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Room Temperature Magnetic Field Measurements as a Tool to Localize Inter-turns Electrical Short Circuits in the LHC Main Dipole coils

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Abstract

In this report the method for the localization of the electric shorts circuits in the main LHC dipoles using the magnetic measurements at room temperature is presented. The steps of the method are discussed, and two cases are studied in detail. A complete statistics of the 12 cases analyzed up to now is given.

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1. INTRODUCTION

The active part of the LHC dipole is the collared coil, i.e. the superconducting coils clamped in the stainless steel collars. The assembly of the coils in the collars takes place under the collaring press. At each applied loads of the press, cable insulation tests are performed to check the electrical integrity of the coil. Since December 2003, a few cases of electrical shorts during collaring have been detected. In some of them the short disappeared after the disassembly of the coil, making impossible its localization. For this reason, following the experience given in [1] and [2], the use of the warm magnetic measurements performed on the collared coils has been proposed to locate the short during the collaring using its signature on the magnetic field harmonics.

In this report, after a brief introduction of the layout of the collared coil, we present a method to localize the short circuit by means of the magnetic field measurement at room temperature. The localization goes through the following steps: identification of the affected aperture and the pole, of the longitudinal position, of the radial position in the transverse cross-section, and finally of the cables. The method is applied in detail to two cases, and an overview of all the analyzed cases is reported.

2. LHC COLLARED COIL LAYOUT

The LHC main dipole consists of a cold mass, which contains all the components that are cooled by liquid helium, inside a cryostat [3]. The active part of the cold mass is the collared coil, which is composed of the following components: (see Figure 1):

- A common non-magnetic, force-retaining laminated structure, made up of austenitic steel collars taken in place by three locking rods. This structure confines and pre-stresses the coils, keeping their geometry notwithstanding the large electromagnetic forces that occur during the powering.
- Two superconducting dipole coils connected in series so that the magnetic fields are in opposite directions.
    - Each dipole coil features two poles (upper and lower) 14.5 m long.
        - Each pole consists of an inner and outer layer, which are electrically connected in series through the layer jump. In each layer the conductor turns are grouped in blocks approximating the ideal $cos\theta$ current distribution to generate a homogenous dipole field.

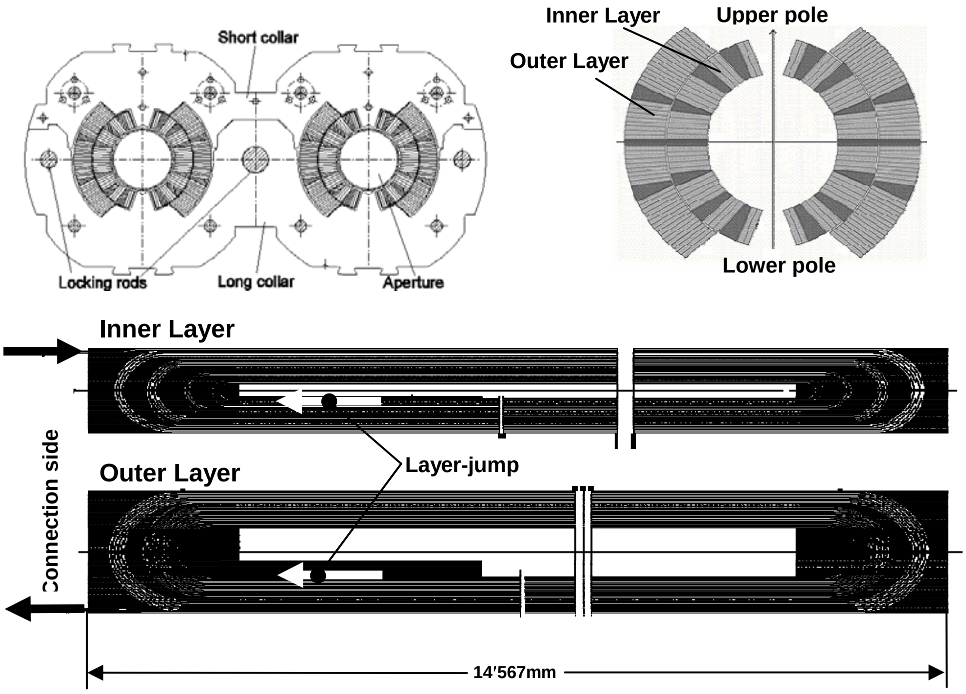

Figure 1: *Top left*: collared coil cross section. *Top right*: the superconducting coil cross-section. *Bottom*: layout of the two layers of a pole seen longitudinally.

3 SHORT CIRCUIT LOCALIZATION THROUGH MAGNETIC MEASUREMENT: THE METHOD

3.1 Magnetic measurements at room temperature

The magnetic field, in a dipole, can be expressed according to the well-known multipolar expansion:

$$B(x,y) = B_y + iB_x = B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

where the coefficient b_n and a_n are the multipoles, (x,y) are the transverse coordinates, B_1 is the main component (dipolar magnetic field) and R_{ref} the reference radius used to have dimensionless multipolar coefficients (17 mm for LHC main dipoles). In the ideal case of a "perfect geometry" (the aperture is up-down and left-right symmetric) all the coefficients are zero except b_3, b_5, $b_7 \ldots b_{2n+1}$ (the so-called allowed multipoles). If the symmetry is broken, either for a not-ideal geometry of the component or, as in our case, to a not ideal flow of the current inside the coil, the not allowed multipoles are generated. They can be split in 3 groups with respect to the anti-symmetry type:

- Even normal: b_2, b_4, … b_{2n}, are generated by a left-right anti-symmetry
- Even skew: a_2, a_4, … a_{2n} are generated by an up-down anti-symmetry
- Odd skew: a_3, a_5, … a_{2n+1} are generated by an anti-symmetry that is a 180° rotation with respect to the centre of the aperture.

A magnetic field measurement consists in the evaluation of the coefficients of the field expansion in several positions along the magnet axis [4]. For the LHC dipoles, the measurements are performed with a 750mm long rotating coil in 20 positions: in the 1st and in the 20th (the positions corresponding to the ends of the coil) the mole enters in the aperture only for 534mm while in the intermediate positions (2-19: the so called *straight part*) the whole length of the mole is inside the coil.

3.2 Steps of the procedure

Magnetic measurements at room temperature give a deep insight on the distribution of the current lines. For this reason, when a short circuit occurs it produces an anomaly in the magnetic field whose signature can be used to detect the short location. A standard warm magnetic measurement is performed on both apertures of the collared coil and the measurement of the aperture without the short is used as a reference.

The localization of a short circuit in a collared coil passes through the following steps:

- Computation of the field anomaly
- Identification of the aperture and the pole
- Localization of the longitudinal and radial position
- Identification of the cable inside the coil.

3.3 Field anomaly computation

The measurement of the magnetic field during a short is compared to a reference case, and subtracting the reference from the measurement one obtains the field anomaly. This procedure is important for allowed multipoles, which always have a systematic component, and for measurements carried out under the collaring press, which induces a strong magnetic perturbation on normal multipoles. The other aperture (i.e. without the short) can be taken as the reference value. If the short appears only at a certain phase of the assembly (for instance, at a certain value of the collaring pressure), the same aperture without short can be taken as a reference *if it has been measured in the same conditions*.

