Shimming plan for MCBXFBP2 inner dipole

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1. Introduction

This document describes the shimming plan for the inner dipole of the second prototype of MCBXFB magnet, so called MCBXFBP2. The results of the powering tests of the first prototype are analysed, together with the mechanical measurements, to understand the behavior of this type of coils and support structure.

2. Analysis of MCBXFBP1 strain gauge measurements

The pre-compression on the MCBXFBP1 coils was increased progressively in three assemblies, based on the powering test performed after each assembly. In the final configuration, the magnet was able to achieve nominal field in any powering combination. Some training was still necessary each time the powering polarity was reversed. It was understood as a lack of mechanical support at the coil ends.

Table I shows the average measurements of the strain gauges of the collars during the different assemblies. Positive values (no compression) are discarded. Measurements at SM18 should be the same than the ones made after the press release. The only difference was the number of channels: at SM18 there are not enough channels to measure all the gauges. Some of the gauges were damaged: the number of gauges was decreasing after each assembly operation.

	March 2019				June 2019				August 2019			
	Press	Spring	SM18	Cool	Press	Spring	SM18	Cool	Press	Spring	SM18	Cool
Inner	-538	-372	-390	-90	-741	-571	-499	-102	-736	-631	-626	-185
Outer	-832	-721	-685	-273	-775	-668	-599	-189	-744	-647	-598	-277

Table Ia. Strain gauges measurements on collar nose in microstrain at different assemblies and steps.

	March 2019				June 2019				August 2019			
	Press	Spring	SM18	Cool	Press	Spring	SM18	Cool	Press	Spring	SM18	Cool
Inner	-104	-72	-76	-18	-144	-111	-97	-21	-143	-122	-121	-37
Outer	-161	-140	-133	-55	-150	-130	-116	-38	-144	-126	-116	-56

Table Ib. Strain gauges measurements on collar nose in MPa at different assemblies and steps.

After careful analysis of the strain gauge measurements, the main conclusions are:

- During the collaring operation, for small gaps (about 0.3 mm, nominal position of collared coils) between both halves of the collaring tooling, the strain gauges measurements for inner and outer collars were similar (736 microstrain for the inner, 775 for the outer). In that moment, the stiffness of the collars can be neglected, because they are blocked by the collaring tooling, which is very stiff. At large gaps, the outer coils were much more compressed, they were stiffer in the first steps of collaring assembly (1 mm gap: 324 microstrain for the inner, 517 for the outer).
- Once the pressure was released, the stiffness of the collars played an important role. The inner collars kept 626 microstrain while the outer collars felt 598 microstrain. That is, the outer collars lost more pre-compression (177 microstrain vs. 110) due to the flexibility of the collared structure.
- During cool down, inner collars lost 441 microstrain while outer lost 345. However, in the previous assembly (June 2019), both dipoles about the same value (397 vs. 410) with more gauges providing valid measurements. In the first assembly of full magnet (March

2019), inner dipole lost 300 microstrain, while the outer one lost 412, but some of the gauges of the inner dipole measured positive values (complete loss of compression), so that value is not representative. We can assume that both dipoles perform a similar loss of compression, around 410 microstrain. Based on the thermal contraction measurements of the 11 T and MQXF cables, we have estimated a value of 4.7 per mil of integrated thermal contraction for MCBXFB cables. Since the Nippon steel collars contract as 2.7 per mil, the differential thermal contraction is 2 per mil, that is, about 390 microstrain, which is very close to measured values.

No significant information was provided by the bullet gauges. The axial pre-compression was kept after cooling down. There is no hint of movement of the coils in longitudinal direction. When the axial preload was increased, the magnet performance was unchanged.

2. Analysis of shimming plan of MCBXFBP1

All the coils are below nominal dimensions, mainly due to the contraction of the epoxy resin once it is cured, when the mould cools down. Figure 1 shows the deviation of the arc length of the coils of the inner dipole (both MCBXFBP1 –coils IC2 and IC3- and 2 – coils IC4 and IC5). That is the feature defining the necessary shims to achieve the azimuthal pre-compression target (0 in Fig. 1). Please notice that it is a mean measurement, that is, averaging both sides of the coils. In IC2 and IC3 (first prototype coils), there were no measurements of the pole window width. In IC4 and IC5 (second prototype coils), the pole windows width was measured at the center and both ends, that is why those curves depicts a step in Fig. 1.

