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AT-MAS

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Corrective actions on the LHC main dipole coil cross-section for steering systematic b_3, b_5, b_7

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Summary

A second modification of the coil cross-section of the LHC main dipole would simplify the control of the odd lower order harmonics during the production. At the present state, any corrective action should minimize hardware changes, and avoid modification of collars or of the tooling for coil winding and curing. In this note we present some proposals to improve the lower order multipoles b_3, b_5 and b_7. Besides the application of an additional insulation on the mid-plane, which is currently in the test phase in the companies, other alternatives are discussed.

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1. Introduction

The steering of the systematic values of the low order odd multipoles b_3, b_5 and b_7 has shown to be the most critical aspect of field quality in the main LHC dipoles [1]. The nominal coil lay-out V6-1 [2] (hereafter denoted as cross-section 1) was giving unacceptably high values for b_3 and b_5, and after a fine tuning of the copper wedges geometry (denoted as cross-section 2), the values of these multipoles have been brought at the limit of the beam dynamic targets [3]. If the systematic obtained with cross-section 2 would be met at the end of the production, the LHC machine would have an optimal field quality [4]. Indeed, since we are close to values that would limit the machine performances, we became very sensitive to any trend and therefore it is not considered safe to start the mass production in such a condition. During the field quality workshop held in March 2003, several possibilities have been presented [5], and the so-called solution 4 (additional insulation in the mid-plane of 0.125 mm) has been chosen for testing on nine series magnets. In this note, we complement the set of solutions presented in [5] by exploring further possibilities.

2. Hardware constraints

Due to the advanced state of the dipole production (one octant of the machine is already produced at the level of collared coils), changes of the coil cross-section in the LHC main dipoles are very limited. Any change should satisfy three features:

- Retain the shape of the coil to avoid changes in the tooling for winding and curing.
- Retain the shape of the collars that are the most complicated component in terms of geometrical shape.
- Avoid as much as possible changes of pre-stress. We recall that the allowed window for pre-stress after collaring is ±15 MPa both on inner and outer layer, which corresponds to a variation of the coil size of 0.12 mm. As a general rule, one could set to one fourth of the window (i.e. 7.5 MPa) as the maximum acceptable variation given by coil optimization that are aimed at field quality improvements. Especially an increase of pre-stress towards the upper limit should be avoided since this can have a serious consequences on the assembly process.

This limits the changes in the components to adjustments in the size of the pole shims, of insulation, or of copper wedges.

3. Field quality targets

Trend plots for the so far produced collared coils are shown in the Figs. 1-3 for b_3, b_5 and b_7. All data are reduced to nominal shims. These plots show the warm measurements of the multipoles, carried out at 300 K on the assembled collared coils. The blue and black markers give the values of the two apertures, and the continuous line shows the best estimate for the systematic. The red lines are the upper and lower systematic targets for beam dynamics [6]. Optimal targets for systematics are the center of the range for b_5, b_7. For b_3 it is preferable to be closer to the upper limit to reduce its value at injection. Since the range (±3.5 units) is rather large with respect to the measured b_3 spread (1.2 units in X-section 2), AB-ABP and AT-MAS group agreed to place the target in the upper third of the band. The aimed improvement obtained by the first and second corrections of the coil cross-section are indicated in

Figs. 1-3 in green and pink, respectively. The objectives for the second correction of the coil cross-section are: $\Delta b_3 = -2.5$ units, $\Delta b_5 = -0.71$ units and $\Delta b_7 = -0.52$ units[1].