The field anomaly is then compared to the control limits of the production. These have been set for each multipole at ±3.5 sigma, using the statistics of the collared coils that are considered as "normal" [5]. The comparison to the control limit allows to judge if a field anomaly is relevant or not. We will show that electrical shorts give very strong effects on multipoles that are well beyond the control limits of the production. This makes the method to detect short very reliable.

3.4 Aperture and pole localization

An electrical short circuit occurs either in the upper or in the lower pole, and therefore it generates a strong up-down asymmetry.

Let's take a simple dipole cross section made of two poles of three cable turns each (Figure 2). With a short circuit placed somewhere in the coil length of the upper pole the ideal current pattern is lost: in two cables (one in the right and the other in the left side of the pole) the current is not flowing (crossed cables in Figure 2). In the showed example all the symmetries are broken. But if we look the problem from the point of view of the field quality the Up-Down asymmetry that the short generates is stronger that the Left-Right one. Actually, suppose that the crossed cable of the right part of the aperture of Figure 2 produces an anomaly on the four classes of field harmonics equal to: $\Delta b'_{2n+1}$, $\Delta a'_{2n}$, $\Delta b'_{2n}$, $\Delta a'_{2n+1}$, then the anomaly of the left-side cable (taking into account the proprieties of the field harmonics mentioned above) are $\Delta b''_{2n+1}$, $\Delta a''_{2n}$, $-\Delta b''_{2n}$, $-\Delta a''_{2n+1}$. The global influence on field quality is computed by summing the two effects. The more similar the angular positions of two cables w.r.t. the mid plane the closer the absolute values of the effects on field quality. Following this argument and the assumption that we discuss later that the short can be appear only among two contiguous cables one can state that the most affected classes of multipoles are the allowed and the even skew, and since the field harmonics decay with the multipole order the biggest effects are expected on a_2 and b_3.

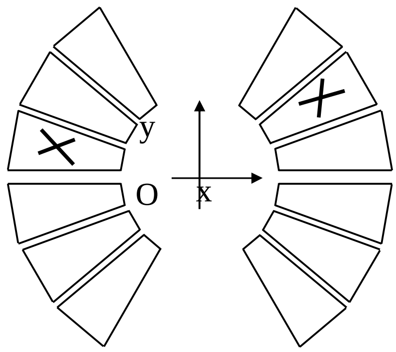

Figure 2: Schematic dipole cross section made of two poles of three cable turns each. The crossed cables do not transport current.

We will show that an electrical short of two neighbour cables, occurred in a LHC dipole aperture, gives 5 to 60 units of a2 , that are well beyond the control limit of 3.2 units. The smallest contribution (5 units) is given for shorts close to the mid plane. In this case there is a strong effect on b3 (45 units) that can also be used to double check the analysis on a2. The aperture that is featuring a field anomaly in a2 has the electrical short.

If one computes the derivative of the magnetic field expansion with respect to “y” in the centre of the aperture:

$$\left.\frac{\partial B_y}{\partial y}\right|_{x,y=0} = \left.\left(-a_2 - 2b_3\frac{y}{R_{ref}} - 2a_3\frac{x}{R_{ref}} + o(x,y) \right)\right|_{x,y=0} = -a_2$$

the sign of a2 is related to the pole localization: according to the above equation, if the short is in the upper pole a2 is positive, and if it is in the lower pole a2 is negative.

3.5 Longitudinal localization

To analyze the problem we can use a simple model: an aperture of two poles made up of a single layer, with three cable turns (see Figure 2). Let us consider a short circuit in a given longitudinal position along the magnet axis, where the current by-passes an entire turn, as shown by the dashed line in Fig. 2a. A coil cross section taken between the short and the connection side features a current distribution with a left-right asymmetry (see Fig. 2b, were the crossed cables are the ones that do not carry current). On the other hand, a coil cross-section taken between the short and the non connection side has a left-right current symmetry (see Fig. 2c). This gives a tool to longitudinally locate the short through magnetic measurements:

- if anomalies are seen in all the four families of multipoles, the short is between this location and the non connection side;
- if anomalies are seen in odd normal and even skew multipoles only, the short is between this location and the connection side.

Therefore, looking at the pattern of the even normal and odd skew harmonics along the aperture, we can locate the short in the magnetic measuring position where the anomaly in these multipoles falls to zero. We also have two extreme cases, i.e., when the short is located in one of the coil ends:

- If the even normal and odd skew field harmonics show no anomaly all along the axis, the short will be located in the connection side end.
- If the even normal and odd skew field harmonics show anomalies all along the axis, the short will be located in the non connection side end.

The indetermination in the longitudinal localization is given by the length of the measuring position: 534mm in the ends and 750 in the straight part. A shorter mole of 125mm is available to better locate the short in the longitudinal coordinate.

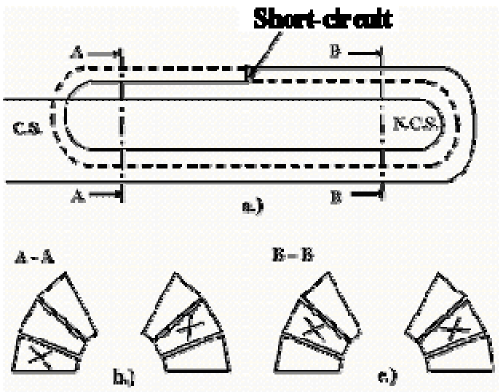

Figure 3: a.) Simplified model of a layer with three cable turns; the dashed line represent the turn bypassed by the current. b.-c.) Cross section of the coil respectively toward the connection side and the non connection side with respect to the short; the crosses inside the cables indicate that no current is flowing inside.

3.6 Radial Localization: layer identification

We now proceed with the identification of the position in the coil cross-section. A simple method can be used to detect if the short is in the inner or in the outer layer, following the approach given in [6]. The used principle is that the field anomaly has a slow decay with the multipole order if the short is close to the aperture (inner layer), and a fast one if it is far (outer layer). Let (Δb_n,Δa_n) be the field anomalies measured in the multipoles, that can be computed as the differences between the measurement averaged over the straight part of the aperture with the defect and the ones of the reference aperture. According to Biot-Savart law, the field anomalies linearly decay with the multipole order n as a power law

$$\sqrt{(\Delta b_n)^2 + (\Delta a_n)^2} \approx A\left(\frac{R_{\text{ref}}}{R_s}\right)^n \tag{1}$$

where the unknown R_s is the distance of the source of the field anomaly from the aperture centre, and R_{ref} =17 mm is the reference radius. Therefore, we have

$$f(n) \equiv \ln\sqrt{(\Delta b_n)^2 + (\Delta a_n)^2} \approx n \ln\frac{R_{\text{ref}}}{R_s} + \log A \tag{2}$$

and making a linear fit of the function $f(n)$.

$$f(n) \approx P + Qn \tag{3}$$

We can deduce R_s through the fitted slope Q (where Q>0):

$$R_s = R_{\text{ref}} \exp(Q) \tag{4}$$

Therefore, if R_s is between 28 and 43 mm, the short is in the inner layer, and if it is between 43 to 59mm is in the outer layer.

