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THE QUADRUPOLE MAGNETS FOR THE LHC INJECTION TRANSFER LINES

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Abstract

Two injection transfer lines, each about 2.8 km long, are being built to transfer protons at 450 GeV from the Super Proton Synchrotron (SPS) to the Large Hadron Collider (LHC). A total of 180 quadrupole magnets are required; they are produced in the framework of the contribution of the Russian Federation to the construction of the LHC. The classical quadrupoles, built from laminated steel cores and copper coils, have a core length of 1.4 m, an inscribed diameter of 32 mm and a strength of 53.5 T/m at a current of 530 A. The total weight of one magnet is 1.1 ton. For obtaining the required field quality at the small inscribed diameter, great care in the stamping of the laminations and the assembly of quadrants is necessary. Special instruments have been developed to measure, with a precision of some μm, the variations of the pole gaps over the full length of the magnet and correlate them to the obtained field distribution. The design has been developed in a collaboration between BINP and CERN. Fabrication and the magnetic measurements are done at BINP and should be finished at the end of the year 2000.

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***Abstract* — Two injection transfer lines, each about 2.8 km long, are being built to transfer protons at 450 GeV from the Super Proton Synchrotron (SPS) to the Large Hadron Collider (LHC). A total of 180 quadrupole magnets are required; they are produced in the framework of the contribution of the Russian Federation to the construction of the LHC. The classical quadrupoles, built from laminated steel cores and copper coils, have a core length of 1.4 m, an inscribed diameter of 32 mm and a strength of 53.5 T/m at a current of 530 A. The total weight of one magnet is 1.1 ton. For obtaining the required field quality at the small inscribed diameter, great care in the stamping of the laminations and the assembly of quadrants is necessary. Special instruments have been developed to measure, with a precision of some µm, the variations of the pole gaps over the full length of the magnet and correlate them to the obtained field distribution. The design has been developed in a collaboration between BINP and CERN. Fabrication and the magnetic measurements are done at BINP and should be finished at the end of the year 2000.**

I. INTRODUCTION

The magnet system for the LHC Injection transfer lines[1,2] will consist of a large number of recuperated magnets from then closed facilities and of newly constructed magnets[3] of three different types. Two of them, the main dipoles MBI and the main quadrupoles MQI have been designed in a collaboration between BINP and CERN and are now fabricated and measured at BINP Novosibirsk. An evaluation of the total costs of construction and operation comparing super-conducting and classical technology lead to a clear advantage of warm magnets, keeping in mind, that the transfer lines will be used only during short periods per day for filling the LHC. Table 1 is summarizing the main parameters of the MQI quadrupole.

II. DESIGN

The MQI quadrupole is built from four quadrants made of laminated low-carbon steel sheet of 1 mm thickness, massive end-plates (30 mm) and water cooled copper coils. Its ratio of length to half-aperture is large (87.5). Stiffness is obtained by a welded construction using angular plates of 140 mm x 140 mm. The coils are operated electrically and hydraulically in series. One of the basic design aims was a minimization of the physical size of the magnet. It was obtained by extending a good field region $\Delta\int G dz/\int G_0 dz < 2*10^{-3}$ over x,y = ±20 mm, including an area outside the inscribed circle of 16 mm radius between the poles. Thus, in places where a larger aperture is needed elliptic vacuum chambers will be used.

Table 1: MQI main parameters

Number of MQI magnets	**180**
Radius of inscribed circle	16 mm
Nominal gradient	53.5 T/m
Dimensions	
Core length	1.4 m
Overall magnet width	392 mm
Overall magnet height	441 mm
Coil	
Resistance (20° C)	36 mΩ
Inductance	13 mH
Excitation	
Nominal current	530 A
Dissipated power	2.2 kW
Water flow rate at 4 bar	1.5 l/min
Weight	
Total weight	1100 kg

The pole profile has been chosen such that all influence of end-fields on the integral of the gradient is exclusively corrected in the end regions by an optimized end chamfer. The gradient profile inside the magnet will then be flat up-to the limits of the good field region. A different approach would be to include some compensation of end-field effects in the 2-D-profile. This concept was also analyzed, but because of some non-flatness of the gradient profile off-axis at x>10 mm it was finally not realized. A plot of the gradient distribution from 2-D calculations (MERMAID; OPERA – 2D) for the pole profile chosen is shown in fig. 1.