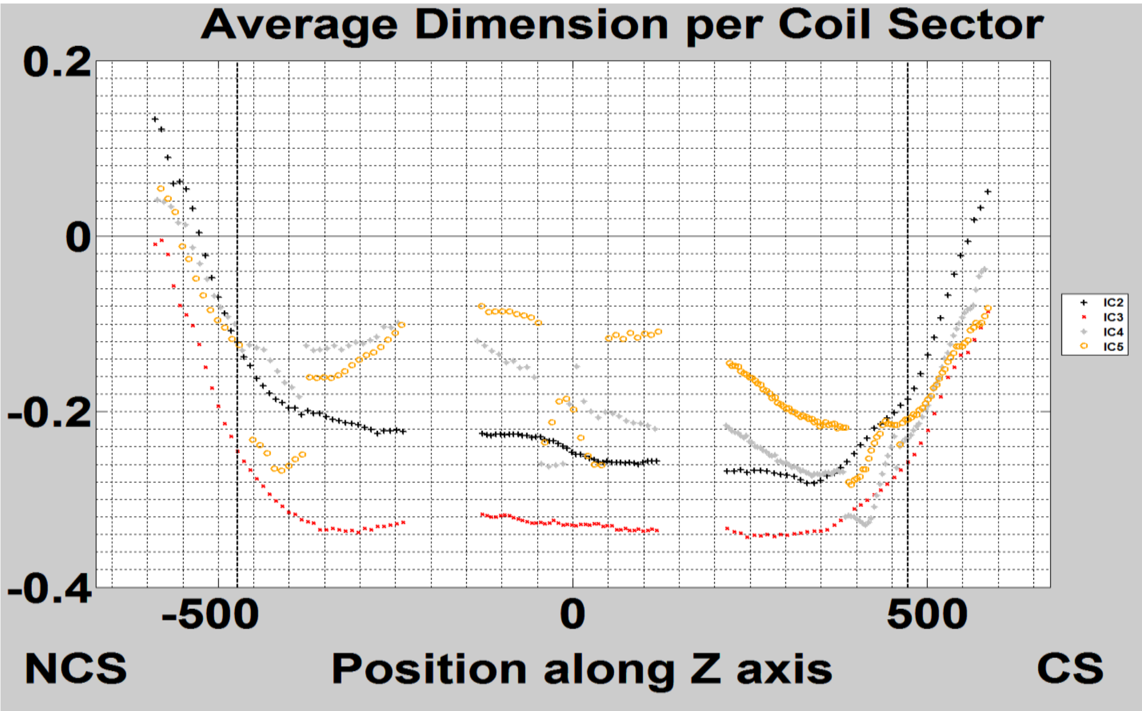

Fig. 1. Average deviation (mm) from nominal coil arc length along its longitudinal axis.

Figure 2 depicts the effect of the additional shims added on the first prototype dipole assembly to achieve the target preload. It shows clearly that pre-compression at the end of the coil pole is lower than in the coil straight section. Since the torque at that position is close to nominal, it is very likely that the coils slide there. It seems that preload at connection side end is smaller. During the powering tests, more quenches were induced in that coil end.

Additional shims are necessary to compensate some features which were not properly modeled in the calculations. The smeared-off coil modulus of elasticity was assumed as 55 GPa (40 GPa cables), but measurements of cable Young's modulus yielded only 20 GPa, which means a coil with 32.8 GPa for the inner dipole coil and 29.8 GPa for the outer one. The coils contracted more than foreseen: 4.7 per mil instead 3.2. And some creeping was noticed, estimated about 50 micron for the inner dipole coil and 75 micron for the outer one.

Figure 3 shows the inner dipole coil ends. The straight section of the cables of the mid-plane outer layer block is 36 mm longer than the coil pole window. We are assuming that this is the part of the coil which needs a similar thickness of shims to support properly the angular deformation due to the torque during combined operation.