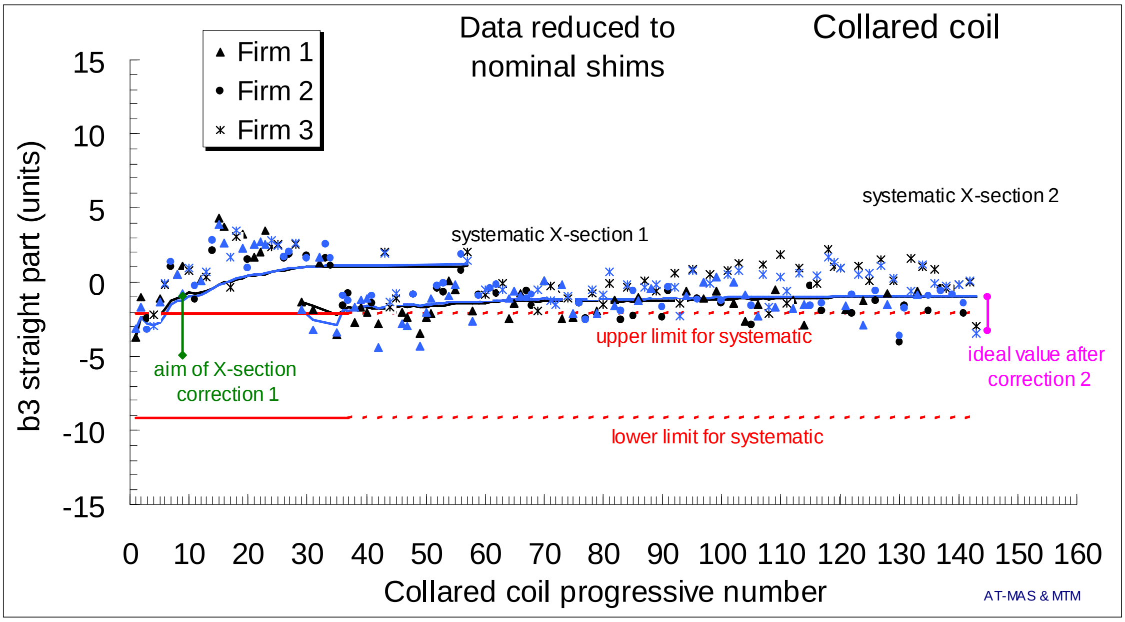


Figure 1: Measured b_3 in units at 17 mm reference radius vs. collared coil progressive number. Green and pink arrows indicate the aim of the correction of the coil cross-section 1 and 2 respectively. For b_3 a value in the upper third of the range is aimed.

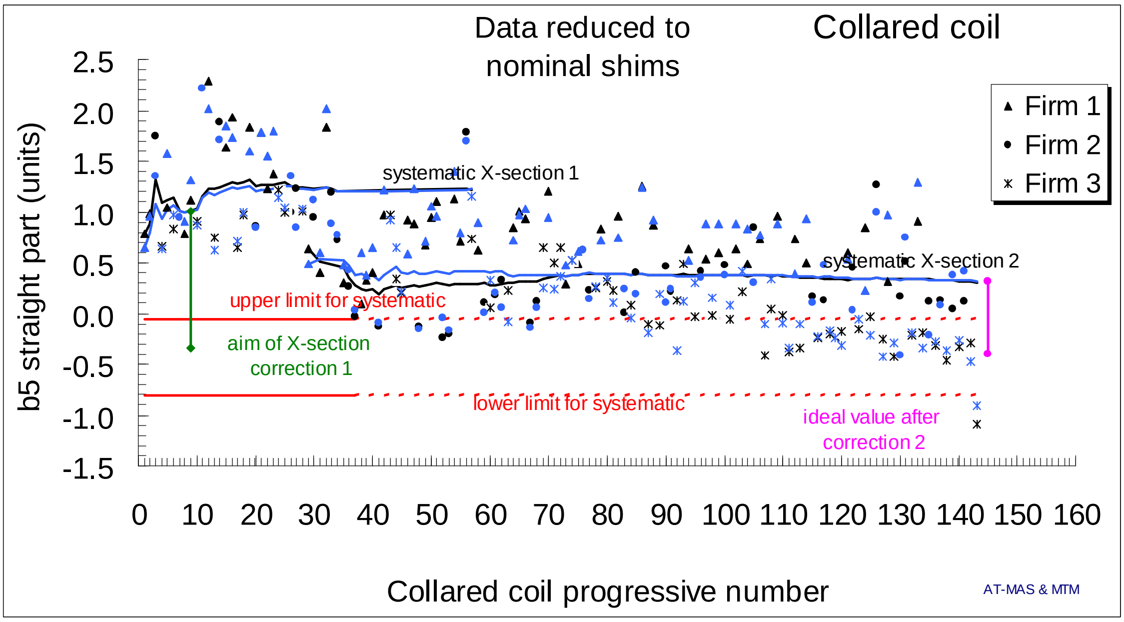


Figure 2: Measured b_5 in units at 17 mm reference radius vs. collared coil progressive number. Green and pink arrows indicate the aim of the correction of the coil cross-section 1 and 2 respectively. For b_5 the center of the allowed range is aimed.

