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# QUALITY CONTROL OF THE LHC MAIN DIPOLE COLD MASS THROUGH MAGNETIC MEASUREMENTS AT ROOM TEMPERATURE

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**Abstract**

The result of the magnetic measurements after the cold mass assembly is a holding point for the production of the LHC main dipoles. Here we describe how the magnetic measurements are screened to validate them and to work out faulty components or assembly procedures. The control limits are based on the experience acquired on the first 13 measured cold masses, and comparison to collared coil magnetic measurements. These limits are applied to 58 cold masses to carry out the quality control. The strategy used to set control limits and the main results of the quality control are discussed.

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# 1. Introduction

All the dipoles of the Large Hadron Collider will be measured at 300 K at two different stages of the assembly procedure: after the collaring and after the welding of the cold mass. Since March 2002, magnetic measurements are a holding point of the production, i.e., CERN must allow the continuation of the assembly on the basis of the measurements analysis or indicate corrective actions if necessary. The decisions are taken by the MAS-MD Project Engineers on the advice of the MAS-MA analysts. Indeed, in October 2001 the MAS-MA section had already started a program of automatic control of magnetic measurements with the support of ASP (Associazione Sviluppo Piemonte) fellows. The first stage, devoted to the collared coil analysis, has been completed in February 2002 [1]. The second stage, devoted to cold masses, has been completed in October 2002, relying on the analysis of 13 cold masses available at that time.

The strategy is based on the principle of separating out the targets required from beam dynamics from the control limits used to analyse magnetic measurements. The latter are worked out from a consistent set of data to define what is the field quality achievable with the tooling and processes used at a given point of the dipole production. These data provide average and standard deviation of a typical magnetic field, and control limits are based on these values to single out anomalies. Two cases are given: wrong measurements and wrong components or assembly procedures. The automatic control does not allow to distinguish between these two cases, but only to single out a field anomaly. A control based on the beam dynamics targets would be by far less effective, since it would check values averaged along the 15 m long magnet axis: indeed, faulty components are usually present only in a short section of the magnet and therefore the average magnetic field is weakly affected. For cold masses, we made our control even tighter by analysing the difference with respect to the collared coil measurements.

The measurements for each collared coil are loaded into an Excel® template containing a Visual Basic® macro capable of automatically making an acceptance test already at the manufacturer. This acceptance test is based on the control limits set up according to the statistical analysis. The Excel workbook is stored as a document in the EDMS (Engineering Data Management System [2]), in particular in the MTF (Manufacturing and Test Folder) and is therefore a validated measurement data set.

The plan of the paper is the following: in Section 2 we outline the strategy used for quality control. The overview of the statistics used to set control limits is given in Section 3. The main results of the quality control over 71 cold masses are listed in Section 4. In the Appendix we give analytical estimates about the dependence of magnetic length on assembly parameters.

# 2. Quality control strategy

## 2.1. Parameters to be controlled

Magnetic field is measured along the magnet axis with a 750 mm-long rotating coil in 20 consecutive measurement points (positions 1 to 20) at room temperature with a typical excitation of 8 to 12 A. Here, we follow the same approach outlined in Ref. [1] for the collared coil analysis. The first and the last points (positions 1, i.e, connection side [CS] and 20, i.e, non connection side [NCS]) are in the magnet ends and therefore are treated separately. Positions 2 to 19 are considered as a homogeneous set and an average and a sigma is evaluated. These four quantities (average in the straight part, sigma along the straight part, measurement in the head CS and in the head NCS) are analysed for each normal and skew multipole $b_j$, $a_j$ ($j$=2 to 15). The magnetic centre is computed locally (i.e., for each position 1

to 20) by the feed down of $b_{11}$ giving $a_{10}$=$b_{10}$=0, therefore no control on $a_{10}$ and $b_{10}$ can be performed.

The linear part is decomposed in main field divided by the measuring current $c_1/i$ (in mT/kA) and in the field angle (in mrad). The main field is normalized to the current since different currents have been used. Average and standard deviation in positions 3 to 18 are analysed. Contributions of positions 1 and 20 (heads) are analysed separately, and they are normalized to the average in the straight part. A separate analysis is also required for positions 2 and 19 that are affected by the heads (more details are given in section 3.2). The field angle is decomposed in average and standard deviation of the straight part (mrad); positions 1 and 20 are treated separately and are given as a difference with respect to the straight part average (in mrad).

For each aperture we analyse the magnetic length. The difference of the average field direction between the two apertures is also analysed for the 1st generation measuring systems. This test is not available for the 2nd generation systems, which use two different moles for the two apertures, the reason being that the calibration with respect to gravitation is not available.

## 2.2. Testing cold mass data or differences with respect to collared coil

Cold mass data are used to carry out a quality control of the assembly operations carried out on the collared coil to obtain a cold mass. For this reason, we consider the differences in magnetic field measurements between cold mass and collared coil. This strategy has the advantage of being able to single out anomalies in the iron yoke assembly, and to not considering anomalies in the collared coil assembly, that should have been already seen on previous magnetic measurements on the collared coil. Indeed, there are some features that must be pointed out:

- The collared coil has no rigidity and therefore the measurement of its field angle is only an indication of the straightness of its support. On the other hand, the cold mass has a rigidity and therefore the angle is relative to the assembly and not to the support. For this reason, the test on the angle is carried out on the cold mass and not on the difference.
- For the main field variation along the axis and in the heads, we control values referred to the straight part and therefore we analyse the cold mass and not the difference.
- For the multipoles, we have to point out that the effect of the yoke is to increase the main field of a factor $k$=1.18 in the straight part and of about 1.12 in coil heads (see Table 1). This effect reduces the multipoles in the cold mass of $1/k$ with respect to the collared coil values, since they are always referred to the main field. For this reason, one should not simply analyse the difference between collared coil and cold mass multipoles, but rather the quantity $b_{n,cm-cc}$, defined according to the following expression

$$b_{n,cm-cc} = b_{n,cm} - \frac{b_{n,cc}}{k},$$

where *cm* stands for cold mass and *cc* for collared coil.

| | Straight part | Position 1 | Position 20 |
|---|---|---|---|
| **Average all** | 1.1820 | 1.12 | 1.11 |
| **St. dev all** | 0.0010 | 0.07 | 0.07 |
| **Average Firm1** | 1.1812 | 1.13 | 1.09 |
| **St. dev Firm1** | 0.0006 | 0.09 | 0.08 |
| **Average Firm2** | 1.1823 | 1.07 | 1.15 |
| **St. dev Firm2** | 0.0007 | 0.04 | 0.08 |
| **Average Firm3** | 1.1819 | 1.14 | 1.12 |
| **St. dev Firm3** | 0.0004 | 0.03 | 0.05 |

**Table 1:** Field increase $k$ from collared coil to cold mass, measured on 13 cold masses.

## 2.3. Evaluation of the statistics and data rejection

Control limits have been computed on the set of the first 13 cold masses: seven from Firm1 (1001, 1003-8), three from Firm2 (2001-3), and three from Firm3 (3001-3). Nearly 60 cold masses have been analysed using these control limits. An update of the control limits using more statistics could be envisaged (for instance, at the end of the pre-series). Indeed, control limits based on the first sampling of 13 cold masses have shown to be very effective to single out bad measurements or assembly problems, as shown in Section 4.

For each of the analysed parameters, we evaluate the average and the standard deviation over the available data. We did not include in the statistics cold masses that have known peculiar features in the magnetic field: this happens for $b_2$ in 1005, which is out of statistics due to different shimming of the insert. One cold mass has incomplete data: 2001 has not been measured in aperture 1, position 20, and therefore all integral values and head non-connection side are not available.

Our sample is very small, and we did not find evidence of systematic differences between firms in the cold mass contribution to the magnetic field and therefore data of different firms are considered to belong to the same distribution. Indeed, the software keeps the possibility of giving different control limits for different firms (see Section 2.5).

## 2.4. Control bounds

Having estimated the average and the standard deviation of the typical distribution for each parameter, we set control bounds for average quantities at 3.5 σ (warning level, yellow alarm). In the hypothesis of a Gaussian distribution, 99.95% of data are within 3.5 σ: this means that about one measurement of a 'normal' case over 2400 (that correspond to 1200 magnets, i.e. over all the production) will be outside the control limits. This corresponds to having a rate of one false alarm over all the production. If we had fixed the limits at 3 σ, i.e. 99.7%, we would have had 0.3% measurements of 'normal' magnets outside the control limits, i.e. 8 magnets. For the variations along the axis one has 18 times more data, and therefore the control bound is set at 4 σ, corresponding to about one false warning in one position over all the production. These control bounds are doubled (7 σ and 8 σ respectively) to point out strong anomalies of the magnetic field (red alarm). An example of a control sheet with all parameters within control bounds is given in Fig. 1.

## 2.5. Implementation in an Excel® macro

The quality control is performed in an Excel worksheet where magnetic measurements of a cold mass are loaded. Data of the corresponding collared coil are also loaded and the difference of the measurements of the collared coil (rescaled by the main field increase $k$) and the cold mass is calculated. Results are then compared to a table containing the statistical limits worked out on a given set of magnets. The table could be updated during the production to include a more significant sample of measurements. The macro is based on a code originally developed for the collared coil analysis [1].