3.7 Cable localization

The convention we use in this note for numbering cables in the coil cross-section is shown in Figure 4, where the upper pole of a LHC aperture is sketched. For both left and right quadrants, the lowest cable of the first block is the cable number 1, then, moving azimuthally, the last cable of the outer layer is the number 25; cable number 26 is the lowest one of the inner layer and cable 40 is the upper one.

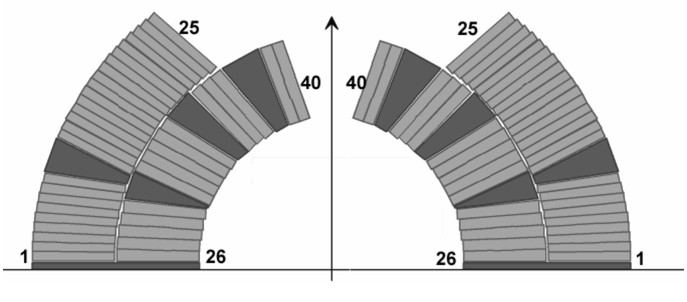

Figure 4: Cable numbering for half aperture of a LHC dipole.

As we already discussed, when a short occurs an entire turn of the coil is by-passed. This means that there are two cables in the coil cross-section, one on the left and one on the right part, that do not transport any current. From here on we assume that the short is located in the upper pole of the aperture (all the considerations are also valid for a short in the lower pole, taking care to apply the right symmetries: the effects on b_{2n+1} and a_{2n+1} are the same whilst they change sign for b_{2n} and a_{2n}). We have to define all the possible short circuits that can be detected in a pole. We assume that:

- Shorts between inner and outer layer are not allowed: an inter layer shim is interposed between the two layers.
- Short can be appear only among two contiguous cables (it is physically improbable that two cable that do not share a surface can be short-circuited).

Let *m* be the cable of the right quadrant of the pole which does not transport any current: we denote by (*k,l*) the couple of cables in the left and in the right part of the coil respectively where no current flows. Using the simplified models of the inner and outer layer of Figure 5 one can state that the possible shorts are:

- For the inner layer, we have *(m+1,m)* between the short and the connection side, and (*m,m)* between the short and the non connection side
- For the outer layer we have *(m,m+1)* for the cross-section between the short and the connection side, and (*m+1,m+1)* for the short between the short and the non connection side.

According to our hypothesis, a few combinations are forbidden, such as, for instance, 9-10, as a wedge is placed between the 9th and the 10th.

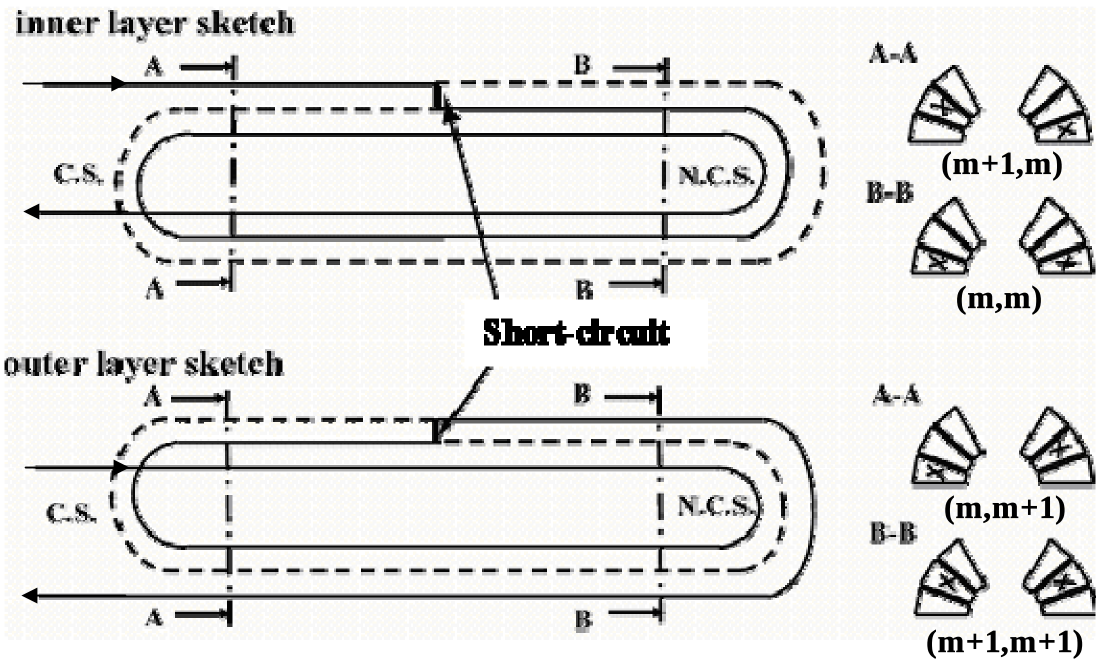

Figure 5: Short in the inner and outer layer, longitudinal view (left) and cross-section view (right).

The two cables that do not transport current create a different current distribution with respect to design; this causes a field anomaly. We evaluate the anomalies given by all the possible short circuits using a magneto-static model of the cross section. In Figure 1A-6A in Appendix A, the results of the model are shown; we present the two most representative harmonics of each group of field harmonic. It is worth to point out that the field anomalies are strongly dependent on the angular positions (θ) of the cables that are "switched off": the effects on b_{2n+1} and on a_{2n+1} can be approximated with $\cos[(2n+1)\theta]$ whilst the ones on b_{2n} and on a_{2n} with $\sin[(2n)\theta]$.

The largest effects on field quality are observed for short circuits placed in the inner layer, the most affected harmonics are b_3 and a_2([-40;40] and [0;90]units respectively): this is why we use these two multipoles as proof of the presence of the short. By comparing the measured anomaly with the expected effects of all possible shorts we identify the short location in the coil cross-section. Since we are using several multipoles, the solution is always unique.

It can happen that the short circuit is not "perfect"; this means that a certain amount of the total current still flow inside the cable. In this case, after an approximate localization, one can improve the simulations by having a non-zero current in the cables that are affected by the short. In the next two sections we will give two examples: the first is a perfect short and the second is a partial one.

4 APPLICATION OF THE METHOD ON A PERFECT SHORT: COLLARED COIL 2101

4.1 Detection of the case and field anomaly

This collared coil was first successfully measured without anomalies. Then, during an insulation test, a drop of about 30mΩ of the resistance of the coil was measured in aperture 2, corresponding to a short circuit of one turn. Aperture 2 was then measured again. The measurement of aperture 2 without the short was used as a reference. The anomaly was uniform along the axis, thus suggesting that the short is in the coil end. In Table I we present the field harmonics averaged over the measuring positions of the straight part with and without the short circuit. We evaluate the field anomaly as the difference between these values, and we express them in units of the control limits set on the production (that are 3.5 times the measured standard deviation).

Table I: Field harmonics averaged over the straight part of aperture 2 of the two measurements of collared coil 2101, difference, control limits on the production, and ratio between the difference and the control limits.