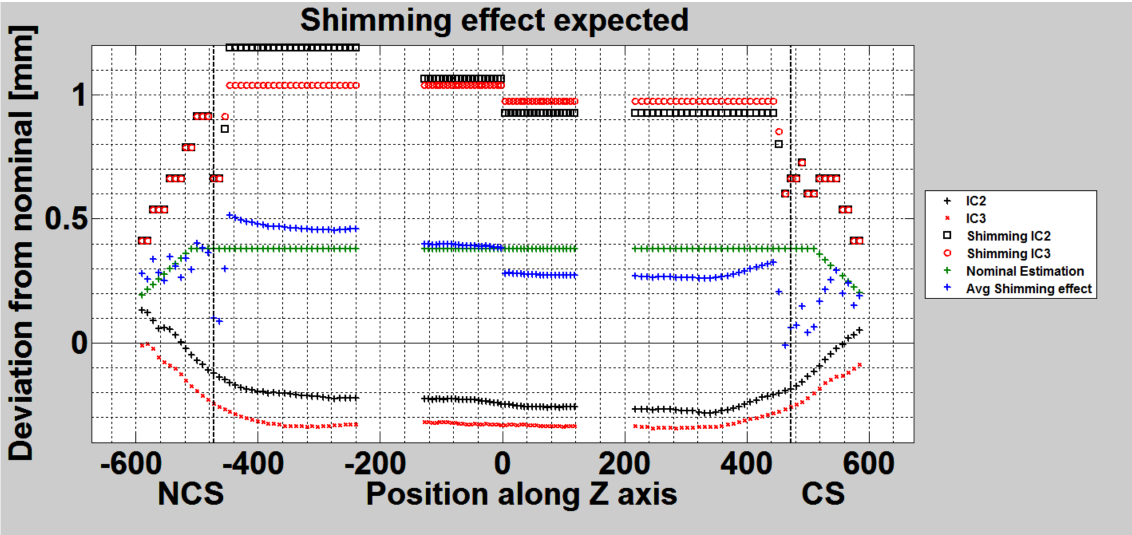

Fig. 2. Effect of additional shims on first prototype inner dipole. Red and black crosses show the deviation of coil arc length from nominal (small coils). Black and red circles depict the additional shims. Green line shows the known physical phenomena to be compensated: actual coil modulus of elasticity is smaller (32.8 GPa vs 55), real thermal contraction coefficient is larger (4.7 vs 3.2 per mil), creeping. Blue line is the computed additional interference: it is the result of substracting the coil off-dimensions and the green curve from the additional shims. Positive means higher pre-compression. Vertical lines show the position of the coil pole. Pre-compression at that region is lower than in the straight section.