The pole shape consists of the hyperbolic part, tangent to the hyperbola and then a parallel straight section for the convenience of assembly and control of the assembly precision. For the first order correction of end-fields a chamfer was developed on the pre-series magnets MQI001 and MQI002 in view of obtaining maximum homogeneity of the integrated gradient within the specified good field region. For a simple 45° flat end chamfer the optimum length was reached at around 8.5 mm.

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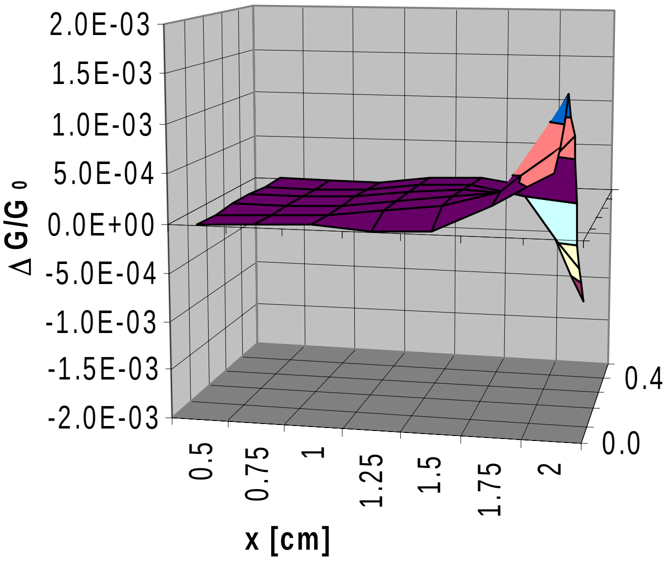

Fig. 1: Flatness of the gradient profile in the x-y plane from 2-D-calculations.

Beam optics calculations of the transfer lines have shown that the sextupole component, i.e. the linear component of the $\Delta\int Gdz$ (x) distribution, has to be carefully limited for avoiding an emittance blow-up of the 450 GeV proton beam. Thus the requirements for the integrated gradient distribution were refined as it is shown in Fig.2 by dotted and dashed lines, the "allowance cone". The dashed lines stand for less strict limitations of the field quality at x,y > 10 mm, whereas the field closer to the magnetic center has to obey smaller limits.

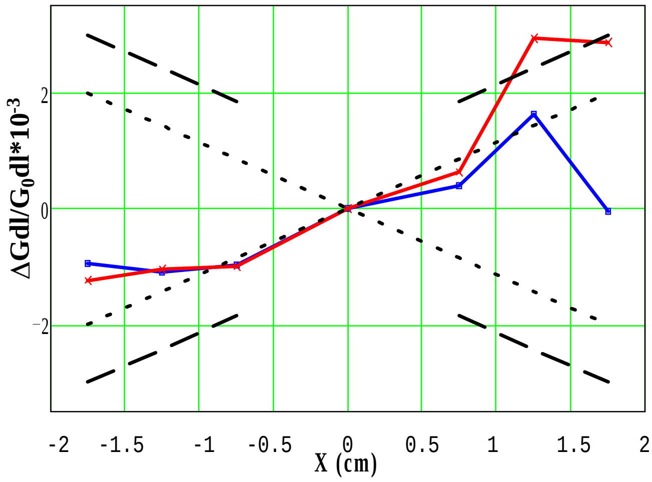

Fig.2: The "allowance cone" for the integrated gradient distribution and measured curves before (x) and after (□) end- tip corrections at nominal current (530A).

III. DETAILS OF THE PRODUCTION

A. *Coil production*

The MQI coils consist of 11 turns of high-purity (>99.95%) OF copper (Outokumpu) bars of 10.5 mm x 10.5 mm section including a central cooling channel of 6 mm diameter. The turn-to-turn insulation by glass-fiber tape of 0.15 mm is applied in two layers, the ground insulation has 1.5 mm thickness. Assembled coils are impregnated with an epoxy compound under 3 bar pressure. Every coil has to be tested after 6 hours in water with a voltage up-to 4 kV AC and 2.5 kV DC in successive cycles.