[1] Please note that this correction is reduced by the scaling factor 1.18 when the iron yoke is added. Therefore, we aim at a correction of $\Delta b_3 = -2.1$ units, $\Delta b_5 = -0.38$ units and $\Delta b_7 = -0.44$ units in the assembled cold mass.

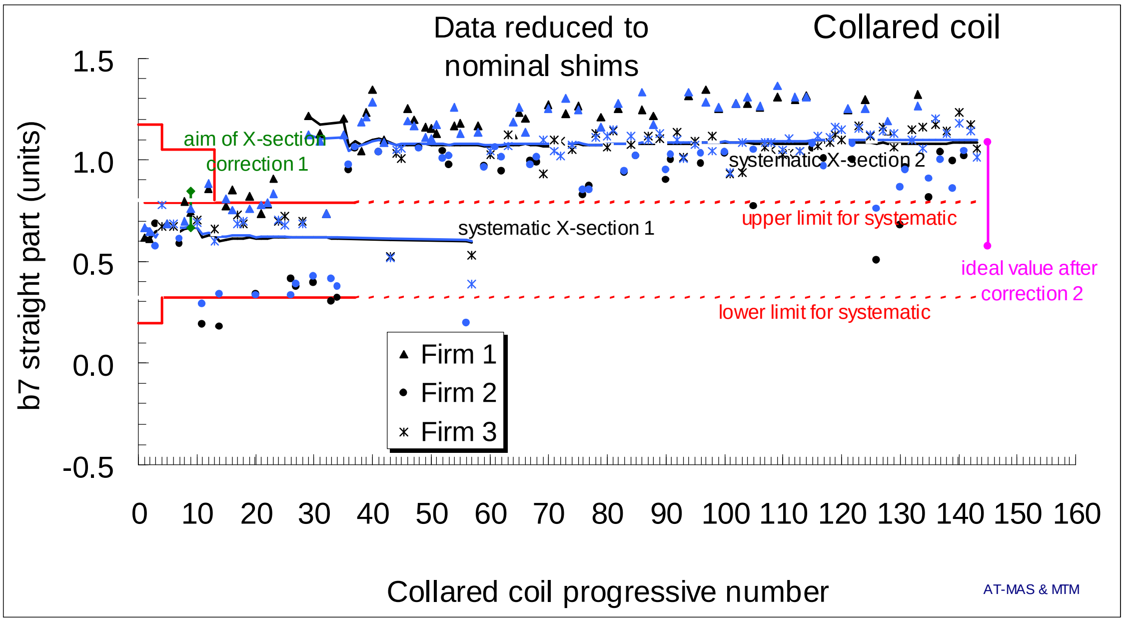
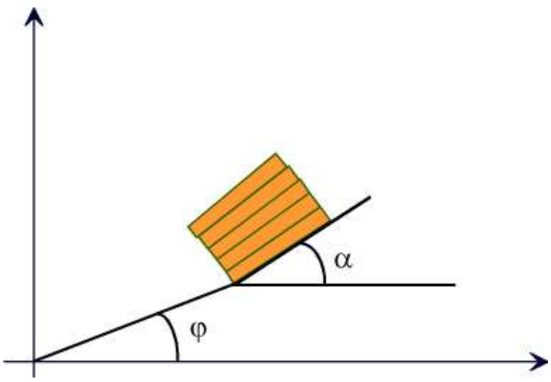


Figure 3: Measured b_7 in units at 17 mm reference radius vs. collared coil progressive number. Green and pink arrows indicate the aim of the correction of the coil cross-section 1 and 2 respectively. For b_7 the center of the allowed range is aimed.