Harmonic	with defect	without defect	Δ	Control limits	Δ/control limits
b2	0.15	-0.69	0.83	±1.82	0.5
b3	5.87	-5.87	11.73	±2.59	4.5
b4	0.47	0.02	0.45	±0.46	1.0
b5	12.44	0.04	12.40	±0.70	17.7
b6	-0.05	0.05	-0.10	±0.21	-0.5
b7	2.22	0.79	1.42	±0.22	6.3
b8	-0.04	-0.02	-0.02	±0.08	-0.2
b9	-0.22	0.45	-0.66	±0.05	-12.6
b10	0.00	-0.00	0.01	-	-
b11	0.51	0.71	-0.19	±0.02	-8.9
a2	89.02	0.17	88.85	±2.45	36.3
a3	-0.57	-0.48	-0.08	±1.12	-0.1
a4	15.18	0.43	14.75	±0.98	15.1
a5	-0.42	-0.17	-0.25	±0.46	-0.5
a6	-3.15	-0.10	-3.05	±0.25	-12.4
a7	-0.08	-0.04	-0.04	±0.17	-0.2
a8	-1.70	0.07	-1.77	±0.08	-21.1
a9	-0.00	-0.04	0.04	±0.07	0.6
a10	-0.00	0.00	-0.00	-	-
a11	-0.02	-0.06	0.05	±0.03	1.7

4.2 Short localization

Aperture and Pole: as already said the fault is in the aperture 2 and is confirmed by our method: average a_2 is about 40 times the control limits of the production. Since the a_2 is positive, the pole with the short is the *upper* one.

Measuring position and *layer identification*: in the last column of Table II the field anomaly is divided by the control limits set on the production. It is clear that the field anomaly is only on odd normal and even skew multipoles: therefore, the short is in the connection side end. The linear fit of the function $f(n)$ defined in Eq. (3) gives a slope of 0.79 (see Figure 6). Using Eq. (4) we evaluate the distance of the short from the centre as R_s=37 mm, i.e. in the *inner layer* (whose distance from the centre is 28 to 43.9 mm).

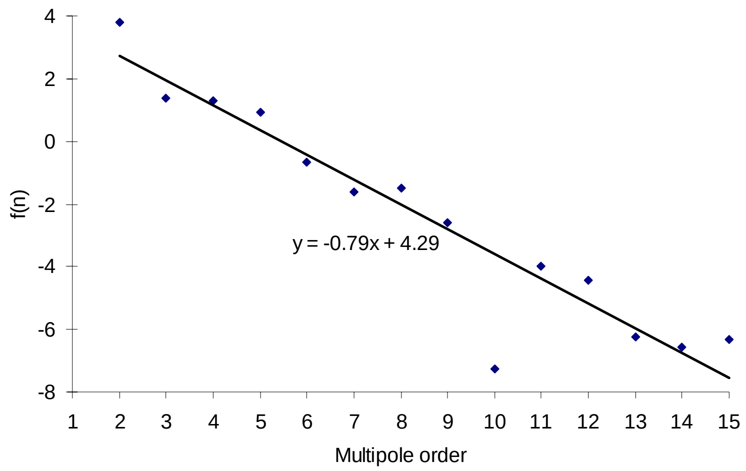

Figure 6: Function $f(n)$ as defined in Eq. (3) versus multipole order n for the field anomaly of collared coil 2101, and linear fit.

Cables identification: The short circuit configuration that minimizes the difference between the measurement and the model is the 34-34 (see Table II): expected and measured values match within a fraction of unit. In Figures 7 and 8 expected and measured effects on the even normal and odd skew multipoles are plotted. The short is placed somewhere within the first magnetic measuring position among the cable 34 and the cable 33, as shown in Figure 9.

Table II: Field harmonics anomaly induced by a short: measured and expected.

Field harmonics	measured	expected: 34-34	meas.-exp.
b3	11.74	11.89	-0.15
b5	12.40	12.12	0.29
b7	1.42	1.35	0.07
b9	-0.66	-0.69	0.03
b11	-0.19	-0.23	0.04
a2	88.85	88.69	0.15
a4	14.75	15.37	-0.62
a6	-3.05	-3.21	0.16
a8	-1.77	-1.72	-0.05
a10	-0.00	-0.06	0.06

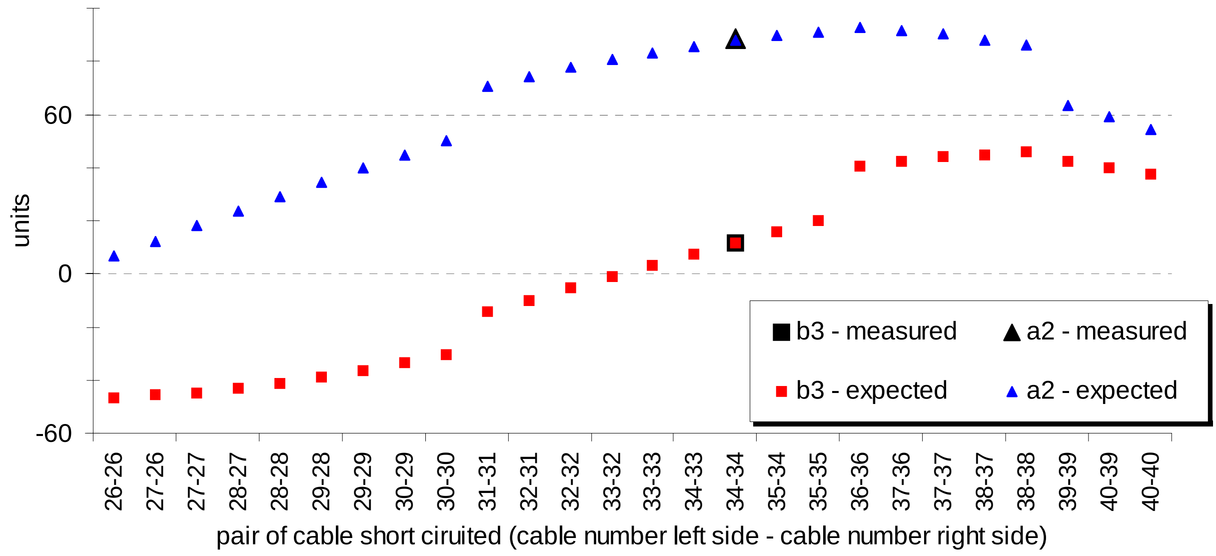

Figure 7: Expected and measured (case 2101) field anomalies in a_2, b_3 versus short position.