B. *Quadrants*

The magnetic properties of the steel laminations are specified by minimum values of the induction B(H) like: B(500 A/m)) ≥ 1.38 T; B(1000 A/m) ≥ 1.5 T and B (10000 A/m) ≥ 1.81 T. All laminations for one magnet are stamped from the same roll of steel sheet. The steel sheet of 1 mm thickness and a surface insulation by blue steaming is provided by the Verkh-Isetsky Metallurgical Plant (Ekaterinburg; Russia), the stamping of laminations is sub-contracted to ZVI (Moscow; Russia). The chemical analysis and measurements of the induction are performed by the steel supplier. Control measurements of magnetic properties are done at ZVI and on a CERN permeameter set-up[4] in St. Petersburg, where steel sheet from the same production (the initial rolls have been divided 1/3:2/3 between MQI and MBI steel) is used for the MBI magnet half-core production. Every quadrant is assembled from about 1350 laminations of 1 mm thickness whilst keeping the total weight within ± 0.1%. The stacking factor is exceeding 0.98. Before assembly the laminations are mixed carefully at BINP for distributing the spread in the magnetic behavior equally over the four quadrants. Two solid end-plates of 30 mm thickness, machined to a precision of 50 µm and equipped with removable end-tips (16 mm), are included in each quadrant. The angular plates are finally fixed by argon arc welding.

C. *Assembly*

Assembled quadrants are equipped with coils and fixed on a solid assembly frame under use of spacers in the pole gaps. The whole construction is then, after alignment including some pre-stress, fixed by welding on the tie-plates along the sides in a specific welding sequence. Coil ends are brazed on afterwards. The sag after assembly is less than 0.2 mm, twist < 1 mrad. After some leakage and insulation tests of the coils the spacers can be removed from the gaps and the magnet is ready for geometry and magnetic field measurements.

D. *Production schedule*

The initial production rate of five magnets per month, after construction and evaluation of the two pre-series MQI, has been realized without major difficulties. All tooling is now ready to increase the rate to the full production speed of 10 units per month. As almost half of the coils are produced and tested by September 1999 already, it seems realistic to expect the termination of the fabrication in December 2000, as it was initially scheduled.

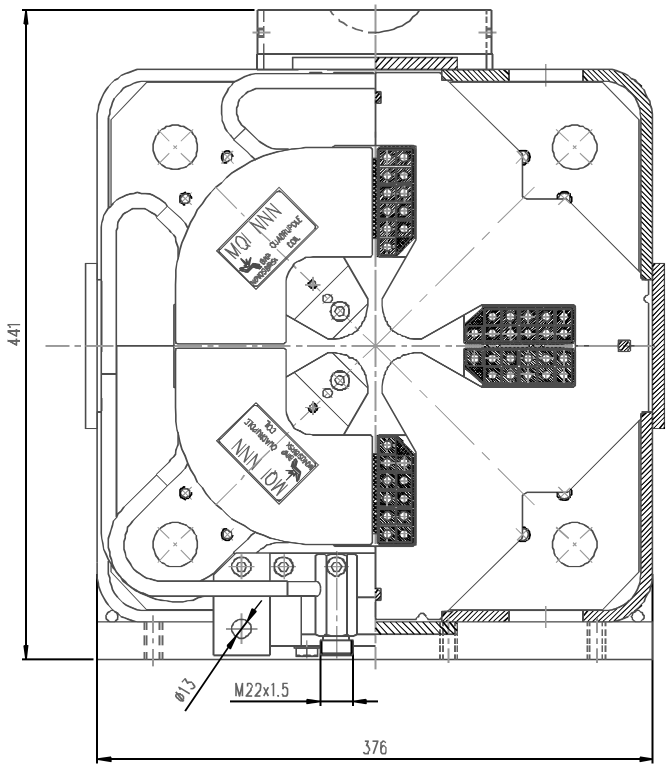

Fig.3: MQI front view with section.