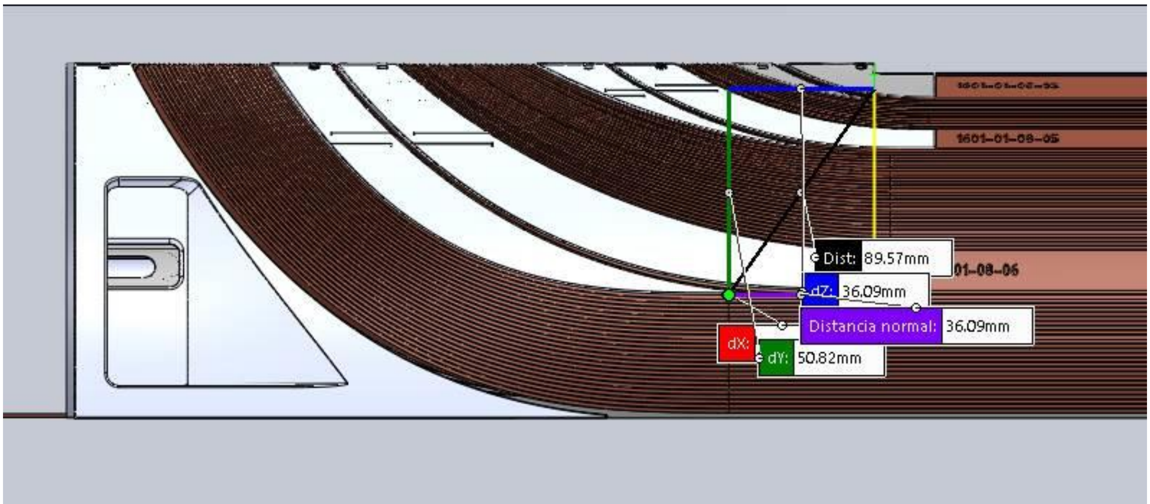

Fig. 3. Inner dipole coil end: the midplane block cables of the outer layer are 36 mm longer than the coil pole window.

In the case of the outer dipole, coils were also smaller than expected (see Fig. 4). The deviation is proportional to the arc length, so it is consistent with the inner dipole coil deviations.

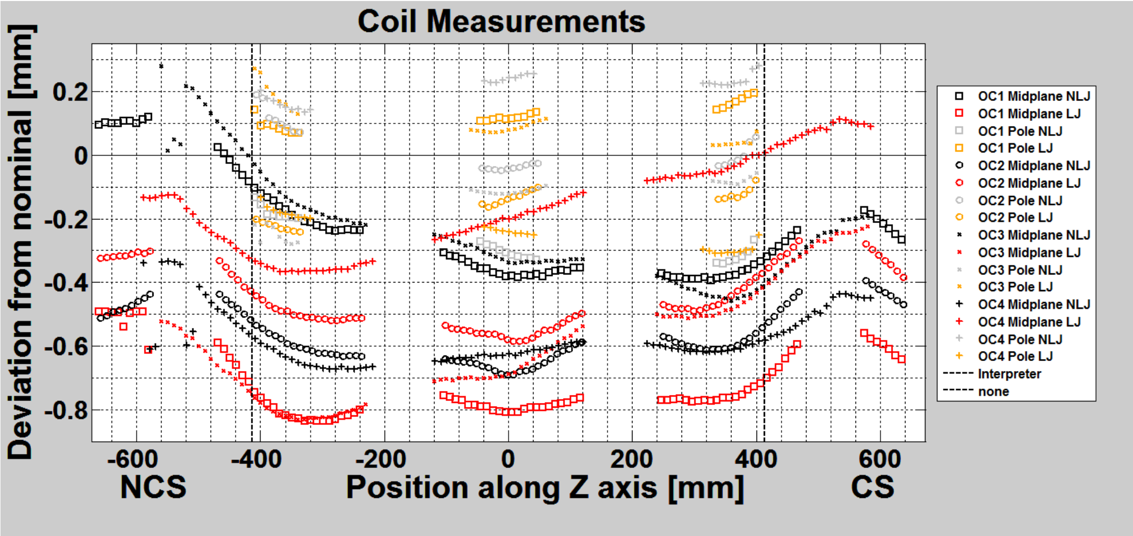

Fig. 4. Measurements of the arc length of the outer dipole coils: OC1 and OC2 were assembled in the first prototype, while OC3 and OC4 will be assembled in the second prototype.

Following the same rationale, Fig. 5 shows the additional shims which were necessary to achieve the nominal preload. It seems that the coils get loose, with smaller preload at coil ends. However, during the powering tests, the outer dipole hardly triggered a quench. It can be due to the smaller forces acting on the outer dipole because of the combined powering. Several features have been analyzed, which are not fully understood. The measurements of the outer dipole collar strain gauges overestimated about 10% the stress, according to the simulations showed in Fig. 6, for a given displacement. On the other hand, friction plays an important role, because even for large gaps of the collaring tooling (about 1 mm), there is a significant pre-load. In any case, the preload at the coil ends should be increased in the next prototype.

