work packages: magnet reception, mechanical and electrical assembly, longitudinal welding, assembly of the extremities and the final checks. Based on the experience gained in the pre-series, the details of the fabrication steps were slightly revised to ease the work flow and to improve the quality control. The main improvements are the following:

The analysis of the alignment data of the pre-series magnets measured with a laser tracker showed that the magnet laminations are aligned to better than ±0.2 mm independently of the magnet length. Estimated as sufficient, the individual magnet geometry is no longer systematically measured.

The positioning of the magnet in the half shell has a major influence on the final geometry of the cold mass. The influence of the assembly benches, tooling and shell geometry were examined in detail. Several improvements were introduced: sorting of the shells based on geometry reports, machining of a reference surface on the alignment cradles and replacing the level gauge measuring system by measurements with a laser tracker. The laser tracker is also used to determine the magnet straightness and positions once the cradles are removed.

Another delicate step in the assembly is the connection of the magnet electrical circuits and instrumentation wiring. The interconnection tooling was improved and considerable care is taken in the use of appropriate materials to guaranty the integrity and stability of the connections. Mobile acquisition racks and dedicated software were developed to perform electrical tests during the assembly process.

Considerable effort went into development and qualification of the longitudinal welding. As a consequence, we have not detected any major non-conformity in the X-ray examination of the welds. The complete revision of the welding press before series production has also contributed to the weld quality.

The positioning of the end domes on the cold mass is one of the most critical operations which must guarantee tight tolerances necessary for interconnecting the beam tubes and cryogenic lines between adjacent cryo-magnets. Substantial work has been done to develop efficient software and to refine the measuring procedure so that assembly of the end domes is performed with a high accuracy and repeatability.

C. Assembly organization

The assembly of the LHC insertion quadrupoles is performed in the CERN Magnet Assembly Facility shown in Fig 4. The layout of the facility was revised to take into account the requirements of the work flow and to optimize the execution time of each operation. In order to follow the changes in the LHC installation planning, the assembly rate had to be increased considerably with respect to initial planning. The tooling and time distribution strategy and the training of the staff and skills sharing were improved. As a result, the production rate increased by a factor of almost 4 since the beginning of 2005, as shown on Fig 5.

D. Quality control and component traceability

During cold mass assembly, several measurements are taken to check the quality of production. Among the large number of measurements, the most important are uploaded in the MTF (Manufacturing and Test Files) database. A common structure for the insertion quadrupoles was designed in the MTF web interface which allows presentation of results, storage of data and handling of non-conformities. The most important data are the following.

1) Magnet alignment

Before longitudinal welding, the straightness of each magnet in the cold mass reference system is measured and compared to nominal values.

2) Weld examination

The cold mass is designed as a pressure vessel and critical welds are X-rayed at a rate of 100% for the longitudinal welding coupons, and 10 % for the end dome welds. The X-ray tests are performed by qualified companies who also establish test certificates.

3) Cold mass geometry

The cold mass reference coordinate system is defined on the basis of measurements of the beam tubes. Deviations from the nominal position of beam tubes are monitored, and critical interface points are expressed in this reference system.

4) Electrical checks

The impedance and insulation of the magnet and continuity of the instrumentation are checked at several fabrication points. The integrity of the quench heater circuits are also checked by high current discharge. Successfully passed tests are a pre-requisite for proceeding to the next assembly step. The final measurements are up-loaded in the MTF data base.

5) Warm magnetic measurements

As one of the final measurements, the integral harmonics, transfer function and magnetic length are measured at room temperature. These measurements are also used to check the polarity and electrical connections of the quadrupoles. The efficiency of magnet sorting for reduction of the random errors of low-order field multipoles is also evaluated.

6) Pressure and leak tests

The objective of the room temperature leak test is to measure helium leak rates of the cold mass, cold bores and heat exchanger. The leak test is made by measuring the helium concentration in each of the evacuated enclosures after pressurization with helium gas. The test pressures are 2.6 MPa in the cold mass and 0.5 MPa in the heat exchanger (internal pressure).

IV. ALIGNMENT RESULTS

For the purpose of geometry definition, the theoretical shape of an insertion quadrupole is described as two ideal parallel cylinders (beam tubes) separated by 194.4 mm. The mechanical plane of the quadrupole is defined as the best fit to the shape of the two cylinders; the mechanical axis is the intersection of the mechanical plane with an orthogonal plane equidistant (on average) from the two cylinders. The reference system consisting of orthonormal vectors in these two planes and along the mechanical axis is used to express the alignment measurements.

A. Individual magnet alignment

The alignment of the magnets is checked by measuring two precision facets on the magnet laminations with the laser tracker. The magnet axis then corresponds to the best fit of the lamination centers, as shown in Fig. 6. The local coordinate system is defined such that the Z axis minimizes the local twist. The magnet straightness is defined by local deviations in X and Z directions. The statistics of the alignment results of 70 magnets is given in Fig 6.