4. Coil geometry baseline

The present baseline for the coil geometry (the so-called cross-section 2) is given in Fig. 4, where the positioning and inclination angles φ_n and α_n of the individual coil blocks are given.

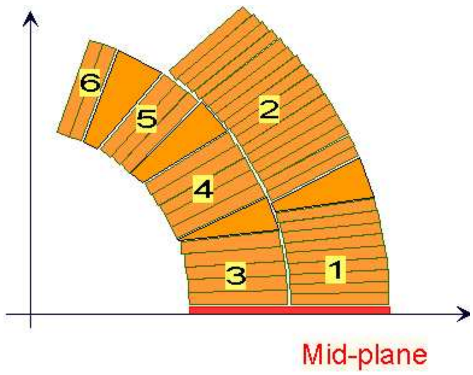


Block	φ (deg)	α (deg)
1	0.157	0.000
2	21.900	27.000
3	0.246	0.000
4	22.020	25.430
5	47.980	45.800
6	66.710	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Outer	1.620	1.860
Inner	1.973	2.307

Figure 4: Definition of positioning angle φ and inclination angle α of the coil geometry (left) and nominal values for cross-section 2 (right) azimuthally compressed under a nominal prestress, without radial deformations.

5. Correction proposals

Option 0 (solution under test): Add 0.125 mm in the coil mid-plane, on both layers. This is similar to the so-called solution 4 presented in [2], where an additional insulation of 0.100 mm was proposed. This option is being implemented on nine long magnets. It keeps the same coil shape, and it increases the pre-stress of +7.5 MPa on inner and outer layer. The impact on multipoles is about –3.3 units of b_3, -0.81 of b_5 and –0.20 of b_7, bringing them inside the allowed ranges with the exception of b_7 (+0.1 units more than the upper limit).

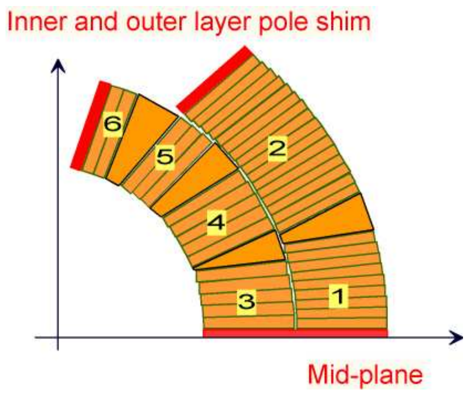


Block	φ (deg)	α (deg)
1	0.239	0.000
2	21.953	27.000
3	0.374	0.000
4	22.106	25.430
5	48.023	45.800
6	66.728	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Outer	1.618	1.858
Inner	1.969	2.303

Figure 5: Changes proposed in option 0: increase the mid-plane insulation thickness by 0.125. Values of coil geometry are given on the right side (changes with respect to baseline are marked in blue).

In order to avoid the increase of pre-stress of 7.5 MPa one can consider different options. We list them starting from the less intrusive corrections.

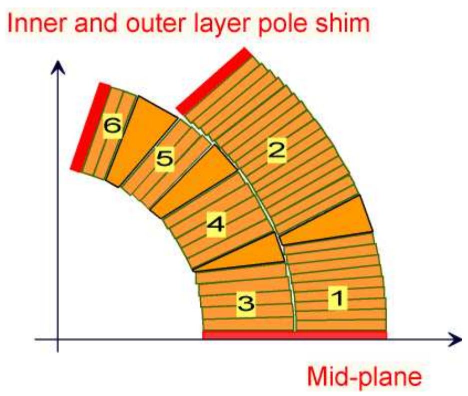
Option 1a (compensation of the additional mid-plane insulation with pole shims): Add 0.125 mm in the coil mid-plane and reduce the pole shims of 0.05 mm (bringing the value from 0.2 to 0.15 mm and from 0.8 to 0.75 mm for inner and outer layer, respectively). Also in this case the coil shape is kept, but the prestress increases only by +1.5 MPa on inner and outer layer. With respect to Option 0, this reduction of pole shims has the effect of increasing the correction of b_3 and b_7 (-5.1 and –0.26 units), and reducing the correction of b_5 (-0.56 units).