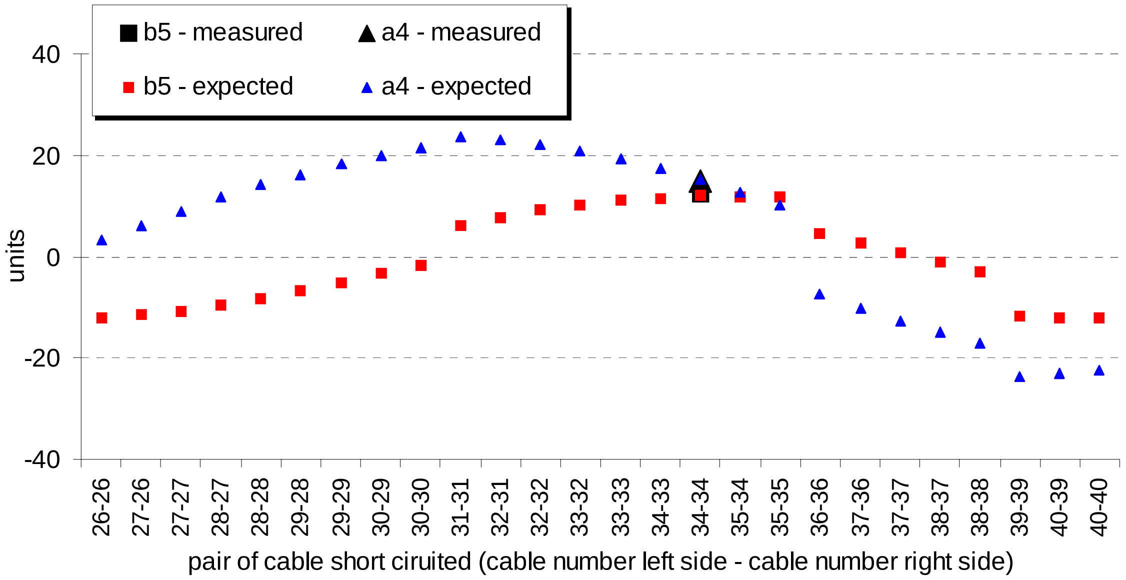

Figure 8: Expected and measured (case 2101) field anomalies in a_4, b_5 versus short position.

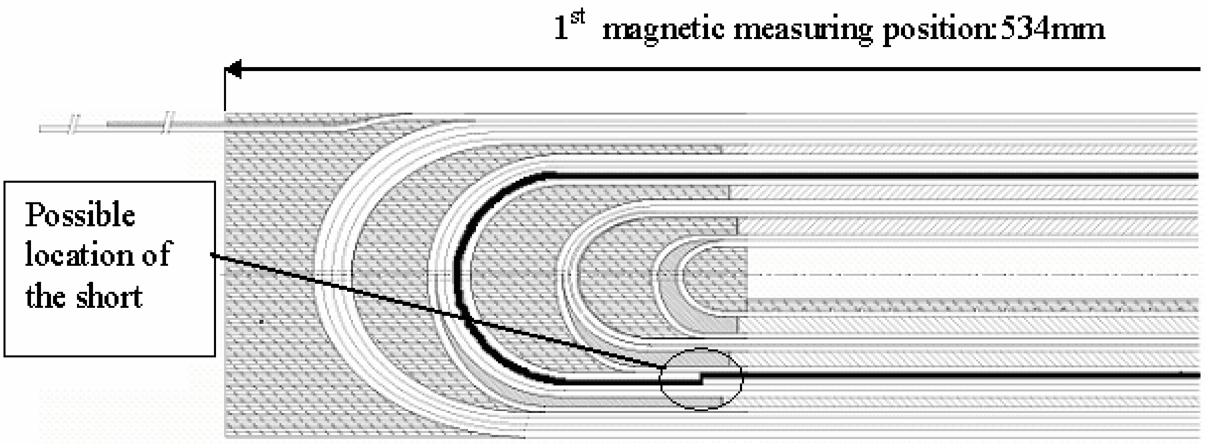

Figure 9: Possible location of the short of collared coil 2101 within the first measuring position.

5 APPLICATION OF THE METHOD ON A "PARTIAL" SHORT: COLLARED COIL 1154

5.1 Detection of the case and field anomaly

A short circuit has been detected in aperture 1 under the press during the collaring at 450bar. A standard magnetic measurement has been performed on both apertures. In this case no measurement of the faulty aperture without short and in similar conditions (i.e. under the press) was available, and therefore the other aperture has been taken as a reference. In both measurements we have very large values of b_2, due to the magnetic perturbation induced by the iron of the press, that disappear in the difference, see Table III.

Table III: Field harmonics averaged over the straight part of aperture 2 of the two measurements of collared coil 1154, difference, control limits on the production, and ratio between the difference and the control limits.

Harmonics	Defect	Reference	Δ	Control limits	Δ/control limits
b2	32.21	31.38	0.83	±1.82	0.5
b3	26.13	-9.11	35.24	±2.59	13.6
b4	0.92	1.28	-0.36	±0.46	-0.8
b5	-1.47	0.28	-1.75	±0.70	-2.5
b6	-0.06	-0.09	0.03	±0.21	0.1
b7	-1.10	0.98	-2.08	±0.22	-9.3
b8	0.10	0.03	0.07	±0.08	0.9
b9	1.13	0.46	0.66	±0.05	12.6
b10	0.00	0.00	0.00	-	-
b11	0.70	0.68	0.02	±0.02	0.9
a2	64.97	0.18	64.78	±2.45	26.4
a3	0.35	0.16	0.18	±1.12	0.2
a4	-13.00	-0.06	-12.94	±0.98	-13.2
a5	0.17	-0.02	0.19	±0.46	0.4
a6	-1.65	0.03	-1.69	±0.25	-6.9
a7	0.03	-0.08	0.11	±0.17	0.7
a8	1.51	-0.01	1.52	±0.08	18.1
a9	-0.09	-0.04	-0.05	±0.07	-0.7
a10	0.00	0.00	0.00	-	-
a11	-0.07	-0.07	0.00	±0.03	0.0

5.2 Short localization

Aperture and Pole: b3 and a2 more than ten times out of the production control limits. Since a2>0, the faulty pole is the upper one.

Measuring position and *layer identification:* the even normal and odd skew multipoles show no anomaly and are within the production control limits, therefore it is on the connection side. The evaluation of the slope of the anomaly decay $f(n)$ fives Q=0.63 and R_c=31.9mm, i.e. the inner layer.

Cables identification: 38-38 is the short circuit configuration that minimizes the difference between the measurement and the model. The match between expected and measured values is worse than the previous case (see Table IV): 20 units of a_2 and 10 of b_3 are not accounted. We can have a better agreement by assuming that the short is partial. The best agreement is obtained for 28% of current flowing in the conductor: here we recover an agreement within a fraction of unit. The short is placed in the first magnetic measuring position among the cable 38 and the cable 37, see Figure 10-11 and 12.

Table IV: Field harmonics anomaly induced by a short: measured and expected for a complete short and for a partial short.

field harmonics	measured	I=0% inside short circuited cable		I=28% inside short circuited cable	
		expected 38-38	meas-exp.	expected 38-38	meas-exp.
b3	35.24	46.24	-11.01	34.68	0.56
b5	-1.75	-2.97	1.22	-2.23	0.47
b7	-2.08	-2.57	0.49	-1.93	-0.15
b9	0.66	0.85	-0.18	0.63	0.03
b11	0.02	0.01	0.01	0.01	0.01
a2	64.78	86.64	-21.86	64.98	-0.20
a4	-12.94	-17.32	4.38	-12.99	0.05
a6	-1.69	-2.01	0.32	-1.51	-0.18
a8	1.52	1.75	-0.23	1.31	0.21
a10	0.00	-0.26	0.27	-0.20	0.20