The position of the MQM and MQY magnets in the cold mass is given by the roll ϕ, pitch θ and yaw ψ angles, as shown on Fig. 7. The dispersion in yaw angle is minimized by the control of the shell straightness. The roll and pitch angles are determined by the alignment cradles, positioned using a laser tracker. Clearly, the good alignment of the magnets is a key point for the final cold mass geometry.

B. Cold mass geometry

The final cold mass geometry is determined by 3D measurements of the two beam tubes using a laser tracker. The statistics of the measurements, shown in Fig. 8, corresponds well to independent Gaussian distributions in the two planes. The spread of the measurements is 0.221 mm in the horizontal plane and 0.339 mm in the vertical plane. The extremities of the beam tubes are aligned to better than ±0.2 mm on the BPM side and ±0.4 mm on the lyra side of the cold mass.

The difference between the two planes comes mostly from the general tendency of the beam tube to sag inside the correctors. From Fig 7, the correctors are on average about 0.3 mm below the quadrupole axis before welding. This is partly expected as the supports of the cold mass are placed in order to minimize the sag along the quadrupole and to keep it bellow 0.25 mm in the correctors. Furthermore, the radial clearance between the beam tubes and magnet coils is larger in the correctors than in the quadrupoles. The shift has been reduced in the recent production by sorting the half shells. In addition, we have found that few beam tubes are locally out of tolerance by as much as 1 mm. To limit the deviations, cold bores are now systematically inspected before assembly. All these measures, in addition to the experience gained in the production process, have contributed to improving the alignment of the cold masses. The spread in beam tube measurements are given in Table 1 for subsets of ten cold masses corresponding to the chronological order of production. As shown, the spread in the vertical plane has steadily reduced to 0.25 mm, and is fully compatible in the recent production to that in the horizontal plane. It should be noted that the measurement reproducibility on a large sample of measurements is about 0.1 mm.

V. Conclusions

The production of the superconducting quadrupoles for the LHC insertions has advanced well. Two thirds of the individual magnets have been delivered. Following a pre-series production and improvements in the tooling and organization, the assembly of the quadrupoles has increased to a steady rate of 4 quadrupoles per month. Half of the production has been completed by September 2005 and its completion is scheduled for mid-2006. Cold tests reveal excellent quench behavior of the magnets and their field quality is stable and well within the tolerances. The alignment of the quadrupoles is conform to the very tight tolerances and continues to improve.

Acknowledgments

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References

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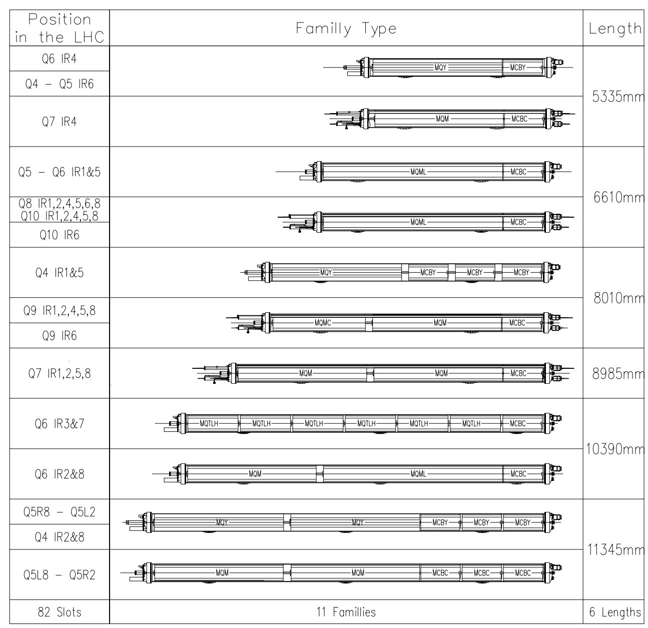


Fig. 1. LHC insertion quadrupoles by type and length.

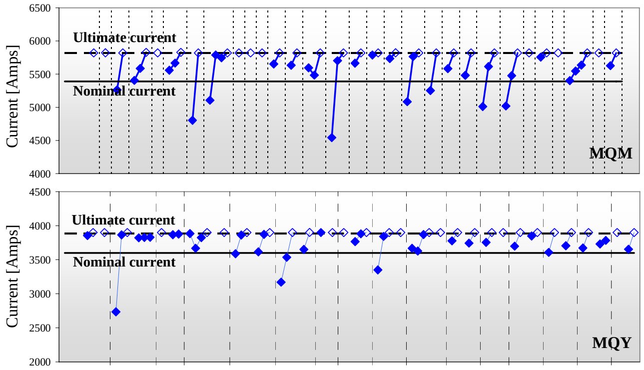


Fig. 2. Powering history of MQM and MQY magnets (open symbols: powering without training quench).