Block	φ (deg)	α (deg)
1	0.239	0.000
2	21.976	27.000
3	0.374	0.000
4	22.139	25.430
5	48.091	45.800
6	66.816	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Inner	1.620	1.860
Outer	1.972	2.306

Figure 6: Changes proposed in option 1: increase the mid-plane insulation thickness by 0.125 mm and reduction of 0.05 mm of both pole shims. Values of coil geometry are given on the right side (changes with respect to baseline are marked in blue).

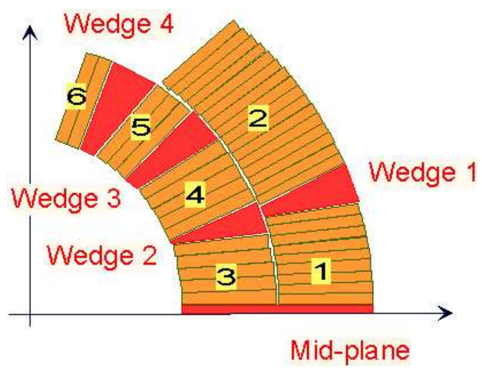
Option 1b (compensation of the additional mid-plane insulation with pole shims): Add only 0.075 mm in the coil mid-plane and reduce the pole shims of 0.05 mm (bringing the value from 0.2 to 0.15 mm and from 0.8 to 0.75 mm for inner and outer layer, respectively). Also in this case the coil shape is kept, and the prestress decreases by -1.5 MPa on both inner and outer layer. With respect to the previous option, we add less on the mid-plane and therefore the effect on b_3, b_5 and b_7 is reduced. This brings b_3 closer to optimal values (-3.7 units), with the drawback of reducing the correction on b_5 and b_7 (-0.25 and –0.19 units, respectively).



Block	φ (deg)	α (deg)
1	0.206	0.000
2	21.950	27.000
3	0.323	0.000
4	22.100	25.430
5	48.061	45.800
6	66.793	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Inner	1.620	1.860
Outer	1.974	2.308

Figure 7: Changes proposed in option 1: increase the mid-plane insulation thickness by 0.075 mm and reduction of 0.05 mm of both pole shims. Values of coil geometry are given on the right side (changes with respect to baseline are marked in blue).

Option 2 (compensation of the additional mid-plane insulation with copper wedge insulation): Add 0.125 mm in the coil mid-plane and reduce the copper wedge insulation of 0.012 mm[2]. In this way we obtain a very similar solution to Option 0 from a magnetic point of view, and we reduce the impact on pre-stress: the coil size is reduced of 0.075 mm and of 0.025 mm on the inner and on the outer layer, respectively. The induced pre-stress change is –1.5 MPa on the inner layer and +4.5 MPa on outer layer. The effect on field quality, which can be estimated from the results given in [7], is -4.0 units of b_3, -0.95 units of b_5 and –0.21 units of b_7.

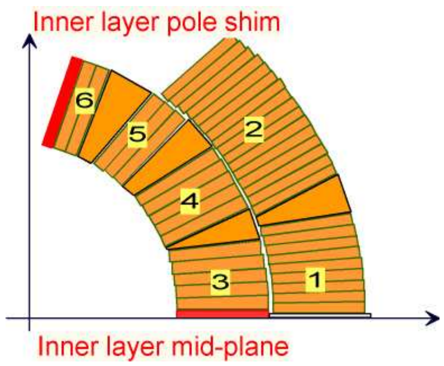


Block	φ (deg)	α (deg)
1	0.239	0.000
2	21.932	27.000
3	0.374	0.000
4	22.106	25.430
5	48.023	45.800
6	66.708	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Outer	1.619	1.859
Inner	1.974	2.308

Figure 8: Changes proposed in option 2: reduction of insulation of all copper wedges of 0.012 mm. Coil geometry is on the right side (changes with respect to baseline are marked in blue).

