EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 874

Focusing Strength Measurements of the Main Quadrupoles for the LHC

N. Smirnov, L. Bottura, M. Calvi, G. Deferne, J. Di Marco, N. Sammut, S. Sanfilippo

Abstract

More than 1100 quadrupole magnets of different types are needed for the Large Hadron Collider (LHC) which is in the construction stage at CERN. The most challenging parameter to measure on these quadrupoles is the integrated gradient (Gdl). An absolute accuracy of 0.1% is needed to control the beta beating. In this paper we briefly describe the whole set of equipment used for Gdl measurements: Automated Scanner system, Single Stretched Wire system and Twin Coils system, concentrating mostly on their absolute accuracies. Most of the possible inherent effects that can introduce systematic errors are discussed along with their preventive methods. In the frame of this qualification some of the magnets were tested with two systems. The results of the intersystem cross-calibrations are presented. In addition, the qualification of the measurement system used at the magnet manufacturer's is based on results of more than 40 quadrupole assemblies tested in cold conditions at CERN and in warm conditions at the vendor site.

CERN, Accelerator Technology Department, Geneva, Switzerland

Presented at the 19th International Conference on Magnet Technology (MT19)
18-23 September 2005, Genova, Italy

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 19 May 2006

TUA06PO04

Focusing Strength Measurements of the Main Quadrupoles for the LHC

N. Smirnov, L. Bottura, M. Calvi, G. Deferne, J. DiMarco, N. Sammut, S. Sanfilippo.

***Abstract*—More than 1100 quadrupole magnets of different types are needed for the Large Hadron Collider (LHC) which is in the construction stage at CERN. The most challenging parameter to measure on these quadrupoles is the integrated gradient (Gdl). An absolute accuracy of 0.1 % is needed to control the beta beating. In this paper we briefly describe the whole set of equipment used for Gdl measurements: Automated Scanner system, Single Stretched Wire system and Twin Coils system, concentrating mostly on their absolute accuracies. Most of the possible inherent effects that can introduce systematic errors are discussed along with their preventive methods. In the frame of this qualification some of the magnets were tested with two systems. The results of the intersystem cross-calibrations are presented. In addition, the qualification of the measurement system used at the magnet manufacturer's is based on results of more than 40 quadrupole assemblies tested in cold conditions at CERN and in warm conditions at the vendor site.**

***Index Terms*—LHC Quadrupole, Magnetic Measurements, Rotating coil, Single Stretched Wire, Integrated Focusing Strength.**

I. INTRODUCTION

The manufacturing and cold testing of the 476 SSS (Short Straight Section assemblies holding the main LHC quadrupoles) is currently in progress [1]. The most challenging parameter to measure on these accelerators' magnets is the integrated gradient. An absolute accuracy target of 0.1 % is needed to control the beta beating of the LHC beam.

There are three main systems available at CERN to measure the integrated gradient for the cold tests of the LHC quadrupoles: the Single Stretched Wire (SSW) [2], the Automated Scanner [3] and the Twin Rotating Coils system [4]. The first is based on the moving stretched wire technique whereas the last two are based on rotating coil technique. The procedure implemented for the calibration of the instrumentation is the most critical step to guarantee the absolute accuracy specified for the measurement. Because there exist two different families of systems, based on different methods and technique, we launched a program to perform an inter calibration among them to check possible systematic errors. This test must be periodically repeated to trace and avoid both the systems' degradation and time-drift in the measurement.

II. SINGLE STRETCHED WIRE (SSW) SYSTEM

The SSW system used at CERN for measuring the integrated gradient of the LHC quadrupoles is similar to the one used at DESY during the tests of the HERA quadrupoles [5] and to the one used in FNAL for testing the Main Injector (FMI) quadrupoles.

A. Ideal Case

Consider an ideal quadrupole field of magnetic length L_m and an ideal wire (i.e. affected neither by gravity nor by the magnetic forces) stretched between stages located on the two quadrupole ends. The integrated gradient is derived as the sum of both fluxes (Φ) obtained for the two directions of synchronous and co-directional motion of both stages in X or in Y direction from their origin by step-length, D, and integrating the induced voltage across the wire as:

$$\int_0^{L_m} G dz = (\Phi_x^+ + \Phi_x^-)/D^2 = (\Phi_y^+ + \Phi_y^-)/D^2 \tag{1}$$

This approach automatically cancels out the offset position of the wire with respect to the centre of the quadrupole.