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | | Aperture 1 | | | | | Aperture 2 | | | |
| 5 | Magnetic length | status ok | | | | Magnetic length | status ok | | | |
| 6 | | Average straight | Variation straight | Heads CS | Heads NCS | | Average straight | Variation straight | Heads CS | Heads NCS |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | Main field | status ok | status ok | status ok | status ok | Main field | status ok | status ok | status ok | status ok |
| 9 | Angle | | status ok | status ok | status ok | Angle | | status ok | status ok | status ok |
| 10 | b2 | status ok | status ok | status ok | status ok | b2 | status ok | status ok | status ok | status ok |
| 11 | b3 | status ok | status ok | status ok | status ok | b3 | status ok | status ok | status ok | status ok |
| 12 | b4 | status ok | status ok | status ok | status ok | b4 | status ok | status ok | status ok | status ok |
| 13 | b5 | status ok | status ok | status ok | status ok | b5 | status ok | status ok | status ok | status ok |
| 14 | b6 | status ok | status ok | status ok | status ok | b6 | status ok | status ok | status ok | status ok |
| 15 | b7 | status ok | status ok | status ok | status ok | b7 | status ok | status ok | status ok | status ok |
| 16 | b8 | status ok | status ok | status ok | status ok | b8 | status ok | status ok | status ok | status ok |
| 17 | b9 | status ok | status ok | status ok | status ok | b9 | status ok | status ok | status ok | status ok |
| 18 | b10 | | | | | b10 | | | | |
| 19 | b11 | status ok | status ok | status ok | status ok | b11 | status ok | status ok | status ok | status ok |
| 20 | b12 | status ok | status ok | status ok | status ok | b12 | status ok | status ok | status ok | status ok |
| 21 | b13 | status ok | status ok | status ok | status ok | b13 | status ok | status ok | status ok | status ok |
| 22 | b14 | status ok | status ok | status ok | status ok | b14 | status ok | status ok | status ok | status ok |
| 23 | b15 | status ok | status ok | status ok | status ok | b15 | status ok | status ok | status ok | status ok |
| 24 | a2 | status ok | status ok | status ok | status ok | a2 | status ok | status ok | status ok | status ok |
| 25 | a3 | status ok | status ok | status ok | status ok | a3 | status ok | status ok | status ok | status ok |
| 26 | a4 | status ok | status ok | status ok | status ok | a4 | status ok | status ok | status ok | status ok |
| 27 | a5 | status ok | status ok | status ok | status ok | a5 | status ok | status ok | status ok | status ok |
| 28 | a6 | status ok | status ok | status ok | status ok | a6 | status ok | status ok | status ok | status ok |
| 29 | a7 | status ok | status ok | status ok | status ok | a7 | status ok | status ok | status ok | status ok |
| 30 | a8 | status ok | status ok | status ok | status ok | a8 | status ok | status ok | status ok | status ok |
| 31 | a9 | status ok | status ok | status ok | status ok | a9 | status ok | status ok | status ok | status ok |
| 32 | a10 | | | | | a10 | | | | |
| 33 | a11 | status ok | status ok | status ok | status ok | a11 | status ok | status ok | status ok | status ok |
| 34 | a12 | status ok | status ok | status ok | status ok | a12 | status ok | status ok | status ok | status ok |
| 35 | a13 | status ok | status ok | status ok | status ok | a13 | status ok | status ok | status ok | status ok |
| 36 | a14 | status ok | status ok | status ok | status ok | a14 | status ok | status ok | status ok | status ok |
| 37 | a15 | status ok | status ok | status ok | status ok | a15 | status ok | status ok | status ok | status ok |
| 38 | Coil Positioning | status ok | | | | Coil Positioning | status ok | | | |
| 39 | Field Colinearity | status ok | | | | | | | | |

**Figure 1**: Control sheet for cold mass magnetic measurements.

# 3. Overview of the statistical analysis

## 3.1. Magnetic length

The magnetic length is defined as the length of a rectangular function having the same integral as the measured magnetic field versus magnet axis length and the height corresponding to the main field in the central part of the magnet. Measured values in the collared coil and in the cold mass are shown in Fig. 2. Averages and standard deviations of the magnetic length of the collared coil, of the cold mass, and of the difference are given in Table 2.

| Magnetic length (m) | | |
|---|---|---|
| | Avg | St Dev |
| cm | 14.39 | 0.009 |
| cc | 14.45 | 0.011 |
| diff | 0.06 | 0.008 |

**Table 2:** Magnetic length in the collared coil and in the cold mass.

The reduction of the magnetic length of about 60 mm from collared coil to cold mass is explained by the presence of nested laminations in the coil heads (see Appendix A.1). The estimate of the impact on the magnetic length of additional iron laminations is given in Appendix A.2. One finds that 100 mm more iron laminations (the maximum allowed in the specification) increase the magnetic length of 8.5 mm, i.e. 6 units (one unit is a relative variation of $10^{-4}$ with respect to the average). This option of magnetic length tuning can be used to reduce the spread in the integrated main field.

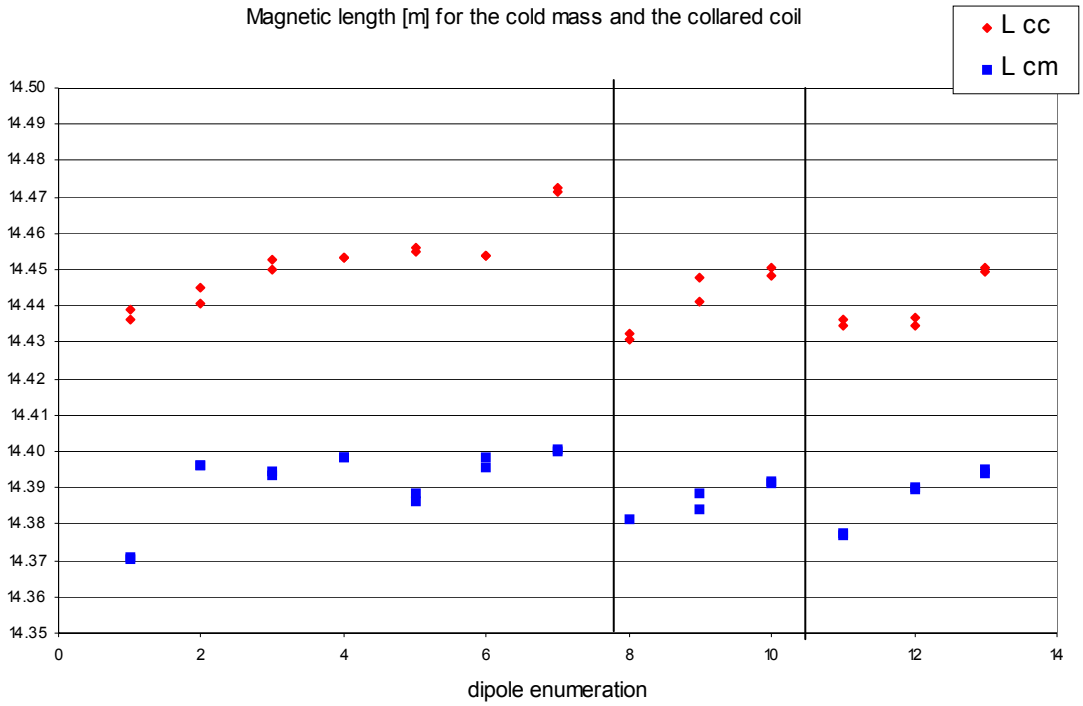


**Figure 2:** Magnetic length for cold mass and collared coil. The vertical lines indicate the limits between the different manufacturers.

## 3.2. Main field module

### 3.2.1. Average

Values of the average of the main field divided by the current along positions 3 to 18 are analysed in Table 3. Average and standard deviation over the analysed set of magnets are given for the collared coil, for the cold mass and for the difference. The control is carried out on the difference between collared coil and cold mass. The increase of 108 mT/kA corresponds to 18.2% increase with respect to the collared coil values already discussed in section 2.2. A first estimate of this increase in the hypothesis of a perfectly circular iron gives 21.2%. An increase of 18.5% can be found through numerical codes based on BEM-FEM methods that take into account the real iron geometry [4]. No dependence on the stacking factor of the iron laminations is expected in the measurements at room temperature, since the iron is not saturated.

| | Transfer function (mT/kA) | |
|---|---|---|
| | Avg | St Dev |
| cm | 704.5 | 0.5 |
| cc | 596.2 | 0.4 |
| diff | 108.3 | 0.4 |

**Table 3:** Transfer function in the collared coil, cold mass and difference.

### 3.2.2. Variations along the magnet axis

The main field variation is calculated with respect to the average in position 2 to 19, and it is expressed in units. Positions 2 and 19 are treated separately, the main field being slightly lower due to the influence of the nested laminations in positions 1 and 20. The analysis is carried out on the measurement of the cold mass, and not on the difference with respect to collared coil. Results are shown in Figs. 3 and 4 and in Table 4. Typical spread along the straight part is 1.5 -2 units (one standard deviation).

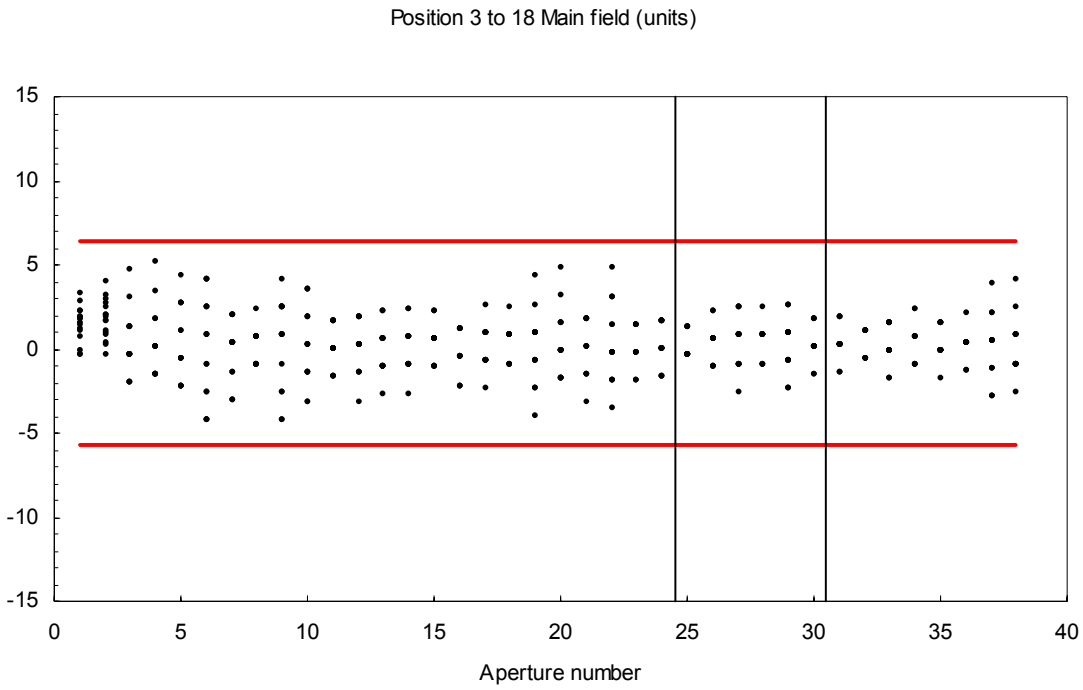


**Figure 3:** The main field for positions 3 to 18 for the cold mass (markers), control limits at 4 σ (red lines) and limits between manufacturers (black lines).