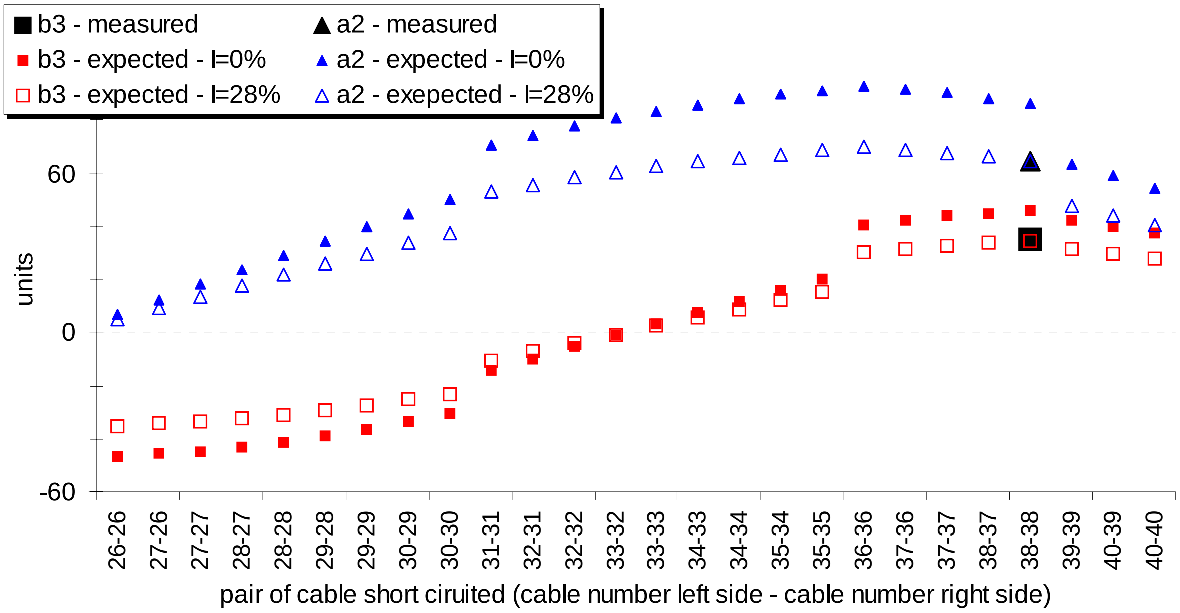

Figure 10: Expected and measured (case 2101) field anomalies in a_2, b_3 versus short position.

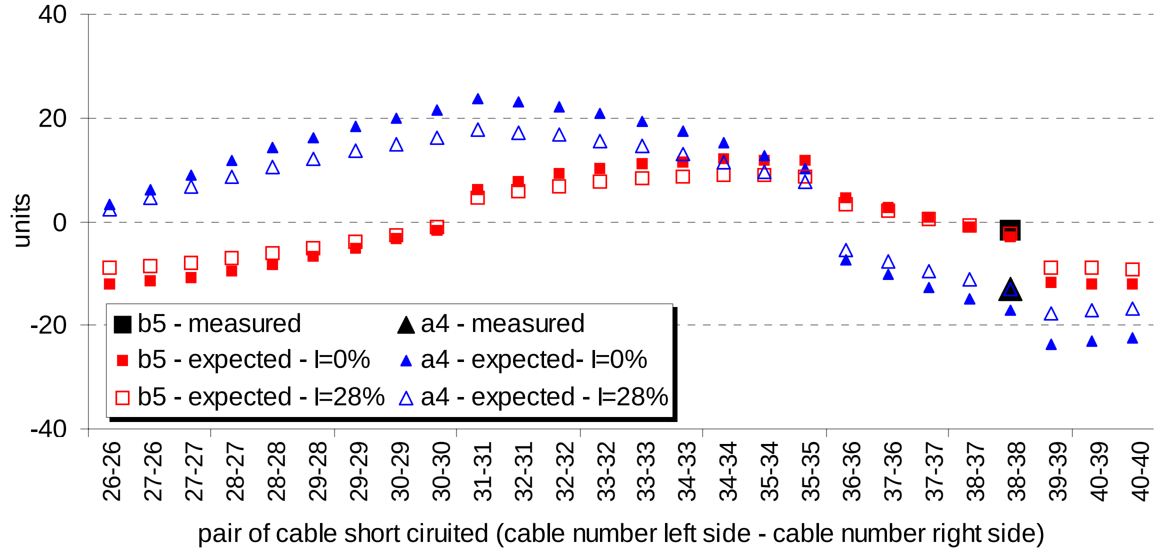

Figure 11: Expected and measured (case 2101) field anomalies in a_2, b_3 versus short position.

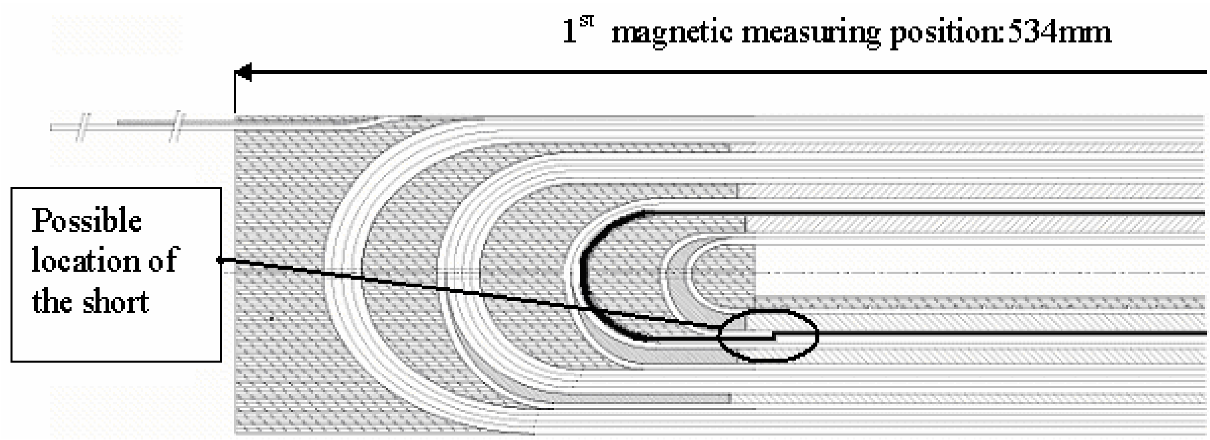

Figure 12: Possible location of the short of collared coil 1154 within the first measuring position.

6. OVERVIEW OF THE DETECTED CASES OF ELECTRIC SHORTS

To date, the localization method has been successfully used for 12 cases in two cold mass manufacturers (9 of Firm1 and 3 of Firm2). Data are given in Table V: all defects have been localized in the magnet ends, and 10 out of 12 in the connection side, which is most critical one due to the asymmetry of the assembly. In all cases the short is in the inner layer. The short are equally shared among upper and lower poles, and aperture 1 and 2 as expected. Five different locations in the cross-section have been found; we had several cases of short in the cable 38-38, probably corresponding to the same manufacturing problem.

In the first two cases, due to the insufficient experience on the problem, it has not been possible to verify the presence of the short where foreseen by the method. These were difficult cases were the short appeared only during the collaring at a given pressure and disappeared after the disassembly of the collared coil. Dedicated procedures to have an experimental evidence of the short have been developed, and have been applied successfully to all the successive cases. In all cases the location of the short matched the result of the method presented here, expect the case of 1217 which is still waiting to be disassembled and checked.

Table V: Main features of all the detected shorts.