The relative accuracy required in the estimation of the step length:

$$\delta(Gdl) = 2 \times \delta D \tag{2}$$

to guarantee 5 units of 10^{-4} accuracy of Gdl (already half of the total budget of 0.1%) is 2.5 units, equivalent to 2.5 µm of absolute accuracy all along the magnet for a stroke of 10 mm. Lengths of the quadrupole assemblies range from 10 to 20 m. This tolerance makes this measurement more challenging than, for instance, the search for the axis requiring 150 µm accuracy. Despite the wire position is known within 1 µm precision at the stages level, its location inside the magnet might be affected by other phenomena like magnetic forces, gravity and air convection. This makes the shape of the wire inside the magnet aperture an important parameter which should be well understood to interpret the results obtained.

B. Stretched wire shape

The weight of the wire and its magnetic properties must be taken into account. The equation for the vertical and horizontal wire positions can be reformulated as follows [6]:

Manuscript received September 21, 2005.

N. Smirnov, L. Bottura, M. Calvi, G. Deferne, S. Sanfilippo, N Sammut, are with CERN, Accelerator Technology Department, CH-1211 Geneva 23, Switzerland. (tel: +4122-767-3784, fax: +4122-767-6230, e-mail: Nikolay.smirnov@cern.ch).

J. DiMarco is with FNAL, USA, e-mail: dimarco@fnal.gov

$$T\frac{\partial^2 Y(z)}{\partial z^2} = wg \pm F_y^{mag}(z), \text{ and } \quad T\frac{\partial^2 X(z)}{\partial z^2} = \pm F_x^{mag}(z) \qquad (3)$$

where T is the wire tension, w is the mass per unit length, χ_{wire} is the magnetic susceptibility, and $F^{mag} \propto \chi B^2$ is magnetic force. The sign in (3) corresponds to the wire magnetic properties and its position. If the wire is paramagnetic and below the quadrupole axis, the magnetic forces have the same direction as the gravity and therefore positive sign must be used. On the contrary a negative sign holds for a diamagnetic wire. Opposite signs are applicable when the wire is upwards. Solving these two equations gives the deflection of the wire inside and outside the magnet depending on wire position with respect to quadrupole axis. The solutions can be formulated as:

$$Y(z) = Y_{gravity}(z) + Y_{mag}(z) \text{ and } X(z) = X_{mag}(z) \qquad (4)$$

where

$$Y_{gravity} \cong -\frac{wg}{2T} z(z - l_{wire}) \text{ and } Y/X_{mag} \propto -\frac{G^2 D^2 \chi}{2\mu_0 T}\rho(z) \qquad (5)$$

are the gravity and magnetic terms expressing the deflection of the wire. The sag of the wire has an amplitude:

$$Sag = -\frac{wg}{8T} l_{wire}^2 \qquad (6)$$

The measurement of the tension with a gauge is affected by friction between the wire and guides bringing some hysteresis in tension reading. The measurement of the fundamental frequency, f, is more accurate being independent from friction. The frequency is proportional to the square root of the tension:

$$f \propto \sqrt{T} \qquad (7)$$

The magnetic term, ρ(z) in (5), has also parabolic shape inside the magnet and linear one outside. Finally the shape of the wire is qualitatively illustrated on Figure 1.

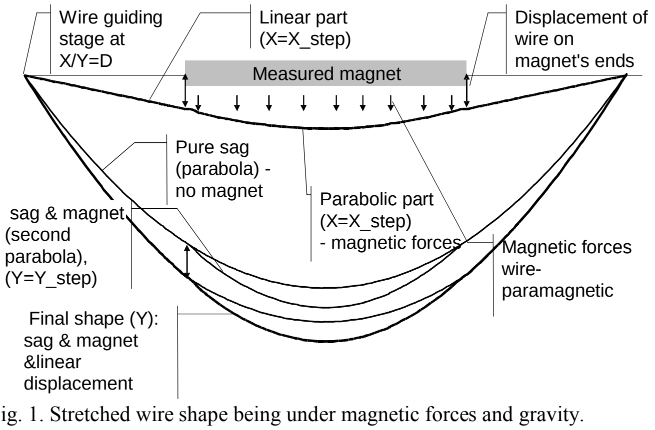

Fig. 1. Stretched wire shape being under magnetic forces and gravity.

C. *Magnetic property of the wire*

Four different types of wire have been tested: #1 – Cu-Be wire (California Fine Wire Co.), #2 - Mg wire, #3 - Cu-Be wire (Good Fellow wire Co.) and #4 - Carbon fibre wire of type HTA5241.