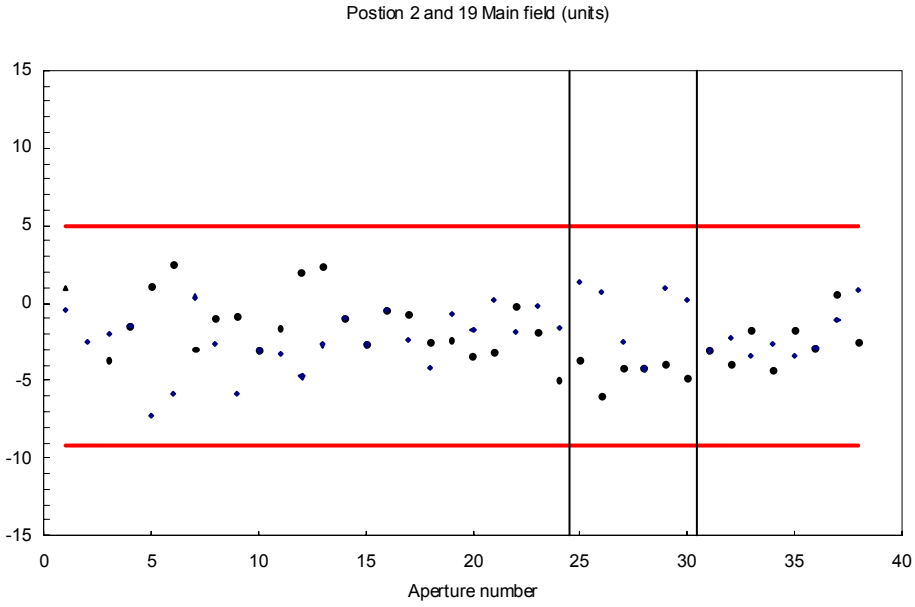


**Figure 4:** The main field for positions 2 and 19 for the cold mass (markers), control limits at 3.5 standard deviations (red lines), and limits between manufacturers (black lines).

| Variation of main field (units) | | |
|---|---|---|
| **Positions** | **Avg** | **St Dev** |
| **3 to 18** | 0.34 | 1.52 |
| **2 and 19** | -2.10 | 2.02 |

**Table 4:** Variations of the main field along the axis measured in the cold mass.

### 3.2.3. Main field module in the heads

The control of the main field in the heads is computed with respect to the straight part value, and given in percent

$$(dB/B)_{head} = (TF_{head} / TF_{straight} - 1) \cdot 100$$

As it is shown in Table 5 and in Fig. 5, the main field in the heads is about 40% less than in the straight part in the cold mass, and about 38% less in the collared coil. We also observe that the spread of the sum of the transfer function in connection side and non-connection side is lower than on one side only. This effect has been already observed for the collared coils: in fact the 2 to 4% spread in the head is mainly given by the longitudinal positioning of the measuring coil whose accuracy can therefore be estimated as 2 to 4% of the measuring coil length, i.e., 15 to 30 mm (one sigma). A separate test is carried out for the sum of the head contribution.

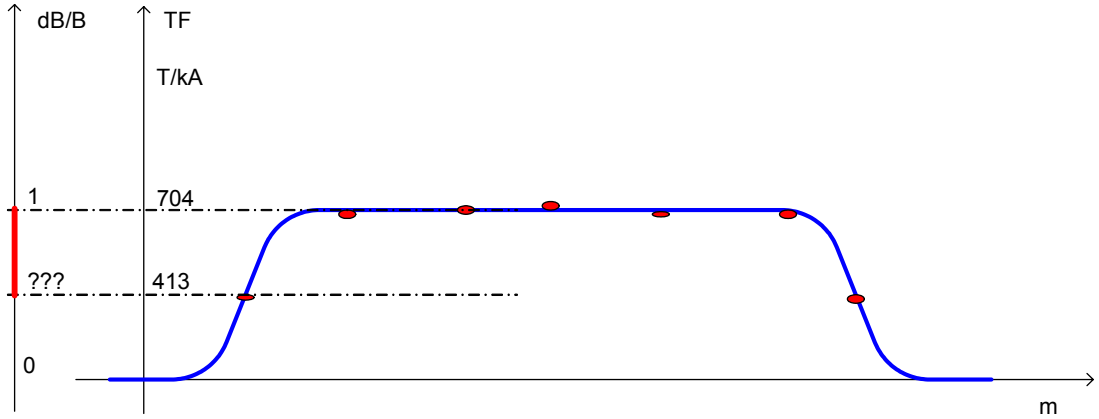


**Figure 5:** Transfer function in the heads and in the straight part in the cold mass.

| | dB/B in the head, CS (%) | | dB/B in the head, NCS (%) | | Mean of dB/B in CS and NCS (%) | |
|---|---|---|---|---|---|---|
| | **Avg** | **St Dev** | **Avg** | **St Dev** | **Avg** | **St Dev** |
| **cm** | -41.4 | 3.8 | -40.2 | 2.1 | -40.7 | 1.0 |
| **cc** | -38.2 | 1.7 | -36.4 | 2.7 | -37.2 | 1.3 |

**Table 5:** Transfer function in the heads with respect to the straight part.

## 3.3. Main field angle

The collared coil has no rigidity and therefore the main field angle depends on the support straightness. On the other hand, in the cold mass the main field angle along the axis is well defined and therefore our analysis is on the cold mass value and not on the differences. No analysis is carried out on the average along the axis since the reference value of the cold mass mid-plane is not available. The variations of the angle in the straight part are shown in Figs. 6-8. In position 1 the main field angle is tilted in the positive sense with the convention that the angle has the same sign of $a_1$ (see Fig. 7) due to the connection side asymmetry; the same tilt was observed in the collared coil [1]. In position 20 the angle has no systematic component but a larger spread (see Fig. 8). Values are given in Table 6.

| Main field angle variations (mrad) | | |
|---|---|---|
| **Position** | **Avg** | **St Dev** |
| **2 to 19** | -0.2 | 1.0 |
| **1** | 3.3 | 0.9 |
| **20** | 1.1 | 1.8 |

**Table 6:** Statistic of the main field angle variations along the axis.

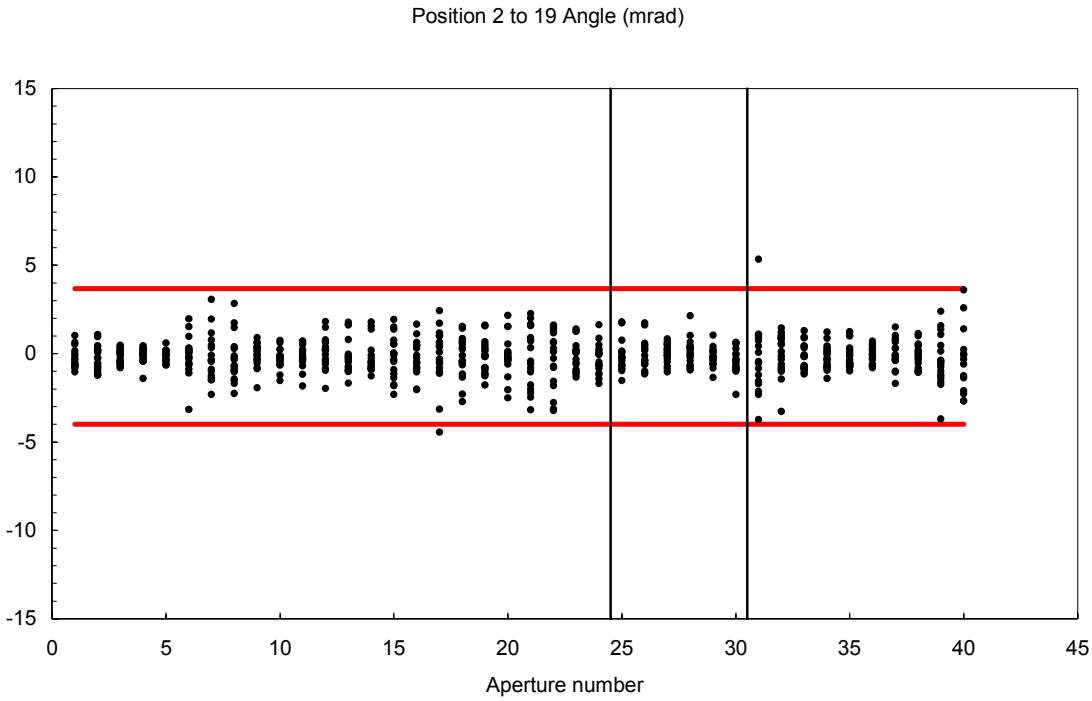


**Figure 6:** The main field direction for the cold mass in position 2 to 19 (markers), control limits at 4 σ (red lines), and limits between different manufacturers (black lines).