[2] This would correspond to replace the external one-layer sticky insulation of 0.068 mm with a one-layer sticky insulation of 0.055 mm, which is that one currently used for the main quadrupoles. The internal insulation with 50% overlapping would stay the same.

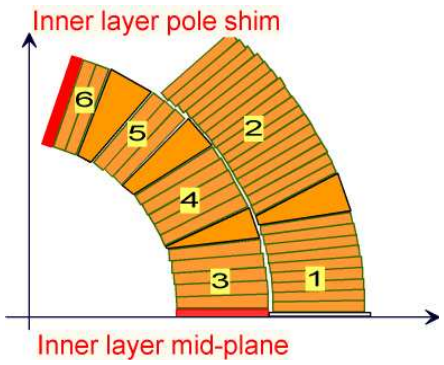
Option 3a (additional mid-plane insulation on inner layer compensated with inner layer pole shims): Another possibility is to add the 0.125 mm mid-plane insulation on the inner layer only, and to compensate it with 0.05 mm less on the inner layer pole shim. The mid-plane insulation in the outer layer stays to its nominal value. The coil size is preserved, and the variation of pre-stress is +1.5 MPa on the inner layer and null in the outer layer. In this way, one can manage to have an impact on b_3 and b_7 similar to Option 0 (-3.6 and –0.26 units respectively), with a reduction of the correction on b_5 (-0.48 units).



Block	φ (deg)	α (deg)
1	0.157	0.000
2	21.900	27.000
3	0.374	0.000
4	22.139	25.430
5	48.091	45.800
6	66.793	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Outer	1.620	1.860
Inner	1.972	2.306

Figure 9: Changes proposed in option 3a: add 0.125 mm insulation thickness on the mid-plane of the inner layer, and reduce inner layer pole shims of 0.05 mm. Values of coil geometry are given on the right side (changes with respect to baseline are marked in blue).

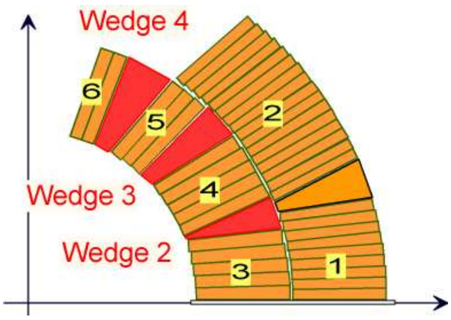
Option 3b (additional mid-plane insulation on inner layer compensated with inner layer pole shims): Another possibility is to add only 0.075 mm of mid-plane insulation on the inner layer only, and to compensate it with 0.05 mm less on the inner layer pole shim. The mid-plane insulation in the outer layer stays to its nominal value. The coil size is preserved, and the variation of pre-stress is -1.5 MPa on the inner layer and null in the outer layer. In this way, one can manage to bring b_3 very close to the objective value (-2.2 units), whereas b_5 and b_7 (-0.24 and –0.17 units, respectively) stay on the limits of their allowed ranges.



Block	φ (deg)	α (deg)
1	0.157	0.000
2	21.900	27.000
3	0.323	0.000
4	22.100	25.430
5	48.061	45.800
6	66.816	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Outer	1.620	1.860
Inner	1.972	2.306

Figure 10: Changes in option 3b: add 0.075 mm insulation thickness on the mid-plane of the inner layer, and reduce inner layer pole shims of 0.05 mm. Values of coil geometry are given on the right side (changes with respect to baseline are marked in blue).