This investigation consists of measuring the integrated transfer function as a function of the wire frequency starting from the maximum possible tension for each type of wire down to half of this limit. The measurements have been performed for three different current levels: 0.76 kA (injection), 5 kA (intermediate) and 11.85 kA (nominal). An example of these measurements performed with Cu-Be of type #1 wire is presented in Fig. 2.

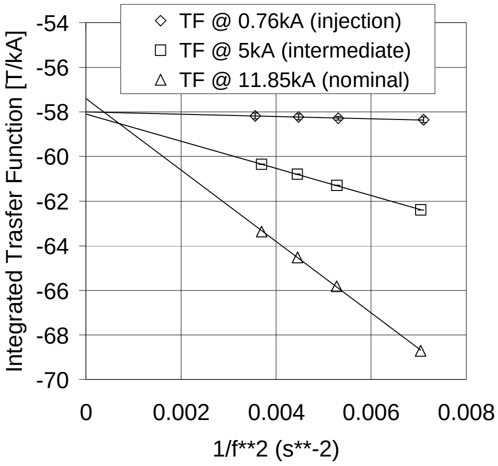

Fig. 2. Typical dependences of transfer function against the inverse frequency squared at three currents displayed by the wire of type #1

The integrated transfer function is presented as a function of $1/f^2$ which is proportional to the inverse of the tension. A higher tension corresponding to a lower transfer function means that this wire moves from its normal position toward the higher field, confirming its paramagnetic properties. For this type of wire the offsets were calculated by using expression (2). The whole range of this wire effective offset at nominal current, mean offset over the wire length being inside the magnet, can reach 1 mm. Finally the results of the investigation are summarised in Table 1, where the average slope and the sign of the susceptibility, χ (positive - paramagnetic, negative - diamagnetic) , are reported for each type of wire.

TABLE 1 SLOPES OF STRENGTH FOR DIFFERENT TYPES OF WIRE IN [T/ s^2]

Wire	0.76kA	5kA	11.85kA	χ
#1	30.4	2000	9480	>0
#2	6.1	500	4977	>0
#3	2.3	50	474	<0
#4	-	-	380	<0

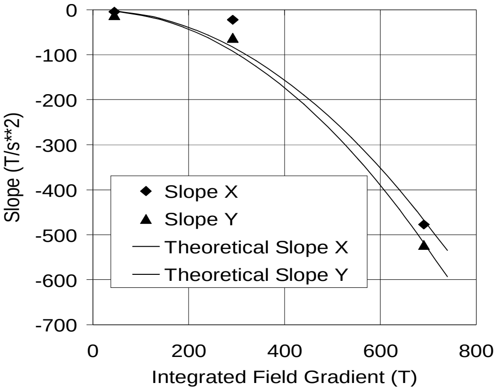

Fig. 3. Average *slope* versus Gdl, estimated over 20 SSS tested.

Despite the higher performance of the carbon wire #4, it has been refused for operational difficulties and the Cu-Be wire #3 has been finally selected for the series tests of the LHC quadrupoles. In addition to its low susceptibility, this wire is homogeneous over several purchases: the standard deviation is found to be within 2 units at nominal current.

Finally the obvious parabolic dependence of the slope versus the field gradient demonstrated in Fig. 3 and Table 1 strongly supports the simple model proposed in (3) to estimate the wire shape during the measurements.

D. Interception calculation

The final value of the quadrupole strength is calculated from the extrapolation of Gdl versus $1/f^2$ to $1/f^2 \rightarrow 0$, (i. e. @ infinite tension). This is the main reason to have the wire with as low susceptibility as possible, to get less uncertainty in the extrapolation.

At the beginning, the Gdl measurements were done only at three different tensions and a linear extrapolation was implemented. In this procedure the third point was used only to estimate the accuracy of the measurements. Controversially it was observed that the Gdl obtained from vertical motion was systematically larger than the horizontal one by about 5 units. The origin of this phenomenon is the different shape of the wire in the vertical and in the horizontal plane. The magnetic forces acting on the wire are proportional to the square of the field magnitude and can be expressed for vertical motion as:

$$F^{y}{}_{mag} \propto G^2 \times (L_{step} + Sag)^2 \qquad (8)$$

On the contrary the *Sag* term is not present for horizontal one. The expansion of this (8) gives the parabolic term of the force versus Sag. By increasing the wire tension from the lowest to the highest value, the wire moves inside the magnet vertically by about 1 mm (the entire Sag is 2.3 mm for Arc SSS). This displacement changes the field value felt by the wire. Despite this effect is very small, it can entirely explain the 5 units of difference observed between X and Y planes. Using the parabolic extrapolation for the Y measurements reduces the systematic difference to a random difference of two units, which is compatible with the reproducibility of the measurement system. To improve the robustness of this new technique the number of different tensions has been increased to four.