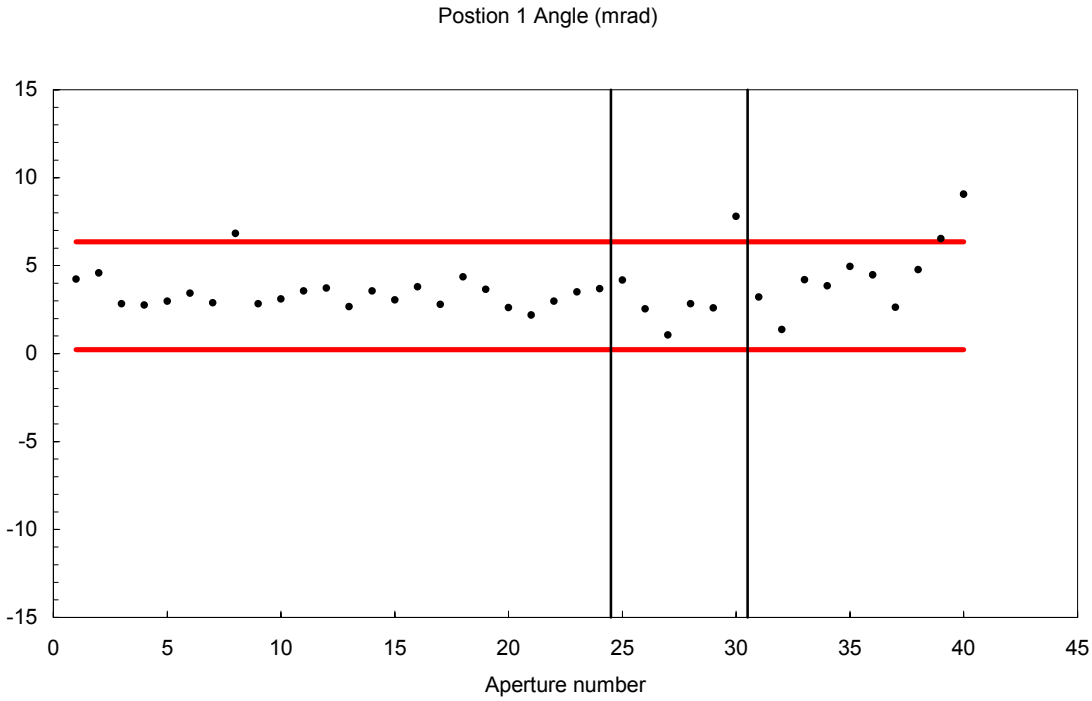


**Figure 7:** The main field direction for the cold mass in position 1 (markers), control limits at 3.5 σ (red lines), and limits between different manufacturers (black lines).

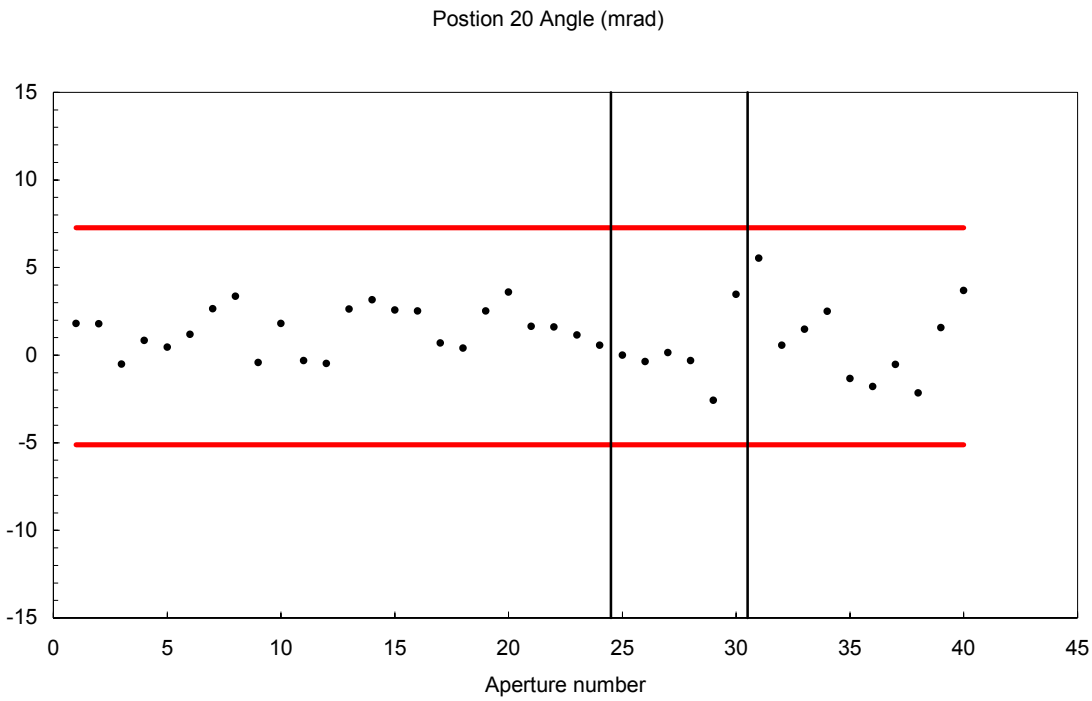


**Figure 8:** The main field direction for the cold mass in position 20 (markers), control limits at 3.5 σ (red lines), and limits between different manufacturers (black lines).

### 3.4. Multipoles

The average and standard deviations of multipoles in the straight part positions and in the heads are shown in Table. 7. We analyse the two apertures together, changing the sign for aperture 2 in even normal multipoles due to the two-in-one left-right anti-symmetry. The test is made on the difference between cold mass and rescaled collared coils (see black values in Table. 7). For the variation of the multipoles along the axis we have used the limits for the collared coil, rescaled to the cold mass and applied to the difference between collared coil and cold mass.

## 4. Quality control results

The outlined strategy has been used to control field quality in 71 cold masses (June 9 2003). Among them, 13 cold masses have been used to work out the control limits that have been applied to the analysis of the following 58 cold masses. Control limits have also been applied *a posteriori* to the first 13 cold masses for completeness. Anomalies can be either due to the measurements or to the assembly. In both cases we can distinguish between faulty cases (measuring system not working correctly or wrong component or assembly procedure) and non-standard cases (for instance, a cold mass measured with positive current only because of the diode already mounted, or a cold mass with a non-standard way of shimming the insert).

| | Mean | Sigma | | Mean | Sigma | | |
|---|---|---|---|---|---|---|---|
| Magnetic Length (mm) | -0.058 | 0.008 | Field Colinearity | 0 | 0.28 | | |
| dB/B Heads CS+NCS (units) | -4070 | 100 | | | | | |
| | Mean Value (3:18) (mT/kA) | | dB/B 3:18 (units) | | dB/B Head CS (units) | | dB/B Head NCS (units) | |
| | Mean | Sigma | Mean | Sigma | Mean | Sigma | Mean | Sigma |
| Main Field Component | 108.30 | 0.38 | 0.34 | 1.52 | -4140 | 380 | -4022 | 211 |
| | Mean Value 2:19 (units) | | Variations 2:19 (units) | | Head CS (units) | | Head NCS (units) | |
| | Mean | Sigma | Mean | Sigma | Mean | Sigma | Mean | Sigma |
| Delta Angle (mrad) | 0 | 0 | -0.16 | 0.9600 | 3.29 | 0.88 | 1.08 | 1.77 |
| b2 (units) | 1.30 | 0.15 | 0 | 0.5085 | 32 | 9 | 30 | 8 |
| b3 (units) | 4.60 | 0.16 | 0 | 0.5085 | 1.44 | 5.50 | 7.55 | 1.64 |
| b4 (units) | 0.060 | 0.034 | 0 | 0.1356 | 0.65 | 1.15 | 0.73 | 0.6 |
| b5 (units) | 0.040 | 0.024 | 0 | 0.1356 | -0.70 | 0.82 | 0.00 | 0.23 |
| b6 (units) | -0.0198 | 0.0054 | 0 | 0.0593 | -0.0032 | 0.62 | 0.00 | 0.07 |
| b7 (units) | -0.0108 | 0.0100 | 0 | 0.0458 | -0.13 | 0.37 | 0.00 | 0.03 |
| b8 (units) | -0.0031 | 0.0034 | 0 | 0.0288 | -0.004 | 0.097 | 0.000 | 0.038 |
| b9 (units) | 0.0098 | 0.0140 | 0 | 0.0169 | 0.032 | 0.073 | 0.029 | 0.025 |
| b10 (units) | 0.0001 | 0.0019 | 0 | 0.0339 | -0.003 | 0.146 | -0.005 | 0.113 |
| b11 (units) | 0.0000 | 0.0210 | 0 | 0.0050 | 0.016 | 0.032 | 0.016 | 0.009 |
| b12 (units) | 0.0000 | 0.0010 | 0 | 0.0052 | -0.002 | 0.020 | 0.0000 | 0.0150 |
| b13 (units) | 0.0000 | 0.0024 | 0 | 0.0021 | 0.0017 | 0.0066 | 0.0000 | 0.0031 |
| b14 (units) | -0.0005 | 0.0062 | 0 | 0.0029 | 0.0016 | 0.0084 | -0.0022 | 0.0071 |
| b15 (units) | 0.0010 | 0.0039 | 0 | 0.0023 | -0.0075 | 0.0115 | -0.0040 | 0.0067 |
| a2 (units) | -0.03 | 0.11 | 0 | 0.9322 | 0.81 | 6.49 | -0.40 | 0.62 |
| a3 (units) | 0.000 | 0.083 | 0 | 0.2966 | -1.63 | 2.13 | 0.00 | 0.20 |
| a4 (units) | 0.000 | 0.018 | 0 | 0.2288 | -0.6 | 1.67 | -0.32 | 0.26 |
| a5 (units) | 0.000 | 0.045 | 0 | 0.1017 | -0.62 | 0.76 | 0.00 | 0.16 |
| a6 (units) | 0.0000 | 0.0049 | 0 | 0.0576 | 0.35 | 0.66 | 0.02 | 0.07 |
| a7 (units) | 0.0000 | 0.0260 | 0 | 0.0475 | -0.21 | 0.23 | 0.000 | 0.019 |
| a8 (units) | 0.0010 | 0.0022 | 0 | 0.0212 | 0.067 | 0.115 | 0.026 | 0.037 |
| a9 (units) | 0.0000 | 0.0180 | 0 | 0.0178 | -0.045 | 0.062 | -0.008 | 0.034 |
| a10 (units) | 0.0000 | 0.0009 | 0 | 0.0288 | 0.152 | 0.157 | 0.098 | 0.116 |
| a11 (units) | -0.0050 | 0.0511 | 0 | 0.0076 | -0.016 | 0.048 | 0.004 | 0.053 |
| a12 (units) | 0.0000 | 0.0008 | 0 | 0.0047 | 0.032 | 0.029 | 0.0076 | 0.0107 |
| a13 (units) | 0.0015 | 0.0060 | 0 | 0.0019 | 0.000 | 0.007 | 0.0015 | 0.0054 |
| a14 (units) | -0.0020 | 0.0039 | 0 | 0.0025 | -0.003 | 0.008 | 0.0021 | 0.0063 |
| a15 (units) | -0.0031 | 0.0066 | 0 | 0.0025 | -0.0032 | 0.011 | 0.0004 | 0.0106 |

