# A STRATEGY FOR SAMPLING THE FIELD QUALITY OF THE LHC DIPOLES

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*Abstract*

We have measured the magnetic field of a large fraction of the LHC main dipoles, to date more than 400 in warm conditions and over 100 in cold conditions. Using the available data we analysed the distributions of the main field and higher order field errors in warm and cold conditions, as well as the distribution of the warm-to-cold correlation. Based on this analysis we predict the minimum number of magnets that should be measured in cold conditions to insure that the LHC will meet its goals. The main outcome of this analysis is that cold measurements on a fraction of the order of one third of the total production, i.e. approximately 400 dipoles, will be sufficient to achieve the above objectives.

## INTRODUCTION

The procurement of the Large Hadron Collider (LHC) main dipoles is well advanced, and has reached the nominal series production rate (30 per month). The total number of dipole cold masses delivered at CERN in May 2004 was 220 units. Among the many installation and operational specifications, the field homogeneity is one of the main targets to be achieved to ensure a successful operation of the machine [1]. Any deviation from the targets is critically examined, and corrective actions are regularly taken to maintain the field errors within the bounds determined by beam optics constraints [2]. Both monitoring and corrective actions are based on field measurements that are performed in warm conditions in industry and at 1.9 K at CERN. To date, we have measured the field quality in 420 magnets in warm conditions and 110 magnets at 1.9 K. All magnets will be measured in warm conditions both for quality control purposes and for monitoring trends in field quality. At the present production rate, the cryogenic test at CERN has become an industrial endeavour, which has to rely on optimized timing to match the production and delivery rate of dipoles. It is hence natural at this point to question the initial baseline of field measurements that was aiming at the integral testing of the dipoles. We do it here comparing warm and cold measurements to the specifications for the commissioning of the LHC. The goal of this work is to evaluate the minimum number of cold measurements necessary to guarantee that (1) the production is controlled within the targets (2) the field is known to a sufficient level for a sound installation and (3) the uncertainty on the knowledge of the magnetic field of the LHC dipoles is small enough for the commissioning of the accelerator and to insure operation of the machine in any condition, including higher energy. A first analysis of this problem has been given in [3].

| Harmonic | Measurement | | Warm/cold | |
|---|---|---|---|---|
| | EOI | NOM | EOI | NOM |
| b1 | 6.3 | 6.3 | 5.5 | 5.0 |
| a1 | 6.3 | 6.3 | 5.5 | 5.0 |
| b2 | 0.62 | 0.57 | 0.39 | 0.43 |
| a2 | 1.17 | 1.11 | 0.52 | 0.19 |
| b3 | 2.20 | 2.13 | 0.74 | 0.25 |
| a3 | 0.33 | 0.31 | 0.12 | 0.10 |
| b4 | 0.11 | 0.09 | 0.06 | 0.04 |
| a4 | 0.32 | 0.28 | 0.17 | 0.04 |
| b5 | 0.60 | 0.54 | 0.20 | 0.07 |
| b7 | 0.26 | 0.22 | 0.04 | 0.02 |

Table I: standard deviation of main field, angle, and field harmonics, measured at 1.9 K (EOI: end of injection, NOM: nominal field) and warm-cold correlations, in units at 17 mm.

## SUMMARY OF MAGNETIC DATA

The standard deviation of the main field and of the harmonics taken over the 110 magnets tested at 1.9 K is given in Tab. I at injection and at nominal field. The values are given in units at 17 mm, i.e. divided by the average main field and scaled by $10^4$. For the field angle a1, measured with respect to the mechanical installation plane, we made the assumption that the spread is the same as measured on the b1, which is a conservative hypothesis compared to the limited number of measurements available at 1.9 K.

The spread in main field and harmonics reflects not only the tolerances of the components and of the assembly procedures, but also known features due to changes in the magnet production. In particular, the spread in b3, b5 and b7 is affected by the changes in the coil layout [2] introduced to bring these harmonics on the target values. For instance, the b3 spread for all dipoles with the cross-section 2 is 1.2 (NOM) to 1.3 (EOI) units against the overall value of 2.1 (NOM) to 2.2 (EOI) units reported in Tab. I. In addition, systematic differences between manufacturers affect the overall spread on a3, a4, b5 and b7.

Table I also reports the standard deviations of the offsets between measurements at room temperature and at 1.9 K. We observe that the spread in correlations is smaller than the spread in the measurements at cold. This is true also if measurements at cold are separated according to the manufacturer and to the coil layout.

We will make the simplifying assumption that the multipoles over the magnet population as well as the warm/cold offsets are normally distributed around the average. While this is true for most distributions of the warm-to-cold offsets [3], in the case of the magnet production this assumption is largely conservative.