Firm	Dipole	Short – Circuit Localization					
		Aperture	Pole	Meas. Position	Layer	Short config.	check
01	1103	1	Upper	1	Inner	38-38	no
01	1124	2	Upper	1	Inner	38-38	no
01	1127	1	Lower	1	Inner	38-38	ok
01	1141	1	Upper	1	Inner	38-38	ok
01	1154	2	Upper	1	Inner	38-38	ok
01	1165	1	Lower	1	Inner	38-38	ok
01	1178	1	Lower	1	Inner	38-38	ok
01	1217	1	Upper	20	Inner	38-37	no*
01	1526	2	Upper	20	Inner	40-39	ok
02	2087	2	Upper	1	Inner	34-34	ok
02	2101	2	Upper	1	Inner	34-34	ok
02	2202	2	Lower	1	Inner	38-38	ok
*- not yet checked.							

7. CONCLUSIONS

A method based on magnetic measurements at room temperature to locate electrical shorts in the coil of the main LHC dipole has been presented. The approach is very reliable since the field anomalies generated by the short are very large compared to the natural spread in field quality induced by tolerances and assembly procedures. We have shown that using an electromagnetic code, one can forecast the effect of shorts between adjacent cables on field quality, and that the comparison to experimental data gives a location of the short without ambiguity. The method is very sensitive, also allowing to detecting if the short is perfect or only partial. 12 coils presenting electrical shorts have been analyzed and rescued using this procedure. The approach can be easily applied to other superconducting magnets.

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APPENDIX A

The influence on field quality of the all possible short circuits that can be detected in a collared coil is presented in the following figures. Since all the possible shorts give an effect on b_{2n+1} and on a_{2n}, to be clear, we split the plots in two: effects of the shorts of the outer layer (Figure 1A and 2A) and the ones of the outer layer (Figure 2A and 4A). Concerning the plots of the b_{2n} and a_{2n+1} in Figure 5A-6A we did not include the effect of the "symmetric" short-circuit (*m-m*) because such configurations have no effects on these harmonics.

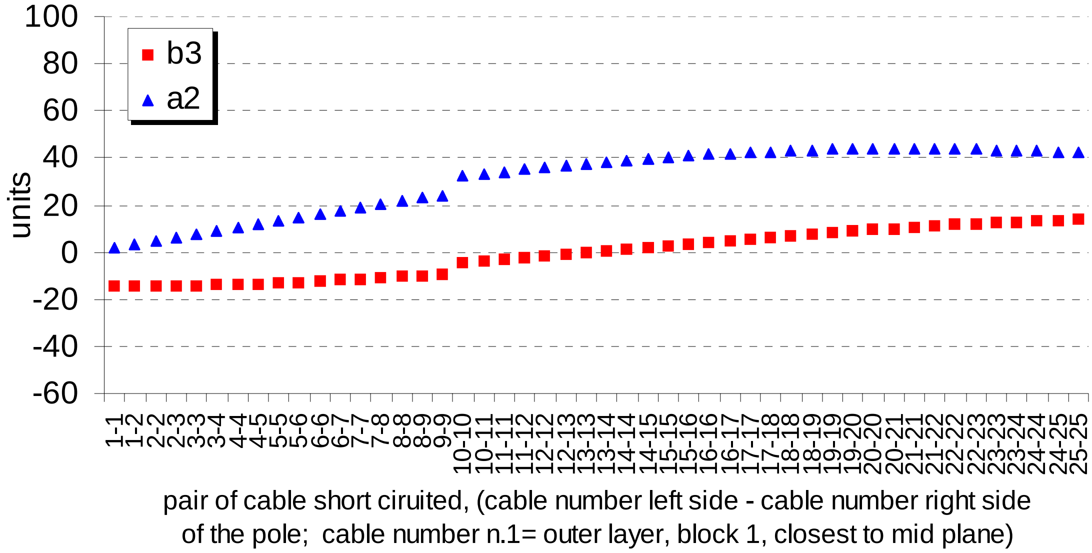

Figure 1A: Effect on b_3 and a_2 of the possible short circuits of the OUTER LAYER

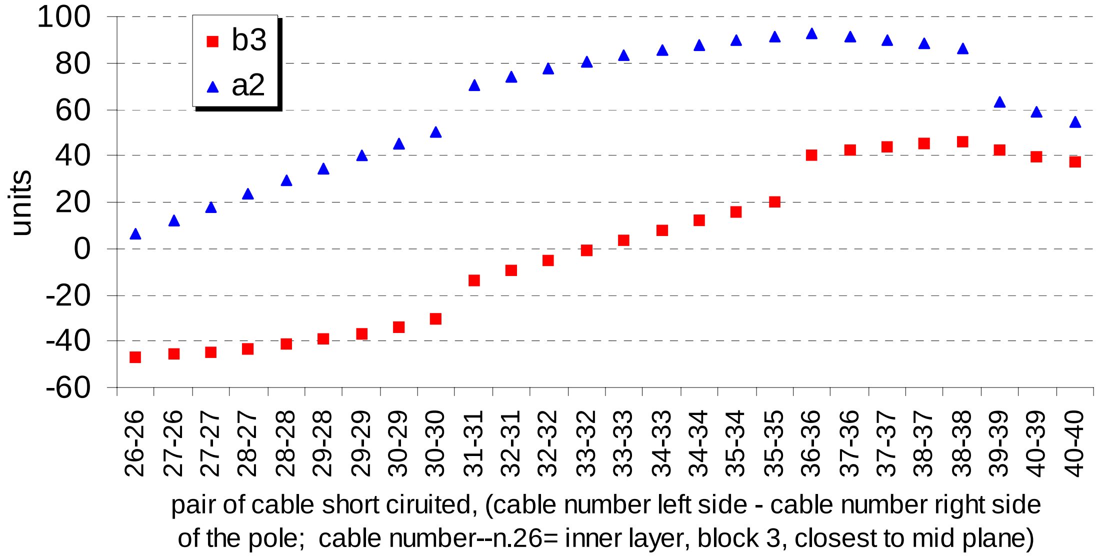

Figure 2A: Effect on b_3 and a_2 of the possible short circuits of the INNER LAYER

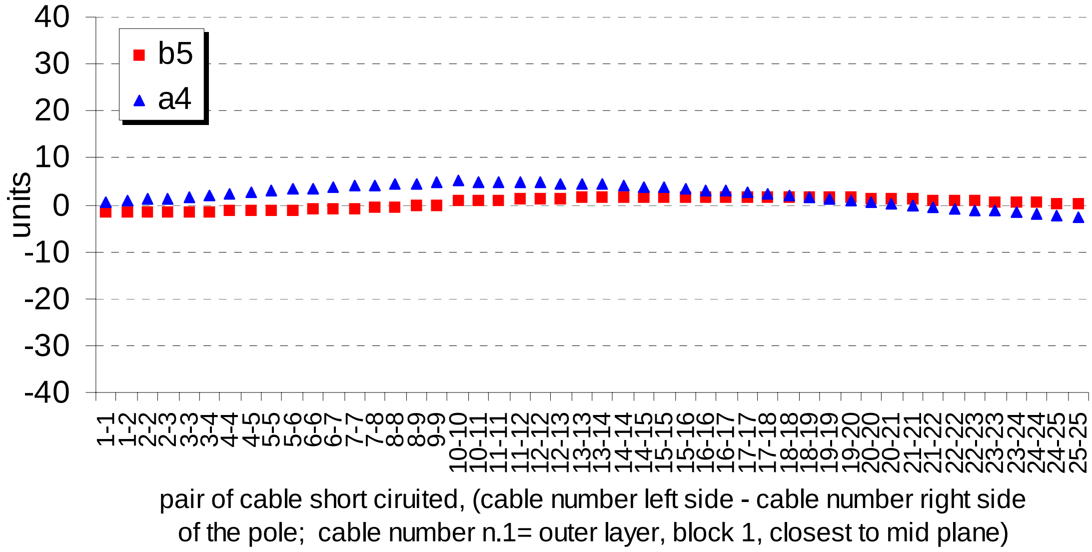

Figure 3A: Effect on b_5 and a_4 of the possible short circuits of the OUTER LAYER