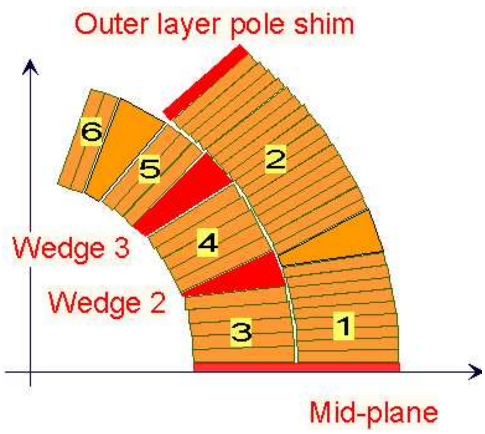
Option 4 (change of copper wedges in inner layer, same coil shape): Here, we consider the same strategy used from the change of cross-section 1 to cross-section 2: a modification of the copper wedges that rearranges blocks 4 and 5, keeping the same coil shape in the inner layer without changing the mid-plane thickness and without touching the pole shims. In this way the optimal value for b_3 correction (-2.3 units) is obtained, whilst b_5 and b_7 are shifted by -0.32 and -0.30 units, respectively, and therefore we are on the upper limit of the allowed range.



Block	φ (deg)	α (deg)
1	0.157	0.000
2	21.900	27.000
3	0.246	0.000
4	22.020	26.468
5	49.000	40.000
6	66.710	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Inner	1.620	1.860
Outer	1.973	2.307

Figure 11: Proposed changes in option 4: inner layer copper wedges; keeping fixed the positions of blocks 3 and 6. The wedge in the outer layer, pole shims and mid-plane insulation do not change (changes with respect to baseline are marked in blue).

Option 5 (mid-plane shim and change of internal copper wedges and outer layer pole shim): Application of an additional insulation thickness of 0.150 mm on the mid-plane (0.075 mm for each pole). The pre-stress in the coil is kept by adjusting the pole shim in the outer layer from 0.8 mm to 0.7 mm, whereas on the inner layer, the wedges 2 and 3 are modified. The change of both wedges togther with the mid-plane insulation offers an additional degree of freedom compared to previous options that results in a perfect centering of all objectives.



Block	φ (deg)	α (deg)
1	0.255	0.000
2	21.900	27.000
3	0.399	0.000
4	22.020	25.190
5	47.980	45.800
6	66.710	68.500
Cable	In.thick(mm)	Ex.thick(mm)
Inner	1.620	1.860
Outer	1.973	2.307

Figure 12: Parameters for the option 4 are the increase the mid-plane thickness by 0.075 mm on both layers of both poles. The pre-stress in the layers is kept by adjusting the pole shim on the outer layer and the wedges 2, 3 in the inner layer, respectively (changes with respect to baseline are marked in blue).

6. Summary of results

A summary of the hardware changes needed for each option is given in Table I.

Table I: Hardware changes needed for each option.

Option	Pole shims (mm)		Mid-plane ins.(mm)		Copper wedges	End spacers
	Inner	Outer	Inner	Outer		
0			+0.125	+0.125		
1a	-0.05	-0.05	+0.125	+0.125		
1b	-0.05	-0.05	+0.075	+0.075		
2			+0.125	+0.125	Inner layer insulation	
3a	-0.05		+0.125			
3b	-0.05		+0.075			
4					Inner layer	Inner layer
5		-0.10	+0.150		2 of inner layer	Inner layer

In Table II we give the expected changes on pre-stress, on the main field, on the multipoles b_3, b_5 and b_7 for the five options describe above, and the objective values. A comparison of the solutions as far as multipoles are concerned is given by evaluating the distance *D* from the objectives weighted by the width of the acceptance ranges (whose values are 2.3, 0.74 and 0.47 units for b_3, b_5 and b_7 respectively), defined as:

$$D = \sqrt{\left(\frac{\Delta b_{3,calc} - \Delta b_{3,obj.}}{2.3}\right)^2 + \left(\frac{\Delta b_{5,calc} - \Delta b_{5,obj.}}{0.74}\right)^2 + \left(\frac{\Delta b_{7,calc} - \Delta b_{7,obj.}}{0.47}\right)^2} \ .$$

The distance is zero if all objectives are exactly reached. As can be seen from the numbers, the multipoles relative to option 5 are closest to the objective values, whereas option 1a shows the largest difference. Indeed, all options would give more space for the control of b_3, b_5 and b_7 during the production.

Table II: Changes in pre-stress, in main field and in b_3, b_5 and b_7 for the options 0-5. The objective values are also given for comparison.