# ESTIMATION OF THE SAMPLE SIZE

The field harmonics of the LHC main dipoles must range in very tight tolerance windows [1] to satisfy different constraints such as: mechanical aperture, dynamic aperture at injection, closed orbit correct-ability and chromaticity at top energy. To estimate the number of cold measurements necessary to satisfy the production steering, installation and commissioning requirements we compare the expected uncertainty on the knowledge of the main field and field errors to the targets.

## *Estimation of the uncertainty and sample size*

We indicate with $\pm u(\alpha,n\text{-}1)$ the confidence interval with probability (1-$\alpha$/2) associated to the estimate of a population mean obtained from a sample of size $n$ drawn from a finite population of $N$ magnets. Assuming that the measured multipoles and warm/cold offsets follow a Gaussian distribution, $u$ reads:

$$u = t(\alpha, n-1)\frac{\sigma}{\sqrt{n}}\sqrt{1-\frac{n}{N}} \tag{1}$$

where σ is the standard deviation taken over the sample. The last factor (under the square root sign) corrects the estimator for a finite population of size $N$, while the factor $t(\alpha,n\text{-}1)$ is the statistics of the Student's $t$ distribution with $n$-1 degrees of freedom corresponding to the quantile α. The quantity $u$ is the uncertainty associated to the mean estimate, to be compared to the specifications for production control, installation and commissioning, as discussed below. We require a confidence level at 99 % probability, corresponding to $t \approx 2.6$ for a sample size $n$ larger than 50. Using Eq. (1) we can compute the size of the sample $n(u,\sigma)$ necessary to reach a specified uncertainty $u$ for a population with given spread σ:

$$n(u,\sigma) = \left[\left(\frac{u}{t(\alpha,n-1)\sigma}\right)^2 + \frac{1}{N}\right]^{-1}, \tag{2}$$

## *Production control*

The more critical field harmonics are of low to medium order (up to order 7) and can be split into two categories:

1) $a_1$, $b_1$, $a_2$, $b_2$, $b_3$, $a_3$, $b_4$ and $b_5$, for which corrector circuits are foreseen in the 8 LHC sectors
2) $a_4$, $a_5$ and $b_7$, which are uncorrected but can be critical, and therefore need a careful monitoring within a narrow range.

With the third cross-section implemented in July 2003 [2], all the systematic multipoles meet the specifications given in [1], except for the systematic $b_7$ for which a careful readjustment of the LHC betatron tunes ($Q_{x,y}$ =.28/.31, i.e. very close to the (7,0) resonance) is needed to recover the target dynamic aperture at injection. The half-ranges allowed for the systematic values $R$ is given in Tab. II (production control half range). To have a safe margin to steer the production, we limit the maximum uncertainty on the average to 1/5 of the specified production control half ranges, i.e. $u_{production} = R/5$ is used in Eq. (2). Such an uncertainty already induces a degradation on the 12 sigma dynamic aperture of the LHC at injection.

| Harmonic | Production half range | Uncertainty at commissioning |
|---|---|---|
| b1 | 13.0 | 3.00 per sector |
| a1 | 13.0 | |
| b2 | 1.08 | 0.20 per sector |
| a2 | 0.87 | 0.20 per sector |
| b3 | 3.00 | 0.35 per ring |
| a3 | 1.50 | 0.20 per sector |
| b4 | 0.31 | 0.04 per ring |
| a4 | 0.13 | |
| b5 | 0.35 | 0.10 per ring |
| b7 | 0.20 | |

Table II: production control half range and maximum allowable uncertainty at commissioning, in units.

## *Installation*

The random multipole components are well within targets for most values, and at the limit for b1/a1 and b3, for which a sorting has been implemented to recover the expected losses of machine performance [4]. This requires estimates on each individual magnet, and not on averages over all magnets as in the previous case.

The statistical bias due to the random b1 and a1 must be limited in each cell to within ±13 units to ensure a full correction of the closed orbit up to 7 TeV using at most 40% of the corrector nominal strength (50% being reserved for correcting the misalignments of the main quadrupoles). With the present spread of main field measured at 1.9 K (6.5 units) the probability of having a sequence of dipoles that do not satisfy the above requirement is finite but extremely small, and a rule to avoid these cases has been defined [4]. If no measurements at 1.9 K are done, using warm measurements one has to add an additional uncertainty of 5 units, at one sigma (see Tab. I). The probability that the rule applied to warm data is not working at 1.9 K is around 1%, i.e., two cells over the whole machine.

A random b3 larger than 1.4 units could affect the LHC dynamic aperture at injection. Using an up-down installation scheme, achieving a local compensation [4], the maximal target of 1.4 unit r.m.s. (allowing a random installation) can be relaxed to 2.4 units. Without measurements at 1.9 K, one knows the b3 on a single magnet within 0.74 units at one sigma, i.e. a factor 2 better than the target of 1.4 units that is acceptable for random installation.