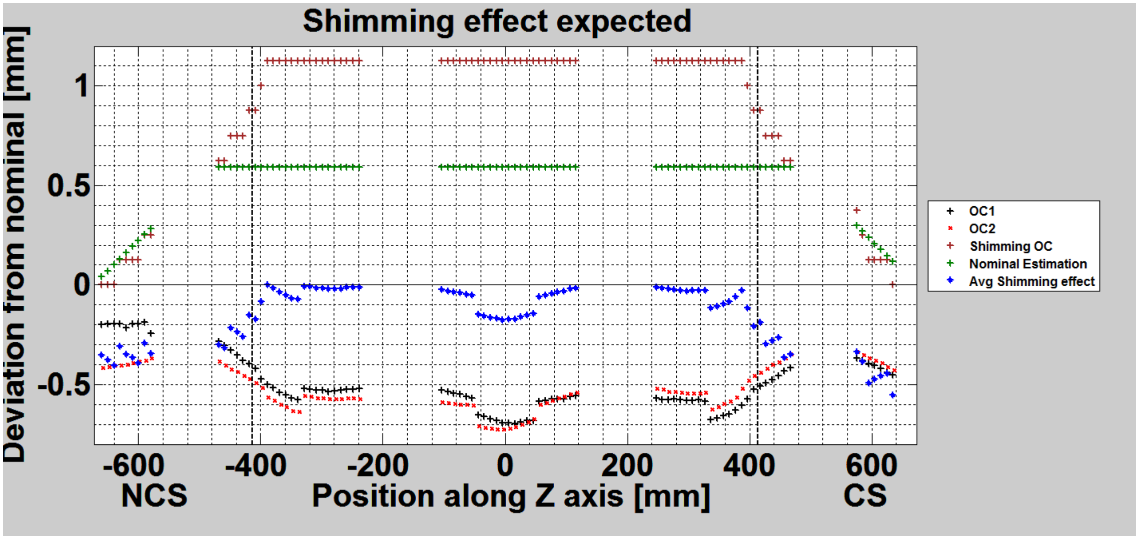

Fig. 5. Additional shims to achieve nominal pre-compression of outer dipole coils in first prototype. Vertical lines show the pole window length.