**Table 7:** Worksheet containing the statistics used to work out the control bounds on cold mass magnetic measurements.

## 4.1. Non-standard or faulty measurements

### 4.1.1. Non-standard measurements of 3004 (diode mounted)

In each position, magnetic measurements are performed 5 times with a positive current and 5 times with a negative current to cancel residual magnetization or systematic effects [3]. For the cold mass, measurements have to be carried out before the diode is mounted in order to be able to power the coil with both current signs. Indeed, in 3004 the diode has been assembled before magnetic measurements and therefore only positive currents have been used for field measurements. This gave strong anomalies in integrated skew multipoles: the offset in $a_2$ is 0.8 and –1.0 units (aperture 1 and 2 respectively) against an expected value of 0.0 units, and a sigma of 0.11 units (see Table 7). This gives anomalies at 8 to 10 $\sigma$, giving rise to a red alarm (see Fig. 9). Other anomalies are observed in $a_3$ and $a_4$, the other multipoles being not affected. The same case happened for 3010 and 3012-4, that were not measured in Firm3 due to a fault in the measuring system. 3013 has been measured at CERN, this time using the procedure defined for cold test, i.e. three different excitation currents to extrapolate the multipoles at zero field. In this case the extrapolated values were fitting in the control limits.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **File name** | HCMBB_A001-03000004_cm.xls | | | | | | | | |
| 2 | **Component ID** | HCMBB_A001 | | | | **Serial Number** | 3000004 | | | |
| 3 | **Date of test Ap 1** | 29.05.2002 | | | | **Date of test Ap 2** | 29.05.2002 | | | |
| 4 | | **Aperture 1** | | | | | **Aperture 2** | | | |
| 5 | **Magnetic length** | status ok | | | | **Magnetic length** | status ok | | | |
| 6 | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | **Main field** | status ok | status ok | status ok | status ok | **Main field** | status ok | status ok | status ok | status ok |
| 9 | **Angle** | | status ok | status ok | status ok | **Angle** | | status ok | status ok | status ok |
| 10 | **a2** | red alarm | status ok | status ok | status ok | **a2** | red alarm | status ok | status ok | yellow alarm |
| 11 | **a3** | yellow alarm | status ok | status ok | yellow alarm | **a3** | status ok | status ok | status ok | status ok |
| 12 | **a4** | yellow alarm | status ok | status ok | status ok | **a4** | yellow alarm | status ok | status ok | status ok |
| 13 | **a5** | status ok | status ok | status ok | status ok | **a5** | status ok | status ok | status ok | status ok |
| 14 | **a6** | status ok | status ok | status ok | status ok | **a6** | status ok | status ok | status ok | status ok |

**Figure 9:** Alarm sheet of cold mass 3004: alarms on skew integrals due to anomalous measurement (positive current only).

### 4.1.2. Faulty measurement of 2020 (wrong calibration file)

Cold mass 2020 showed an anomalous behaviour of integral high order normal multipoles. In particular, $b_7$ showed a shift with respect to collared coil $b_{7,\,cm-cc}$ of 0.1 units against 0.0 expected with a σ of 0.01 units, i.e. an anomaly at 10 σ. Moreover, $b_{13}$ showed a shift $b_{13,cm-cc}$ of 0.018 units against 0.000 units expected, with a σ of 0.0024 units, i.e. an anomaly at 8 σ. Even though the absolute values of these anomalies are very small (of the order of 0.1 units or less), they are very clearly singled out by our automatic control (see Fig. 10). Indeed, high order multipoles are very stable and depend very weakly on the iron yoke; this leads us to investigate the measuring system. In fact, is has been found that the calibration files of the inner and outer measuring coil had been inverted, this error having only a little effect on high order multipoles, and no effect on low order multipoles. Without the automatic control system this error would have been extremely difficult to discover.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | **Component ID** | HCMBARA001 | | | | **Serial Number** | 2000020 | | | |
| 3 | **Date of test Ap 1** | 20.02.2003 | | | | **Date of test Ap 2** | 05.12.2002 | | | |
| 4 | | **Aperture 1** | | | | | **Aperture 2** | | | |
| 5 | **Magnetic length** | status ok | | | | **Magnetic length** | status ok | | | |
| 6 | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | **Main field** | status ok | status ok | status ok | status ok | **Main field** | status ok | status ok | status ok | status ok |
| 9 | **Angle** | | status ok | status ok | status ok | **Angle** | | yellow alarm | status ok | status ok |
| 10 | **b2** | status ok | status ok | status ok | status ok | **b2** | status ok | status ok | status ok | status ok |
| 11 | **b3** | status ok | status ok | status ok | status ok | **b3** | status ok | status ok | status ok | status ok |
| 12 | **b4** | status ok | status ok | status ok | status ok | **b4** | status ok | status ok | status ok | status ok |
| 13 | **b5** | status ok | status ok | status ok | status ok | **b5** | status ok | status ok | status ok | status ok |
| 14 | **b6** | status ok | status ok | status ok | status ok | **b6** | status ok | status ok | status ok | status ok |
| 15 | **b7** | red alarm | status ok | status ok | status ok | **b7** | red alarm | status ok | status ok | status ok |
| 16 | **b8** | status ok | status ok | status ok | status ok | **b8** | status ok | status ok | status ok | status ok |
| 17 | **b9** | yellow alarm | status ok | status ok | status ok | **b9** | yellow alarm | status ok | status ok | status ok |
| 18 | **b10** | | | | | **b10** | | | | |
| 19 | **b11** | yellow alarm | status ok | status ok | red alarm | **b11** | yellow alarm | status ok | status ok | red alarm |
| 20 | **b12** | status ok | status ok | status ok | status ok | **b12** | status ok | status ok | status ok | status ok |
| 21 | **b13** | red alarm | status ok | status ok | yellow alarm | **b13** | red alarm | status ok | status ok | status ok |
| 22 | **b14** | status ok | status ok | status ok | status ok | **b14** | status ok | status ok | status ok | status ok |
| 23 | **b15** | status ok | status ok | status ok | status ok | **b15** | status ok | status ok | status ok | status ok |

**Figure 10:** Alarm sheet of cold mass 2020: alarms on normal integrals due to faulty measurement (calibration files of inner and outer measuring coil inverted).

### 4.1.3. Faulty measurement of 2020 (wrong angle in one position)

Another measurement of 2020 showed problems in the field angle. In one position the field angle has been measured as 40 mrad larger than the average value along the magnet axis. This large variation induced red alarms in skew multipoles (see Fig. 11). The problem was traced back to a faulty levelling of the mole in that measuring position, the measurement was repeated and the data were showing no anomalies. A similar problem with the mole levelling has been found also in the collared coils.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | File name | HCMBARA001-2000020_cm.xls | | | | | | | | |
| 2 | Component ID | HCMBARA001 | | | | Serial Number | 2000020 | | | |
| 3 | Date of test Ap 1 | 05.02.2003 | | | | Date of test Ap 2 | 06.02.2003 | | | |
| 4 | | Aperture 1 | | | | | Aperture 2 | | | |
| 5 | Magnetic length | status ok | | | | Magnetic length | status ok | | | |
| 6 | | Average straight | Variation straight | Heads CS | Heads NCS | | Average straight | Variation straight | Heads CS | Heads NCS |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | Main field | status ok | status ok | status ok | status ok | Main field | status ok | status ok | status ok | status ok |
| 9 | Angle | | red alarm | status ok | status ok | Angle | | yellow alarm | status ok | status ok |
| 10 | b2 | status ok | status ok | status ok | status ok | b2 | status ok | status ok | status ok | status ok |
| 11 | b3 | status ok | status ok | status ok | status ok | b3 | status ok | status ok | status ok | status ok |
| 12 | b4 | status ok | status ok | status ok | status ok | b4 | status ok | status ok | status ok | status ok |
| 13 | b5 | status ok | status ok | status ok | status ok | b5 | status ok | status ok | status ok | status ok |
| 14 | b6 | status ok | status ok | status ok | status ok | b6 | status ok | status ok | status ok | status ok |
| 15 | b7 | status ok | status ok | status ok | status ok | b7 | status ok | status ok | status ok | status ok |
| 16 | b8 | status ok | status ok | status ok | status ok | b8 | status ok | status ok | status ok | status ok |
| 17 | b9 | status ok | status ok | status ok | status ok | b9 | status ok | status ok | status ok | status ok |
| 18 | b10 | | | | | b10 | | | | |
| 19 | b11 | status ok | yellow alarm | status ok | status ok | b11 | status ok | status ok | status ok | status ok |
| 20 | b12 | status ok | status ok | status ok | status ok | b12 | status ok | status ok | status ok | status ok |
| 21 | b13 | status ok | status ok | status ok | status ok | b13 | status ok | status ok | status ok | status ok |
| 22 | b14 | status ok | status ok | status ok | status ok | b14 | status ok | status ok | status ok | status ok |
| 23 | b15 | status ok | yellow alarm | status ok | status ok | b15 | status ok | status ok | status ok | status ok |
| 24 | a2 | status ok | status ok | status ok | status ok | a2 | status ok | status ok | status ok | status ok |
| 25 | a3 | status ok | status ok | status ok | status ok | a3 | status ok | status ok | status ok | status ok |
| 26 | a4 | status ok | status ok | status ok | status ok | a4 | status ok | status ok | status ok | status ok |
| 27 | a5 | status ok | status ok | status ok | status ok | a5 | status ok | status ok | status ok | status ok |
| 28 | a6 | status ok | status ok | status ok | status ok | a6 | status ok | status ok | status ok | status ok |
| 29 | a7 | yellow alarm | yellow alarm | status ok | status ok | a7 | yellow alarm | status ok | status ok | status ok |
| 30 | a8 | status ok | status ok | status ok | status ok | a8 | status ok | status ok | status ok | status ok |
| 31 | a9 | yellow alarm | red alarm | status ok | status ok | a9 | yellow alarm | status ok | status ok | status ok |
| 32 | a10 | | | | | a10 | | | | |
| 33 | a11 | status ok | red alarm | status ok | status ok | a11 | status ok | yellow alarm | status ok | status ok |
| 34 | a12 | status ok | status ok | status ok | status ok | a12 | status ok | status ok | status ok | status ok |
| 35 | a13 | status ok | red alarm | status ok | status ok | a13 | status ok | status ok | status ok | status ok |
| 36 | a14 | status ok | status ok | status ok | status ok | a14 | status ok | status ok | status ok | status ok |
| 37 | a15 | status ok | yellow alarm | status ok | status ok | a15 | status ok | status ok | status ok | status ok |
| 38 | Coil Positioning | status ok | | | | Coil Positioning | status ok | | | |
| 39 | Field Colinearity | red alarm | | | | | | | | |