## *Commissioning*

Operation of the LHC will require the knowledge and the on-line correction of low order multipoles, in some cases to a level that is beyond both the measurement capability and the magnet stability. Examples are the average transfer function, that must be known within 1 unit for RF capture, and the average b3, that must be known and corrected within 0.02 units for chromaticity control ($\Delta Q'$ = ±1). Dedicated beam-based measurement methods and

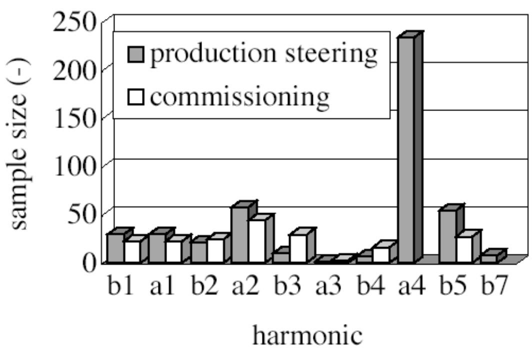


Figure 1: Minimum sample size that satisfies the production control and commissioning requirements, based on the warm-cold correlations at EOI.

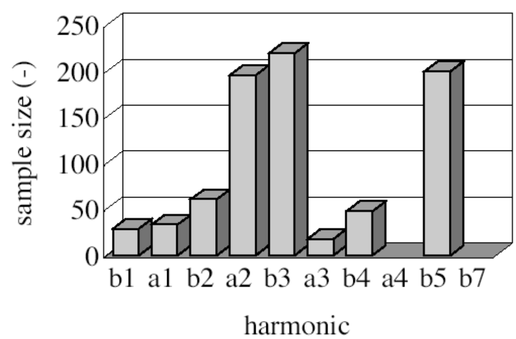


Figure 2: Minimum sample size that satisfies the commissioning requirements, based on spread evaluated on the population tested in cryogenic conditions.

robust feedback systems will be mandatory for operation at nominal conditions. Nonetheless, the machine must be put in the working range of the beam-based measurements to achieve a fast commissioning of the LHC. These requirements have been translated into the maximum allowed uncertainties $u_{commissioning}$ reported in the last column of Tab II [5].

## RESULTS

We have estimated the number of magnets that need to be cold measured to achieve a sufficiently small uncertainty on the average obtained projecting the warm measurements to cold conditions. To do this we have applied Eq. (2) to the warm-cold spread $\sigma_{\text{warm-cold}}$ of Tab. I and the specifications for production control and commissioning of Tab. II. Figure 1 shows the sample sizes $n(u_{production},\sigma_{\text{warm-cold}})$ and $n(u_{commissioning},\sigma_{\text{warm-cold}})$ that satisfy the production control and commissioning requirements. A sample size in the range of 50 magnets meets both requirements for most multipoles, with the only exception of a4. The reason for this particularity is on one hand the tight tolerance on the production specifications for a4, and on the other hand the fact that a4 exhibits a large, gaussian spread in the injection decay, see the results reported in Tab. I.

To provide a term of comparison, we have estimated the number of cold measurements that would be needed to achieve the uncertainty specified for commissioning without making use of warm-cold extrapolation. In this case we have applied Eq. (2) to the measured cold spread, $\sigma_{\text{cold}}$ from Tab. I, to obtain the sample size $n(u_{commissioning},\sigma_{\text{cold}})$. The result is reported in Fig. 2 and shows that, given the considerable spread in the population tested, the sample size required is in the range of 200 to 250 cold measurements, driven by low order multipoles (a2 and b3) as well as high order multipoles (b5). A sample of this size is large but still feasible and a direct extrapolation appears hence viable.

## DISCUSSION AND CONCLUSIONS

The previous results hold in the strong hypothesis that the field quality components, including those that can be only measured at 1.9 K, as well as the correlation between warm and cold multipoles, belong to a homogeneous and stable production normally distributed around the mean. We already mentioned the exception to this assumption due to the different cross sections produced. In addition, we have observed clear distinctions in the allowed multipoles at cold, depending on the superconducting cable, so that we also expect families to single out based on cable properties. At present the installation rule for the 8 sectors of the LHC takes into account the distinction among the manufacturing features, and could produce 8 sub-sets of magnets characterised by different properties. For this reason we propose to sample 50 magnets for each octant, for a total number of 400 measured dipoles at 1.9 K (i.e., one third of the whole set of dipoles). This will guarantee:

- A large sampling of allowed multipoles (b1, b3, b5 and b7) dependent on manufacturing features (coil cross section) and component properties (cable type) to check trends in the production;
- A safe cumulated sample for non-allowed multipoles (e.g. a2 and a4) that are presently compatible with a normal distribution throughout the population tested;
- A sufficient number of cold tests that allows to estimating the systematic values needed for commissioning from cold measurements to back-up and cross-check the results based on warm-cold correlations.

## REFERENCES


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