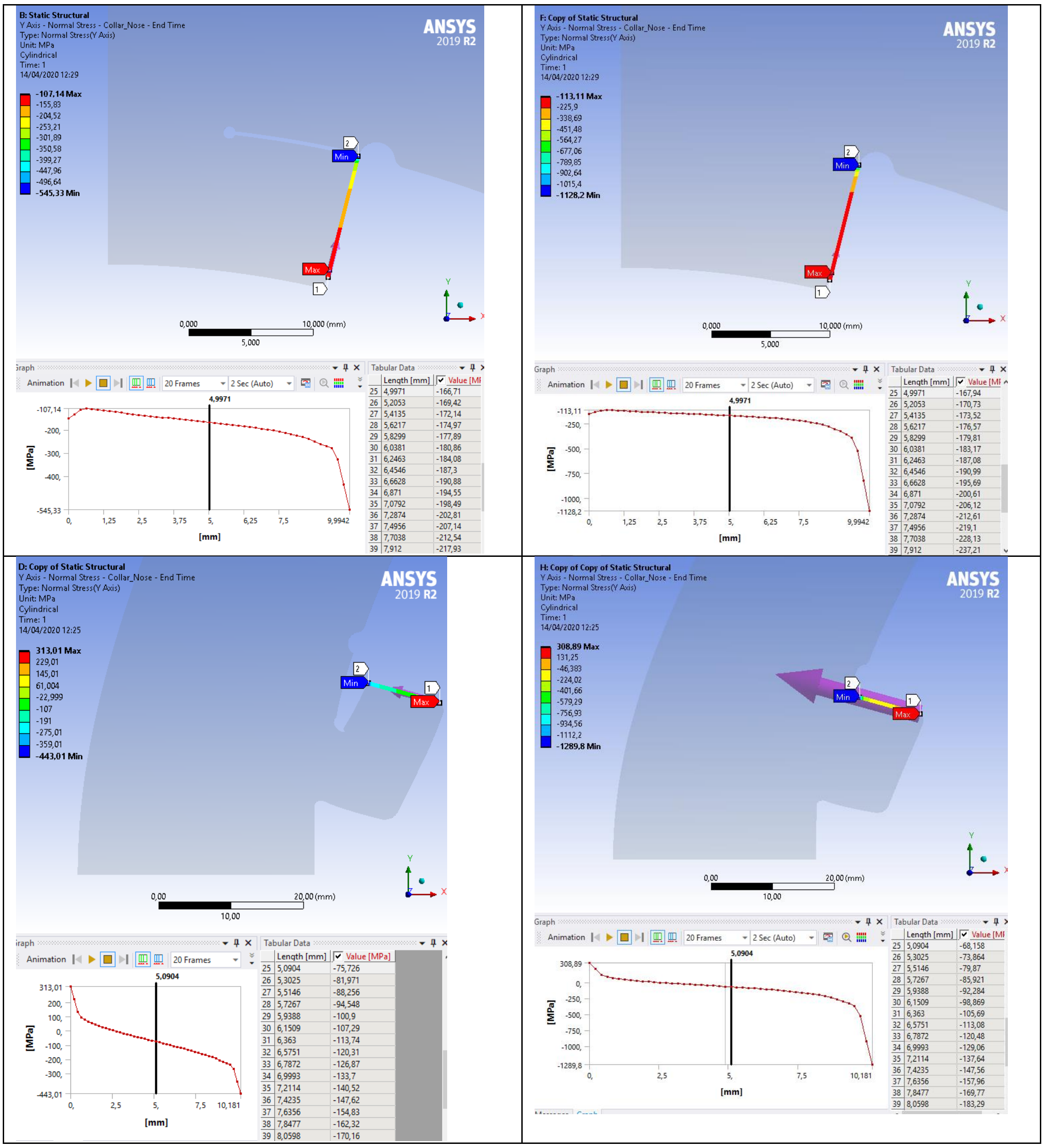

Fig. 6. Above, both inner dipole collars (instrumented and non-instrumented) feels the same pre-load. However, outer dipole instrumented collars (bottom left) feels about 10% more stress than non-instrumented ones.

3. Shimming proposal for the inner dipole of MCBXFBP2

The cables used for the second prototype have undergone an additional heat treatment for oxidation of the tin coating. Therefore, they are softer. The measurements performed on impregnated ten-stack probes yield a modulus of elasticity of 15 GPa compared with 20 GPa of the first prototype ones. Taking into account these values, Fig. 7 depicts the estimation of additional shims necessary for the proper mechanical support of the inner dipole coils. Regarding the straight section of the coil, 0.8 mm shims are necessary at the non-connection side and 0.9 mm at the connection side. In the next section, they will be split between the pole and the midplane turns.

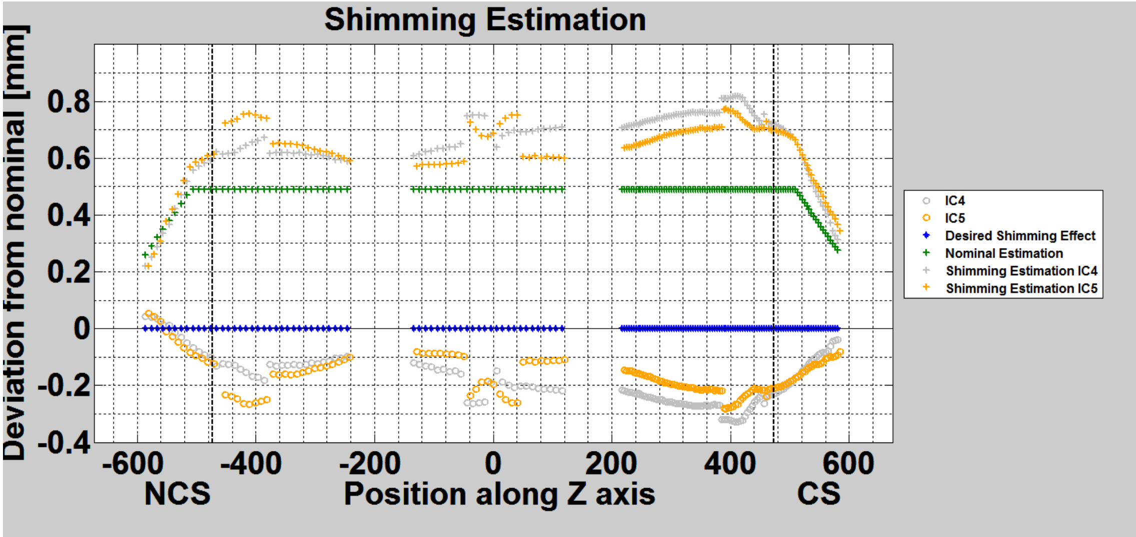

Fig. 7. Estimation of additional shims for inner dipole coils of second prototype.