E. System performance

The system performance usually are analysed in two ways: in terms of systematic errors which qualify its absolute accuracy, and in terms of random errors which qualify the reproducibility of the system.

1) Random errors

We concentrate on most essential source of measured Gdl scattering which is an electrical noise since the SSW is an "open" system, the only shielding is provided by the magnet itself. The mechanical vibration and air convection inside the anti-cryostat are significantly reduced by the measurement methods and signal treatments. The electrical noise remains a critical issue for this system.

The typical dependence of the estimated random error versus the strength is shown on Fig. 4. The observed function could be expressed as:

$$\sigma_n(Gdl) = \delta_n / (\textstyle\int Gdl) + \eta_s \times (\textstyle\int Gdl)^3 \qquad (9)$$

where δ_n is the standard deviation of Gdl at the interception point and η_s is the parameter characterising the effect of the slope (Fig. 2). Indeed, the random error of each measured point (Fig. 2) being projected to the interception axis ($T \rightarrow \infty$) is magnified by roughly factor of two. Moreover the larger is the slope, the larger is the projection of the error bars on the interception axis. The latter is proportional to the square of the slope and the slope is also proportional to the square of Gdl. After normalization by Gdl, the contribution of the slope in the total relative error is proportional to the third power of Gdl (9).

The measurement features of two tested systems (SSW#1 and #2) are summarized in Table 2. As one can see from there the Gdl at injection is 44 T and could be measured within the specification only with certain statistics.

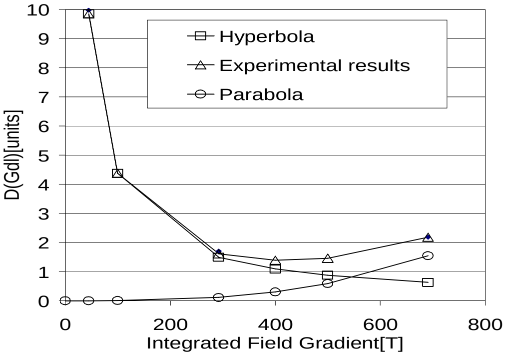

Fig. 4. Composition of σ_n(Gdl): hyperbola – additive noise and parabola – effect of slope.

TABLE 2 MEASUREMENT FEATURES OF TWO SSW SYSTEMS

Parameter/SSW	Units	SSW#1	SSW#2
δ_{noise}	units*T	210	400
η_{slope}	units*T^{-3}	2.5*10^{-9}	5*10^{-9}
Lower limit of Gdl range (5 units at one sigma)	T	42	80

2) Systematic errors

A careful control of the following issues is requested to guarantee the quality of the Gdl measurement.

Powering of the magnet. Stability of the power converter and the accuracy of the readout current is found to be safely less than *0.1 units*.

Alignment of stages. Accuracy and orientation of step length with respect to the magnetic axis and to the main field median plane. Roll must be less than *30 mrad* and in reality it is usually less than 5 mrad. Both yaw and pitch must be less than *20 mrad*.

Amplifiers and integrations. Accuracy and stability of used Precise Digital Integrator (PDI) gain and bias voltage drift is found to be safely below *0.1 units*.

Higher order harmonics. Contribution of high order harmonics into the measured fluxes is estimated to 0.16 units for even (b_4 and b_6) and 0.15 units for odd harmonics (a_3) [7].

Stray field contribution. The configuration and location of the current leads during the cold test are not the same as in the LHC. The current leads can contribute about 2.34 units in X and 2.37 units in Y to the overall integral of MQ. This must be taken into account during the intersystem cross-calibration. Meanwhile their contributions are almost identical in X and Y with a difference of 0.03 units, which is actually due to octupole component of the calculated stray field.

Wire susceptibility. As discussed above.

F. Summary of SSW systems

In principle the system is capable of measuring the integrated strength within the specified accuracy target at intermediate and nominal currents if all the above listed conditions are satisfied. To meet the tolerance at injection more statistics are required. As a result of all these investigations and qualifications of SSW system, it was decided to consider this system as the reference. However, to avoid any systematic error in the measurement, a cross calibration with another independent system, which uses a different method of Gdl measurement, is further needed.