IV. MAGNETIC AND MECHANICAL MEASUREMENTS

A. *Mechanical measurements*

The precision of the assembly of the four quadrants is controlled by an instrument, shown in fig. 4, for measuring the four pole gaps G1 – G4 in one cycle. It has been developed at CERN and produced in industry. Its body consists of three de-coupled (± 2°) cylindrical parts, a guiding header plus vertical and horizontal sensor bodies. The measurement is based on four pairs of pins. They translate any deviation from the nominal gap of 9.18 mm as calibrated in a reference block into an angular move fed into the inductive transducers. Readout of the four analog channels (tilt measurement via inclinometers is an option) and the position as derived from the driving rope in 1 mm steps are displayed on a laptop computer using NI™ LabView software. The resolution is better than five microns.

We have compared gap height measurements obtained by this instrument to curves from a sensor integrated in the magnetic measurement bench (1 gap per cycle), developed by BINP, and we observe exactly the same mechanical profile with about the same resolution.

B. *Magnetic measurements*

All magnets are measured at 530 A DC corresponding to the nominal gradient of 53.5 T/m. In addition, measurements at other field levels are done selectively. We use an array of 8 Hall probes lined up at an equal distance of 5 mm on an aluminum carriage perpendicular to the magnetic axis. The spacing is measured with 5-7 μm accuracy. The Hall probes are calibrated vs. NMR probes and have a long-term accuracy within 2×10^{-4} over the range of 0.5 - 2 T. Vertical mapping is obtained by 90º rotation of the sledge. The Hall probe array is moved along the magnet axis in one cycle by means of a drive mechanism including a stepping motor, reducer and high accuracy 1.2 m long screw. The probe positioning along the axis is precise within 0.1 mm. For one gradient profile each MQI magnet is measured two times. In the first cycle the Hall probe array is displaced in the middle plane by 2.5 mm in one direction, perpendicular to the magnetic axis, in the second by the same distance in opposite direction. This way, every measurement position is covered by two different probes, and it is possible to eliminate individual features of each Hall probe (temperature drift, speed of aging, different calibration curve etc.). The accuracy of the field measurement and the probe spacing allow us to calculate the integral gradient distribution (absolute) with a total accuracy of $\pm1\times10^{-3}$.

V. RESULTS AND CORRELATION OF THE MEASUREMENTS

The relation between mechanical tolerances in the fabrication and the magnetic field profile obtained is a key issue in the MQI production. It was therefore interesting to find out how much information could be obtained from the simple and fast mechanical tracing of the pole gaps. The z resolved measurements of the first two pre-series magnets MQI001/002 have been evaluated in this respect and we obtained a good correlation of mechanics versus magnetic field in the inner region z = 30 – 110 cm. After the correction of some measurement offset a correlation factor $\mu \sim 9$ μm / 10^{-3} in $\Delta G/G$ was determined for the best fit. A very similar factor was obtained also by 2D calculations. Thus even very small variations of the gap of the order of ten microns result in significant variations of the gradient in the order of 10^{-3} in the regions outside the inscribed diameter where the sensitivity is a maximum.

In the series production, however, we have to cope with additional parameters like a larger spread in the magnetic properties of the laminations due to much bigger melts, leading eventually to small magnetic differences in the quadrants at constant stacking factor. This effect is field dependant and results in an additional sextupole component as the poles are saturating. A modified steel mixing based on the results of the steel acceptance measurements is now applied systematically. It turned out in the series production that the mechanical assembly variations are too big for respecting the magnetic tolerances without a local trimming of the integrated gradient. As the measured curves in fig.2 indicate, the MQI magnet needs individual correction in