4. Effect of the additional shimming on the field quality of the inner dipole

Since the coils are smaller and additional shims are necessary, those shims can be positioned either at the pole or the mid-plane, to achieve a good field quality. In the case of the first prototype, about 1 mm shims were added. It is equivalent to say that the actual size of the cables is smaller: since each layer of the inner dipole has 70 cables, each cable should be about 14 micron thinner. If 3 shims of 125 micron are placed at the pole and 5 shims of 125 micron are placed at the midplane, with a cable 14 micron thinner, the value of b3 field harmonic is about the same than the nominal case (simulation with Roxie 2D). B5 value increases.

The final proposal for the shim distribution in MCBXFBP2 is as follows:

- Pole window (length of 946 mm):
    - 1 shim of 935 mm length and 125 micron thickness
    - 1 shim of 930 mm length and 125 micron thickness
    - 1 shim of 400 mm length and 75 micron thickness at connection side
- Mid plane:
    - 1 shim of 80 mm length and 125 micron between the end of the pole window and the end of the first long shim of the midplane.
    - 1 shim of 60 mm length and 75 micron on top of the previous one, centered
    - 1 shim of 40 mm length and 50 micron on top of the previous one, centered
    - 1 shim of 1018 mm length and 125 micron thickness
    - 1 shim of 1096 mm length and 125 micron thickness
    - 1 shim of 1174 mm length and 125 micron thickness
    - 1 shim of 1252 mm length and 75 micron thickness
    - 1 shim of 1272 mm length and 100 micron thickness (in real life, it is a 200 micron thick G-10 foil, shared by both coils, where the rest of shims are fixed with adhesive polyimide tape).

Figure 8 adds this shimming proposal on top of the estimated amount of shimming.

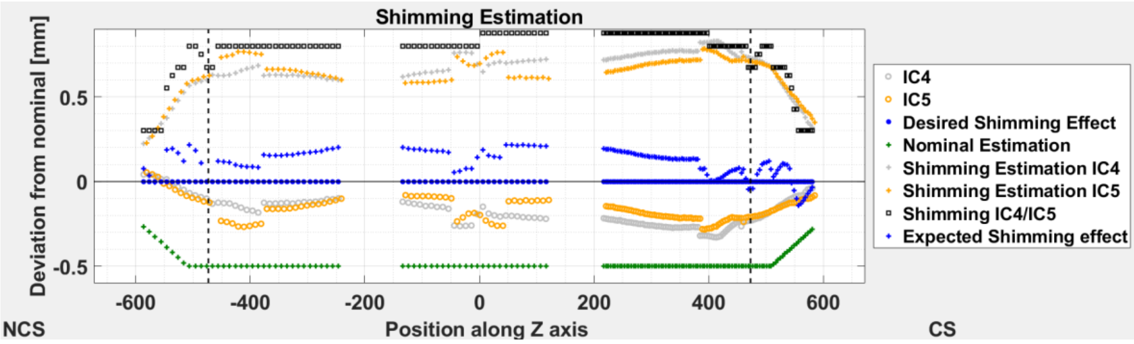

Fig. 8. Shimming proposal for inner dipole coils of second prototype.

5. Conclusions

This document describes the proposal for the shimming of the inner dipole of the second prototype magnet MCBXFBP2. The lessons learned from the first prototype are summarized, and the decisions made for the second prototype are based on the results of the first prototype. There are still some uncertainties for the outer dipole, which will be analyzed again with the results of the collaring of the inner dipole of the second prototype.