III. ROTATING COIL BASED SYSTEMS AND INTERSYSTEM CROSS-CALIBRATION

A. Rotating coil based systems

There are two other systems capable to measure the integrated gradient in cold conditions:

- *Automated scanner* containing one probe – single segment,
- *Twin coils system* containing two shafts consisting of six 810 mm long segments with 110 mm gaps between them– similar design of long shaft used for dipole measurements.

An additional system is used at the quadrupole manufacturer's : the *Quadrupole Industrial Magnetic Mole* (QIMM) containing a single segment of coil assembly [8].

The calibration procedure is the most critical step in the measurements of the integrated gradient with rotating coils. This procedure consists of two main steps: calibration in a reference dipole mapped with NMR and in a reference quadrupole. Despite the high accuracy which can be achieved in the measurement of the magnetic surface of the coils, better than 2 units, the knowledge of the radius of rotation remains the most challenging parameter to be estimated. The actual radius of rotation of each bundle must be known within 10 μm to insure a 0.1 % accuracy of the gradient measurement. The task is further complicated, i.e. for the 7 m long rotating shaft assemblies, because the bearings used for the calibration are not necessarily those of the final setup. Changes in rotation radii are therefore possible.

B. Intersystem cross-calibration

We found systematic differences between integrated gradient values measured with the SSW and rotating coil systems:

- The QIMM measuring the quadrupoles at the manufacturer's have a systematic value lower by 22 units, which could be explained by both: the different measurement conditions and wrong calibration of QIMM coils.
- The scanner measuring the final SSS at cryogenic temperature gives 17 units more.

A special program, already partially conclusive, is focussed to improve the equipment and process to calibrate the rotating coils geometry. All correlations between the two methods currently have an ideal slope of 1 with a standard deviation from the ideal line of 5 units [7, 8]. We can rely on the stability of these two rotating coil based systems.

IV. CONCLUSIONS AND OUTLOOK

The investigation of the absolute accuracy of the different systems available for the Gdl measurements have been carried out and several improvements implemented.

The SSW is found to be the most accurate system and it is nowadays used as the reference one. All possible sources of systematic errors in the SSW method and equipment were thoroughly investigated. This system can guarantee the specified absolute accuracy of Gdl measurement at intermediate and nominal currents if all measurement conditions mentioned are satisfied.

The rotating coil based systems currently guarantee 20 units in the absolute accuracy. The twin rotating coil system cannot so far provide the required accuracy of Gdl measurements. A special method of calibration and measurements for this system is currently under development. On the contrary this last system is the most efficient and enough accurate for the field quality measurements.

Improving the calibration system and procedure for the rotating coil base systems is the next step towards intersystem cross-calibration, mandatory for proving that systematic errors of Gdl measurement are within tolerance.

REFERENCES

[1] T. Tortschanoff, et al., "The short straight sections for the LHC", *Proc. Particle Accelerator Conference -1997*, pp. 3374-3376.

[2] J. DiMarco, H. Glass, M.J. Lamm, P. Schlabach, C. Sylvester, J.C. Tompkins, J. Krzywinski, “Field alignment of quadrupole magnets for the LHC interaction regions”, *IEEE Transactions on Applied Superconductivity*, **10**(1), pp. 127-130, March 2000.

[3] L. Bottura, F. Chiusano, O. Dunkel, P. Legrand, S. Schloss, P. Schnizer, P. Sievers, and N. Smirnov – “A system for series magnetic measurements of the LHC main quadrupoles”, *IEEE Trans. Appl. Supercond.*: 12 (2002) no. 1, pp.168-169.

[4] J. Billan *at al,* “Twin rotating coils for cold magnetic measurements of 15m long LHC dipoles”, *IEEE Trans Appl. Superconduct*. 10 no.1, pp. 1422-1426, 2000.

[5] G. Knies, J. Krzywinski, “The DESY stretched wire system for magnetic measurements”, unpublished.

[6] A. Temnykh, “Vibrating wire field-measuring technique”, *NIM* A399 (1997), pp. 185-194.

[7] S. Sanfilippo et al, “Electrical and magnetic performance of the LHC short straight sections”, submitted to *IEEE Trans. Appl. Supercond.*

[8] P.Hagen et al, “Steering field quality in the production of the main quadrupoles of the Large Hadron Collider”, submitted to *IEEE Trans. Appl. Supercond.*