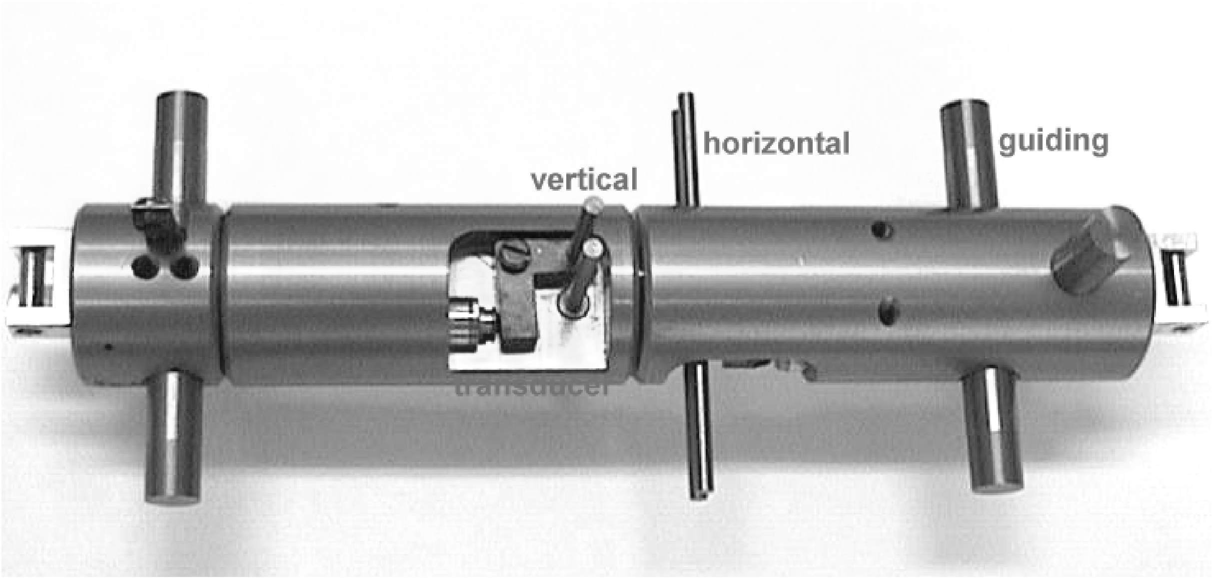

Fig. 4: Mechanical measurement of four pole gaps simultaneously.

addition to the 45º flat chamfer for meeting these requirements. Therefore all MQI magnets have been brought to specifications after the first magnetic measurement by individually correcting the pole tips. This correction method has been developed on the basis of 3D calculations. To adjust the profile of the integral gradient, an additional 59° flat cut on the end tip while simultaneously slightly varying the chamfer length is best suited. The geometry of the cut is shown in Fig.5. This linear correction reduces the value of ∫Gdz in the concerned gap while practically not affecting the gradient distribution in the other three gaps.

VI. CONCLUSIONS

The MQI quadrupole magnet production is well underway with more than half of the coils already produced and successfully tested. Two pre-series magnets have been constructed and intensively evaluated in view of the mechanical and magnetic tolerances. Another 10 magnets have been measured before a clear view concerning the pole profile, assembly tolerances and the end-tips machining was obtained. All 27 magnets produced by now fulfill the specifications. But it seems not possible so far to avoid individual end-shim corrections and the related additional magnetic measurements. Nevertheless, the project is advancing well and the MQI production should be terminated at the end of year 2000.

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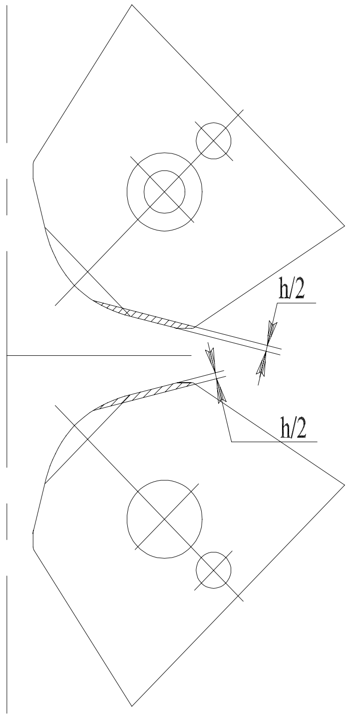

Fig.5: Individual correction of the integrated gradient by a 59° symmetric cut of width h, 15 mm deep, in the end tips on both sides of the magnet.

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