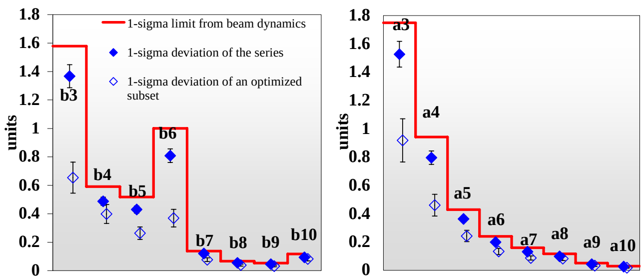


Fig. 3. Random normal and skew field multipoles of the MQM magnets (142 apertures). Target limits are indicated by the full lines.

Fig. 4. LHC Magnet Assembly Facility at CERN.

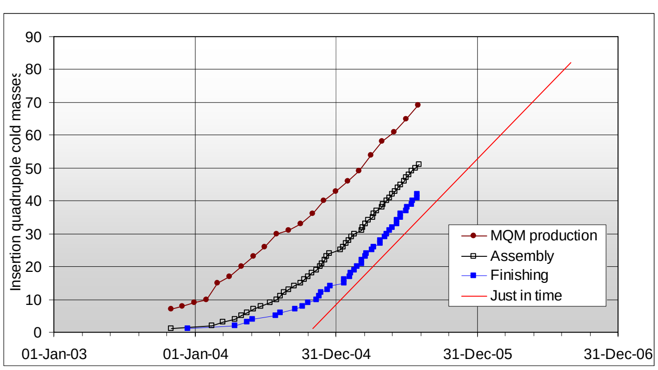
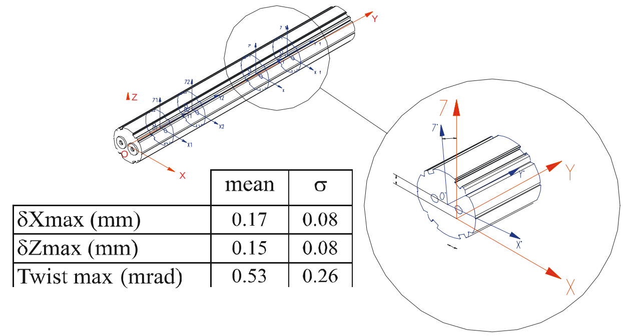
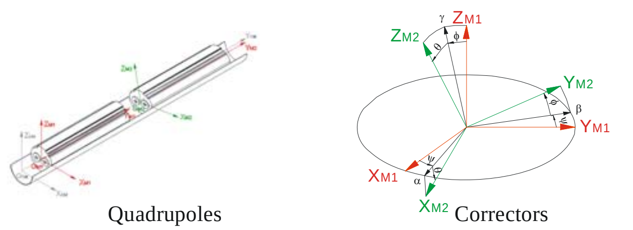


Fig 5. Production rate of the LHC insertion quadrupoles.



	mean	σ
δXmax (mm)	0.17	0.08
δZmax (mm)	0.15	0.08
Twist max (mrad)	0.53	0.26

Fig. 6. Results of individual magnet alignment, straightness and twist.



Quadrupoles

	mean	σ
ΔX (mm)	0.001	0.022
ΔZ (mm)	0.002	0.027
ϕ (mrad)	-0.009	0.078
θ (mrad)	0.006	0.193
ψ (mrad)	-0.012	0.061

Correctors

	mean	σ
ΔX (mm)	0.003	0.250
ΔZ (mm)	-0.303	0.231
ϕ (mrad)	-0.143	0.182
θ (mrad)	-0.059	0.389
ψ (mrad)	-0.036	0.209

Fig 7. Statistics of positioning of the magnets in the half shell.

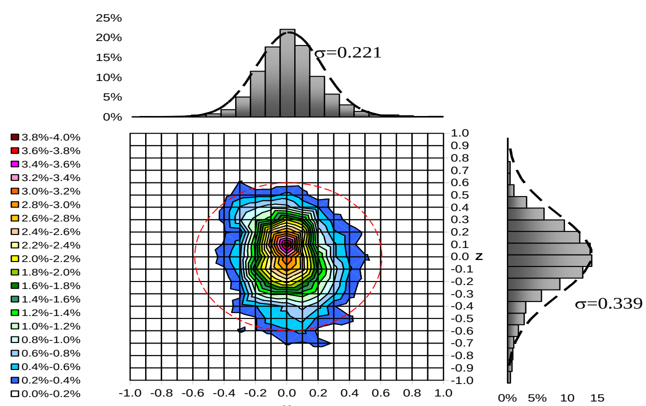


Fig. 8. Distribution of the beam tube measurements in the horizontal and vertical planes.

TABLE I
SPREAD OF THE BEAM TUBE MEASUREMENTS PER FABRICATION DECADE

Series number	1-10	11-20	21-30	31-40
σ_x	0.202	0.241	0.209	0.226
σ_z	0.416	0.333	0.332	0.247