Options	Δ pre-stress (MPa)		Δ Field quality (units)				
	Inner	Outer	Δ c1	Δ b_3	Δ b_5	Δ b_7	Distance *D*
0	+7.5	+7.5	-3.4	-3.3	-0.81	-0.20	0.8
1a	+1.5	+1.5	-8.0	-5.1	-0.56	-0.26	1.4
1b	-1.5	-1.5	-5.6	-3.4	-0.28	-0.17	1.0
2	-1.5	+4.5	-3.7	-4.0	-0.95	-0.21	1.0
3a	+1.5	0.0	-4.6	-3.4	-0.48	-0.26	0.8
3b	-1.5	0.0	-3.3	-2.2	-0.22	-0.18	1.0
4	0.0	0.0	-2.2	-2.3	-0.32	-0.30	0.7
5	0.0	-3.0	-4.4	-2.8	-0.85	-0.45	0.3
Objective	0.0	0.0	0.0	-2.5	-0.71	-0.52	0.0

In Fig. 13, the results are illustrated as follows: The red boxes indicate the range of the systematic multipoles where the optimized result should be located. For the multipoles b_5 and b_7 this range is identical to the allowed target range, whilst for the b_3 we aim at the upper third of the band (dashed zone). The blue triangles show the best estimate for the systematic in the second cross-section based on measured values (the reduction at nominal shims is applied).

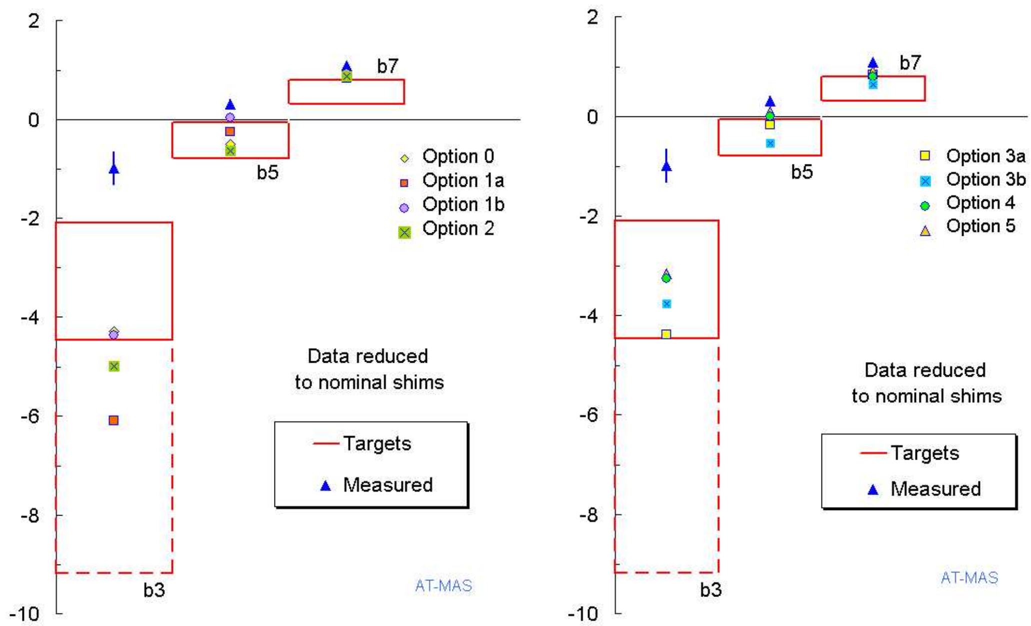


Figure 13: Measured systematic in cross-section 2, and expected shift induced by the different options (markers). Target ranges for systematics are given as red boxes. For b_3, the target is shown as a dashed box, while for the optimization the aim is to reach a value in the upper third of the band.

7. Acknowledgements

We wish to acknowledge W. Scandale for supporting this work and useful comments, and B. Bellesia for providing the sensitivity tables used for computing the effect of copper wedge insulation on field quality. Thanks to M. Modena and D. Tommasini for discussions about the hardware implications of the proposed modifications.

References

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