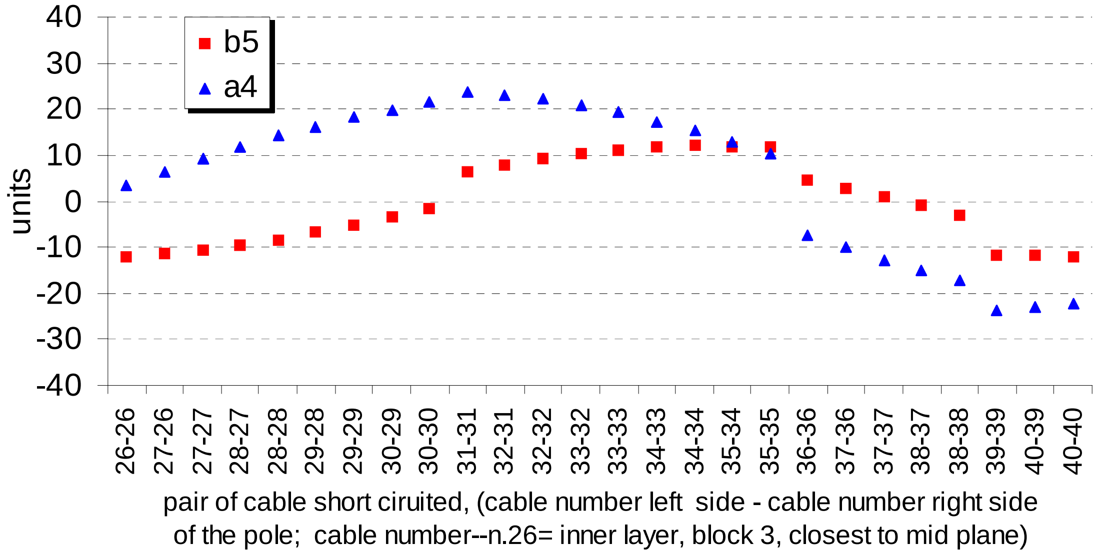

Figure 4A: Effect on b_5 and a_4 of the possible short circuits of the INNER LAYER

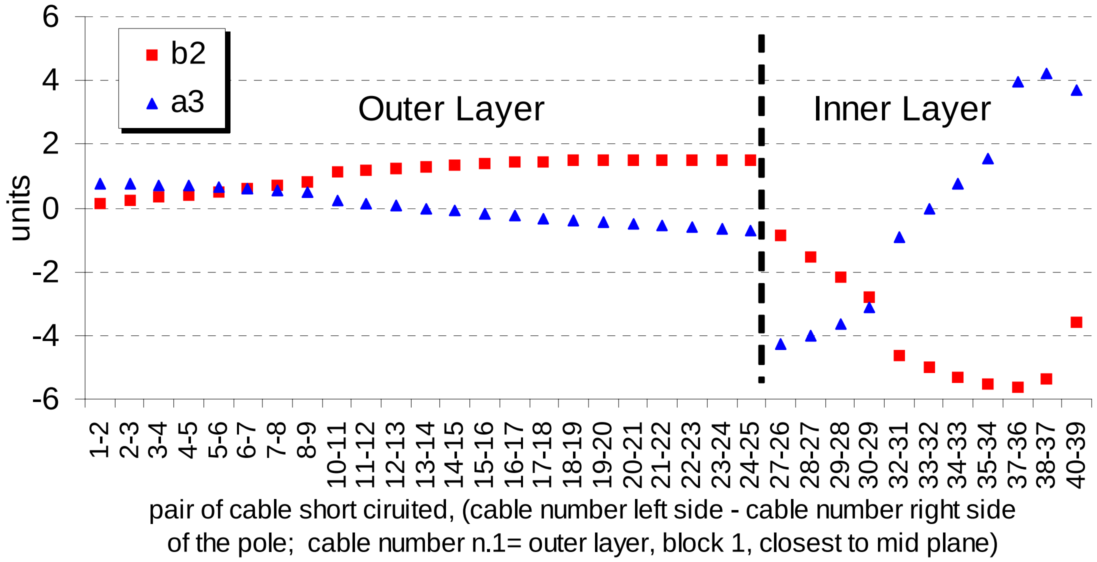

Figure 5A: Effect on b_2 and a_3 of the possible short circuits

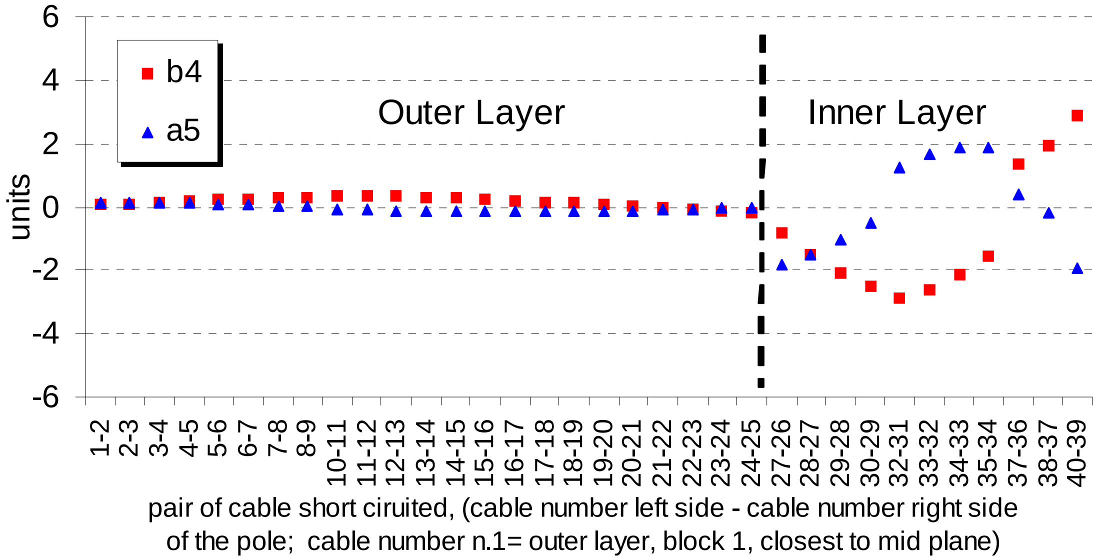

Figure 6A: Effect on b_4 and a_5 of the possible short circuits