**Figure 11:** Alarm sheet of cold mass 2020: alarms on field angle and skew multipoles variations along the axis due to faulty measurement (wrong mole levelling).

### 4.1.4. Faulty measurements of mole Dipole3 (wrong multipole signs)

The measuring mole Dipole3 was cabled with wrong polarities, giving inverted signs for all multipoles. This affected the measurements of 1005, 1018, 1022-5. The problem has been cured by re-cabling correctly the measuring mole and by correcting the signs in the data output. No re-measurement has been asked since the source of the problem was clear.

### 4.1.5. Faulty measurements of 2nd generation system in Firm3 (wrong longitudinal positioning of the mole)

All cold masses measured with the 2nd generation system in Firm3 show an anomaly in the main field module. A typical example is cold mass 3025, where the main field variation with respect to straight part in position 2 is of –10 and –16 units in Aperture 1 and 2 respectively, against an average of –2 units and a sigma of 2 units for normal cold masses. These anomalies are at 4 and 8 $\sigma$ respectively, giving yellow and red alarms (see Fig. 12). These low values in position 2 are associated to high value in positions 19 and 20 with respect to the statistics. Therefore the origin of the anomaly has been traced back to a wrong positioning of the measuring coil along the magnet axis, position 1 being too out of the cold mass, and position 20 being too inside. All cold masses measured with 2nd generation system in Firm3 show the same problem (3008, 3012, 3016, 3018-22,3024-5, 3027). No re-measurement has been asked.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **File name** | HCMBARA001-3000025_cm.xls | | | | | | | | |
| 2 | **Component ID** | HCMBARA001 | | | | **Serial Number** | 3000025 | | | |
| 3 | **Date of test Ap 1** | 06.04.2003 | | | | **Date of test Ap 2** | 06.04.2003 | | | |
| 4 | | **Aperture 1** | | | | | **Aperture 2** | | | |
| 5 | **Magnetic length** | status ok | | | | **Magnetic length** | status ok | | | |
| 6 | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | **Main field** | status ok | yellow alarm | status ok | status ok | **Main field** | status ok | red alarm | yellow alarm | yellow alarm |
| 9 | **Angle** | | status ok | status ok | status ok | **Angle** | | status ok | status ok | status ok |
| 10 | **b2** | status ok | status ok | status ok | status ok | **b2** | status ok | status ok | status ok | status ok |
| 11 | **b3** | status ok | status ok | status ok | status ok | **b3** | status ok | status ok | status ok | status ok |
| 12 | **b4** | yellow alarm | status ok | status ok | status ok | **b4** | status ok | status ok | status ok | status ok |

**Figure 12:** Alarm sheet of cold mass 3025: alarms on main field module due to faulty measurement (wrong longitudinal positioning of the mole).

## 4.2. Non-standard or faulty assembly procedures

### 4.2.1. Non-standard shimming of the insert in 1005

According to the drawings, between the insert and the collars there is a non-ferromagnetic shim whose thickness is 0.3 mm. Moreover, between the insert and the two halves of the iron yoke there is a ferromagnetic shim of 0.5 mm, usually called the 'Chinese hat' due to its peculiar shape. At the beginning of the production two cold masses (1002 and 1005) have been produced in Firm1 with a different assembly of the insert shim: the Chinese hat was removed and the thickness of the shim between collars and insert was increased from 0.3 to 0.8 mm. This new lay-out had the effect of moving the insert 0.5 mm far from the centre of the magnet, thus inducing a change in $b_2$ that has been estimated [4] in 1.2 units (negative in Aperture 1, positive in Aperture 2). The effect on the other multipoles is negligible. The measured variation of $b_2$ with respect to the standard lay-out is -1.3 and 1.0 units (Aperture 1 and 2 respectively); since the sigma of the $b_2$ shift due to cold mass is 0.15 units, we have anomalies at 8 and 6 sigma respectively, that give a red alarm in Aperture 1 and a yellow alarm in Aperture 2 (see Figure 13). The case of 1002 cannot be reported since it has not been measured as a cold mass, but data at 1.9 K confirm what observed in 1005.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **File name** | HCMBB_A001-01000005_cm.xls | | | | | | | | |
| 2 | **Component ID** | HCMBB_A001 | | | | **Serial Number** | 1000005 | | | |
| 3 | **Date of test Ap 1** | 14.03.2002 | | | | **Date of test Ap 2** | 15.03.2002 | | | |
| 4 | | **Aperture 1** | | | | | **Aperture 2** | | | |
| 5 | **Magnetic length** | status ok | | | | **Magnetic length** | status ok | | | |
| 6 | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | **Main field** | status ok | status ok | status ok | status ok | **Main field** | status ok | status ok | status ok | status ok |
| 9 | **Angle** | | status ok | status ok | status ok | **Angle** | | status ok | status ok | status ok |
| 10 | **b2** | red alarm | status ok | status ok | status ok | **b2** | yellow alarm | status ok | status ok | status ok |
| 11 | **b3** | status ok | status ok | status ok | status ok | **b3** | status ok | status ok | status ok | status ok |

**Figure 13:** Alarm sheet of cold mass 1005: alarms due to non-standard insert shims.

### 4.2.2. Faulty assembly: twist of cold masses

In a few cold masses an anomalous variation of the field angle along the axis is observed. In 1021 a peak-to-peak tilt of 10 mrad was observed (6 σ of our statistics), giving rise to yellow alarms (see Fig. 14 and 15). This was the third case of a trend of increasing difficulties in controlling the field angle, and therefore it was decided to un-weld it and to verify the procedure of alignment of the magnet inside the shrinking cylinder. Cold masses 1021 and 2007 also showed similar anomalies, with a lower spread. These data show that the alignment of the collared coil and the yoke laminations inside the cylinder after welding is not optimal. This can be due either to a wrong positioning of the assembly before welding, or to asymmetries in the welding procedure. Measurements of 1021 after the second weld show a field angle within the normal behaviour.

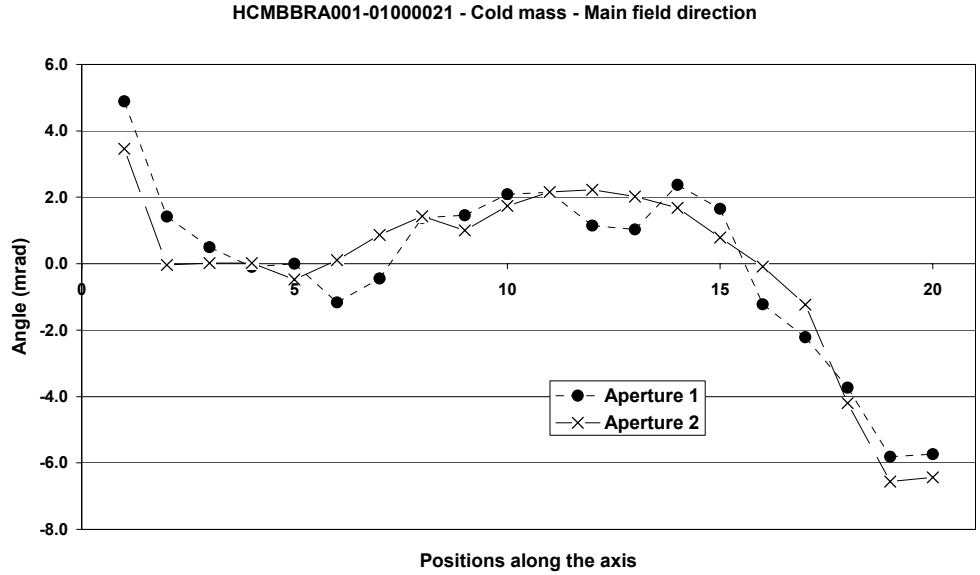


**Figure 14:** Main field direction along the axis of cold mass 1021.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **File name** | HCMBBRA001-1000021_cm.xls | | | | | | | | |
| 2 | **Component ID** | HCMBBRA001 | | | | **Serial Number** | 1000021 | | | |
| 3 | **Date of test Ap 1** | 30/10/2002 | | | | **Date of test Ap 2** | 31/10/2002 | | | |
| 4 | | **Aperture 1** | | | | | **Aperture 2** | | | |
| 5 | **Magnetic length** | status ok | | | | **Magnetic length** | status ok | | | |
| 6 | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | **Main field** | status ok | status ok | status ok | status ok | **Main field** | status ok | status ok | status ok | status ok |
| 9 | **Angle** | | yellow alarm | status ok | yellow alarm | **Angle** | | yellow alarm | status ok | yellow alarm |
| 10 | **b2** | status ok | status ok | status ok | status ok | **b2** | status ok | status ok | status ok | status ok |
| 11 | **b3** | status ok | status ok | status ok | status ok | **b3** | status ok | status ok | status ok | status ok |

**Figure 15:** Alarm sheet of cold mass 1021 (wrong assembly, large twist along axis).

After these bad cases, a criterion based on beam dynamics considerations has been worked out. A hard tolerance is given in terms of bounds on the convolution of the twist along the axis. Six magnets beyond these limits installed in a same cell need all the strength of orbit correctors. Details on the criterion are given in Appendix B. The case of magnet 1037, with red alarms on field twist (see fig. 16 and 17), and peak-to-peak variations of up to 20 mrad, was also overcoming this hard tolerance, the integral being 0.37 rad·m$^2$ instead of the maximum admissible of 0.18 rad·m$^2$. Also in this case the welds have been cut and the second welding has shown correct values.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **File name** | HCMBBRA001-1000037_cm.xls | | | | | | | | |
| 2 | **Component ID** | HCMBBRA001 | | | | **Serial Number** | 1000037 | | | |
| 3 | **Date of test Ap 1** | 09.10.2002 | | | | **Date of test Ap 2** | 10.10.2002 | | | |
| 4 | | **Aperture 1** | | | | | **Aperture 2** | | | |
| 5 | **Magnetic length** | status ok | | | | **Magnetic length** | status ok | | | |
| 6 | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** | | **Average straight** | **Variation straight** | **Heads CS** | **Heads NCS** |
| 7 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 | | positions 2 to 19 | positions 2 to 19 | position 1 | position 20 |
| 8 | **Main field** | status ok | status ok | status ok | status ok | **Main field** | status ok | status ok | status ok | status ok |
| 9 | **Angle** | | red alarm | status ok | yellow alarm | **Angle** | | red alarm | yellow alarm | yellow alarm |
| 10 | **b2** | status ok | status ok | status ok | status ok | **b2** | status ok | status ok | status ok | status ok |
| 11 | **b3** | status ok | status ok | status ok | status ok | **b3** | status ok | status ok | status ok | status ok |

**Figure 16:** Alarm sheet of cold mass 1037 (wrong assembly, large twist along axis).

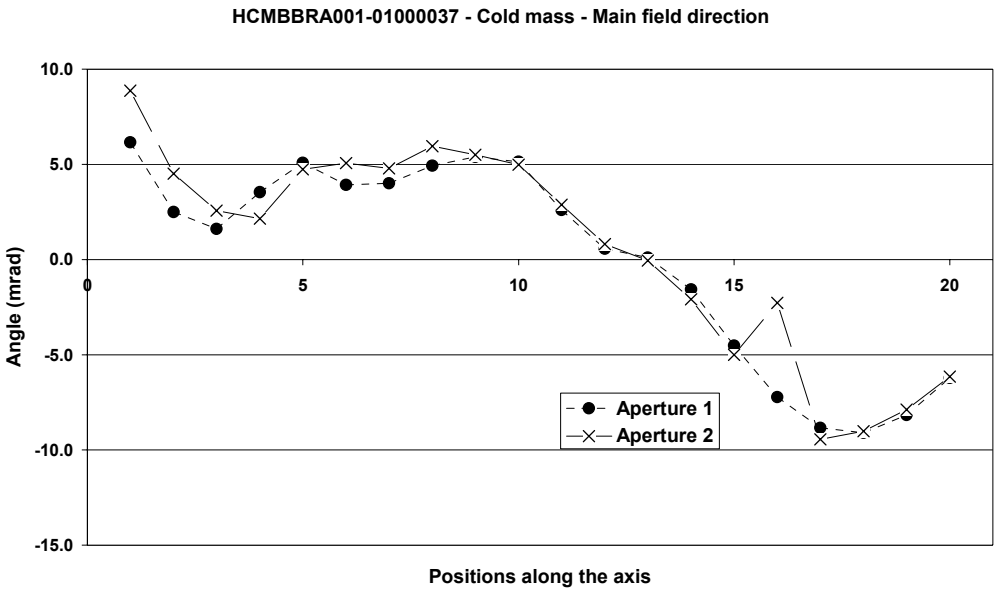


**Figure 17:** Main field direction along the axis of cold mass 1037.

The convolution integral is now being used as an additional criterion to check cold mass twist, the detection of trends still relying on the statistical approach. A further step forward in the twist control has been recently made: the check of the convolution integral has been added also during the measurements of geometric twist, i.e. the measurement of the position of the cold bores. The correlation between geometric and magnetic twist is very good (see Appendix B.2). Nevertheless, due to the relevance of this parameter for machine performance, the geometric twist is first checked with the convolution integral using the geometrical data, and then it is re-checked at the holding point for the magnetic field.

# 5. Conclusions

The automatic procedure to screen magnetic measurement of the cold mass has been presented. Setting of control limits and parameters to be controlled have been chosen following the same strategy successfully used for the collared coil. We perform the test on the difference between collared coil and cold masses to have a more stringent test. The main features of the statistics gathered on the first 13 cold masses have been discussed. The limits are the same for all manufacturers, but this feature could be change when more statistics is available.

The main results of this analysis applied to the control of nearly 60 cold masses are discussed. We distinguish between problems with measurement and problems with the magnet. In both cases we can distinguish faulty measurement or assembly procedures or non standard cases. The automatic analysis allowed us to detect different cases of faulty measurements: wrong calibration file, wrong levelling of the mole, wrong multipole signs due to a non correct cabling of the mole, wrong longitudinal positioning of the mole. A case of non-standard measurement (cold masses with diode already mounted) has been also detected. On the other hand, two different cases of problems related to the cold mass have been detected: a non standard assembly of the insert shims and a faulty assembly producing a large tilt of the main field along the axis.

# A. Estimates on magnetic length

## 5.1. A.1 Variation of magnetic length from collared coil to cold mass

We can give an estimate of the magnetic length in the cold mass according to:

$$l_{cm} = \frac{\int Bdl}{B_c} = \frac{(l_{cc} - l_{ir})B_{nest} + l_{ir}B_{iron}}{B_{iron}}$$

where $l_{cc}$ is the magnetic length of the collared coil, $l_{ir}$ is the length of the iron laminations, $B_{iron}$ is the main field in the standard iron laminations and $B_{nest}$ is the main field where the nested laminations are present (see also Fig. 19). With a little of algebra one obtains

$$l_{cm} = \frac{(l_{cc} - l_{ir})B_{nest} + l_{ir}B_{iron}}{B_{iron}} = l_{cc}\left(\frac{B_{nest}}{B_{iron}} + \frac{l_{ir}}{l_{cc}}\left(1 - \frac{B_{nest}}{B_{iron}}\right)\right)$$

since $B_{iron}$= 1.18 $B_{cc}$ and $B_{nest}$= 1.08 $B_{cc}$ and $l_{cc}$ =14.3 m, $l_{ir}$ =13.8 m, substituting one obtains $l_{cm}$ = *0.997* $l_{cc}$, and the decrease of magnetic length from collared coil to cold mass is of 3%, i.e. 40 mm against a measured value of 60 mm.

## 5.2. A.2 Impact of length of ferromagnetic laminations on magnetic length

From the above formula, one can estimate the impact of a variation $\Delta\, l_{ir}$ of the length of ferromagnetic laminations on the magnetic length $l_{cm}$

$$\Delta l_{cm} = \Delta l_{ir}\left(1 - \frac{B_{nest}}{B_{iron}}\right) = 0.085\Delta l_{ir}$$

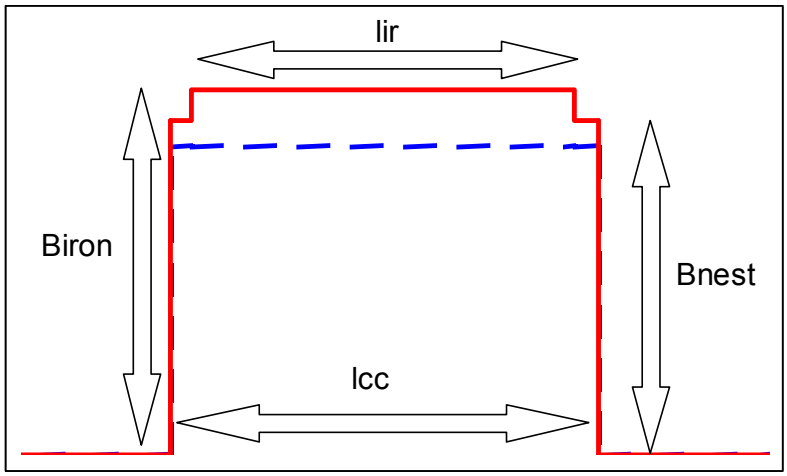


**Figure 18:** Main field versus magnet axis in collared coil (blue dotted line) and cold mass (red solid line).

Therefore, 100 mm additional iron laminations give 8.5 mm more in magnetic length, i.e., 6 units. This estimate has been confirmed by experiments on two cold masses of Firm2, namely 2012 and 2014. In Table 8 we give the difference between collared coil and cold mass magnetic length for 55 magnets. I the first column, all data are analysed. In the second column we select only magnet with the standard length of iron laminations, and in the third column the two magnets with 100 mm more. One finds 9 mm of difference against a foreseen value of 8.5 mm.

| | all data (80) | all but 2012,2014 | 2012 and 2014 |
|---|---|---|---|
| average (mm) | 0.056 | 0.055 | 0.046 |
| stdev(mm) | 0.007 | 0.004 | 0.002 |

**Table 8:** Measured difference between magnetic length in collared coil and in cold masses.

# B. Tolerances on twist

## 5.3. B.1 A criterion for the twist of the field vector

The effect of the twist is that a horizontal field component is created (the change in the vertical field is of second order, and therefore negligible). The tolerance of the effect can be summarized by the following criterion [10]

$$\int_0^L \Theta(s)\cdot(L-s)ds < 0.18 \;\; rad\cdot m^2, \qquad (1)$$

where $s$ is the longitudinal coordinate along the magnet axis from 0 to the magnetic length L, and $\Theta$ is the field angle relative to the mean value of the twist. We recall that the mean value of the magnetic twist is not measured for the cold mass. The criterion is based on available corrector strength for correcting the vertical displacement of the beam resulting from an equal twist on 6 consecutive dipoles.

## 5.4. B.2 Geometric versus magnetic data

The statistics for the twist is based on 53 cold masses for which there has been a magnetic measurement. The results are shown in fig. 1, 2 and 3, where also the geometrical twist is shown [11], i.e. the same integral evaluated with measurement of the position of the centre of the cold bore versus an absolute reference system.

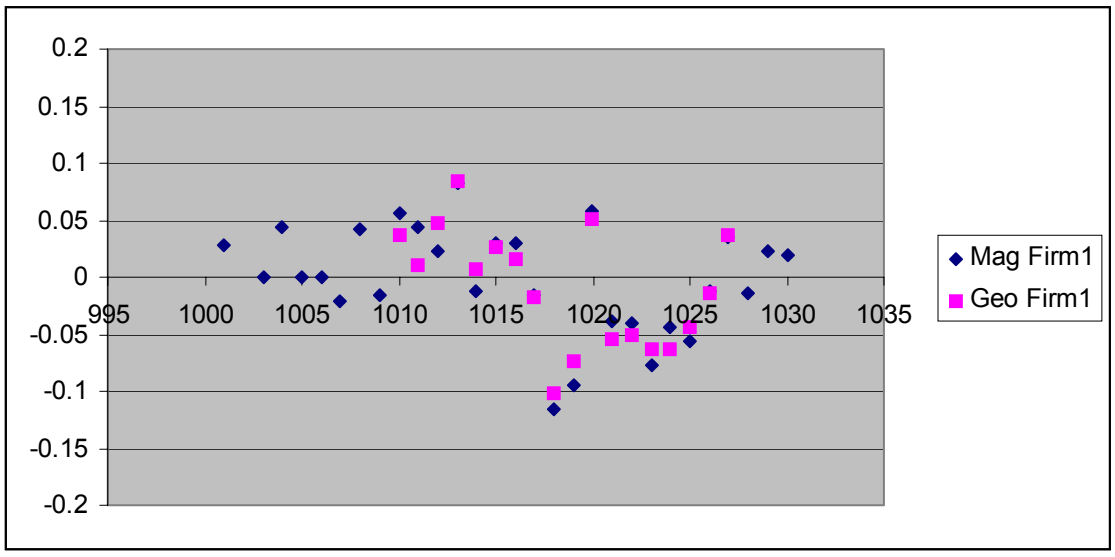


**Figure 19:** Magnetic and geometric twist for Firm 1. The horizontal axis is the magnet number and the vertical axis represents the value of the integral evaluated with geometric or magnetic data.

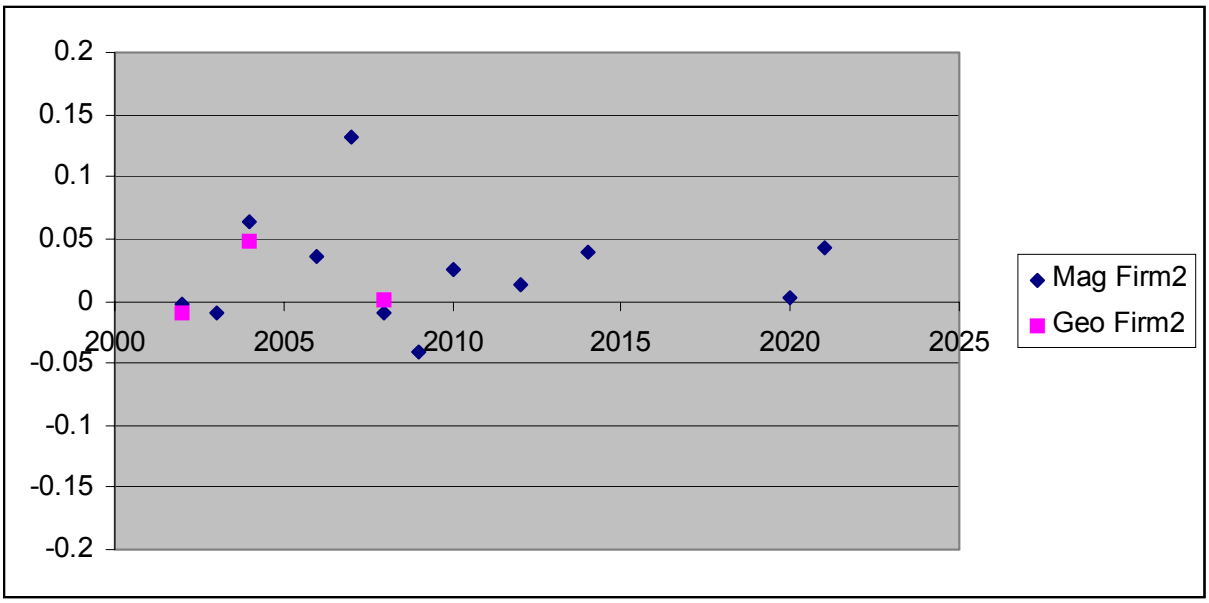


**Figure 20:** Magnetic and geometric twist for Firm 2. The horizontal axis is the magnet number and the vertical axis represents the value of the integral evaluated with geometric or magnetic data.

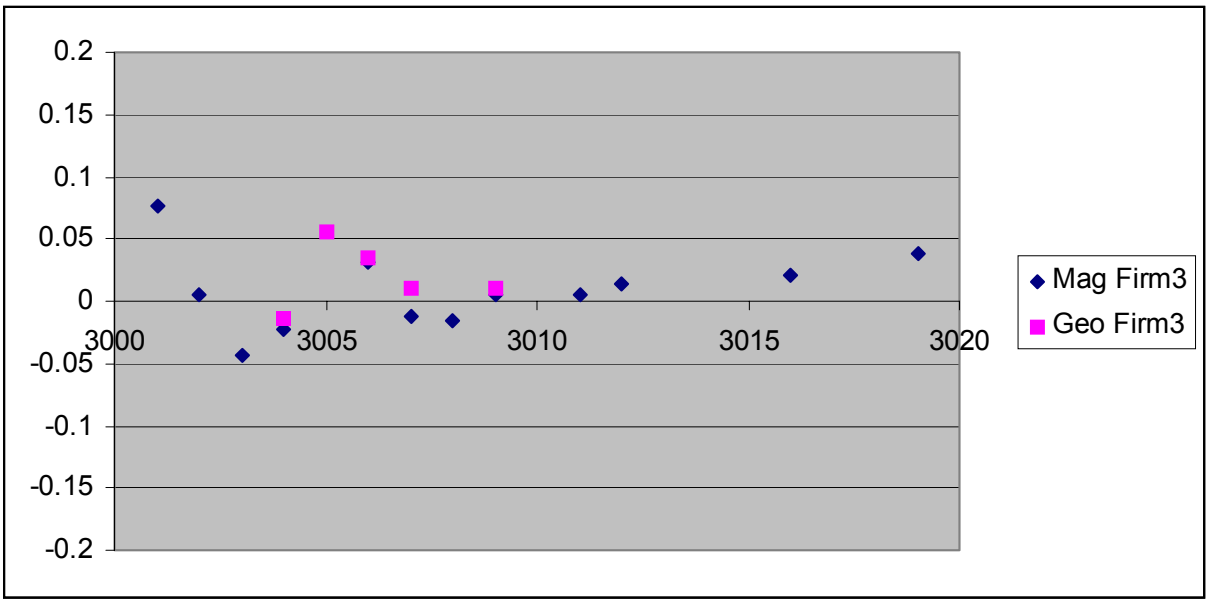


**Figure 21:** Magnetic and geometric twist for Firm 3. The horizontal axis is the magnet number and the vertical axis represents the value of the integral evaluated with geometric or magnetic data.

The geometric [11] and the magnetic twist according to the convolution criterion for a set of cold masses are shown in figures 1 to 3. Figure 4 shows a scatter plot for the magnetic and the geometrical twist. The correlation coefficient is 0.89.

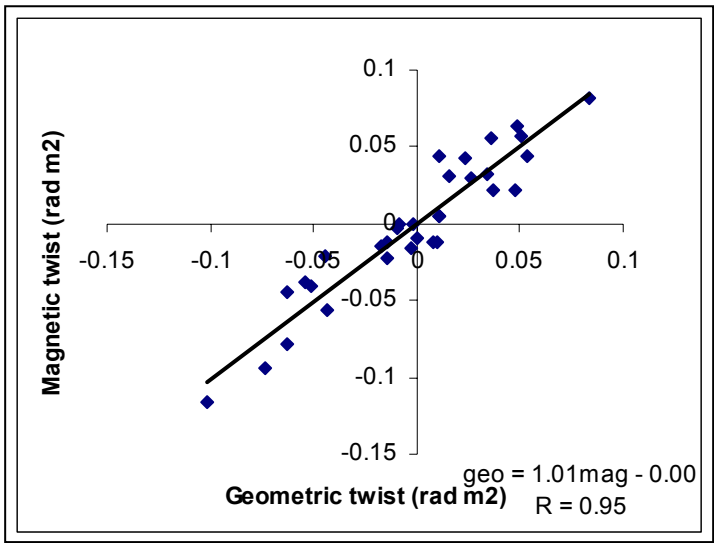


**Figure 22**: Magnetic versus geometric twist in all firms.

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