ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB225



# 3D MAGNETIC FIELD ANALYSIS OF LHC FINAL FOCUS QUADRUPOLES WITH BEAM SCREEN

T. Pugnat*, S. Bagnis, B. Dalena, C. Lorin
CEA, Irfu, DACM, Université Paris-Saclay, F-91191, Gif-sur-Yvette, France

*Abstract*

During the LHC commissioning, a discrepancy on the non-linear correctors strength between the model and the beam-based values has been observed [1]. This has motivated the reconstruction of the 3D finite element model for the LHC final focusing MQXA type magnet. The longitudinal higher orders magnetic field pseudo-harmonics are computed taking into account ovalisation of the magnet, interconnections design and Beam Screens. The effect of this 3D field on the computation of the non linear correctors is evaluated and compared with beam-based corrector values.

## INTRODUCTION

During the LHC commissioning while using amplitude detuning and feed-down data, the beam based values for the octupole corrector strengths have been estimated for both side of the ATLAS and CMS interaction points (respectively IP1 and IP5). A discrepancy is found between beam-based values for the octupole correctors and predicted ones from magnetic field measurements [1]. At collision energy, the main source of this octupole errors are the final focus quadrupoles composing the inner triplet (IT) of the LHC optics.

The Final Focusing quadrupoles in those regions are composed of two types, named MQXA and MQXB. The former have been developed and built at the KEK (Japan) while the latter at FermiLab (USA). The IT quadrupoles $Q_1$ and $Q_3$ consist of MQXA type magnet while the $Q_2$ are of MQXB type. Different potential sources have been studied to explain this discrepancy (detector solenoid Fringe Field, Beam Screen, magnets manufacturing imperfection, etc.). In the CERN magnets documentation [2], it is reported that because of its geometry, the MQXA type quadrupoles have an ovalization of its iron and coil. This generates a systematic $b_4$, which is normally not allowed. It is also worth noticing that the Beam Screen geometry is a source of another $b_4$ harmonics in the Final Focusing quadrupoles.

In [3], we have shown that considering the Fringe Field, i.e. the longitudinal harmonics distribution inside the HL-LHC Inner Triplet could give a change up to 13% in the non-linear corrector strength. The goal here is to repeat this study for the LHC Inner Triplet. Our starting point is the Return End (RE) of the 3D magnetic model (Roxie) and the mechanical drawings of the MQXA magnets, given to us by H. Nakamoto (KEK). Unfortunately, none of this information could be found for the MQXB magnet.

* thomas.pugnat@cea.fr

## THE 3D MAGNETIC MODEL OF MQXA

The aim is to reconstruct a machine-like 3D model of the magnet including the coil, the collar, the yoke as well as the Beam Screen (BS). The BS is a 1 mm thick cut circle with a 0.5 mm thick cooling tube on each flat side. The one of IP1 is vertically oriented while in IP5 it is horizontally oriented as shown in Fig. 1. The BS radius is different in $Q_3$ and $Q_1$, passing from (28.90 mm;24.00 mm) in $Q_3$ to (23.85 mm;18.95 mm) in $Q_1$ (respectively, the circle inner radius and the flat side inner distance to the aperture center).

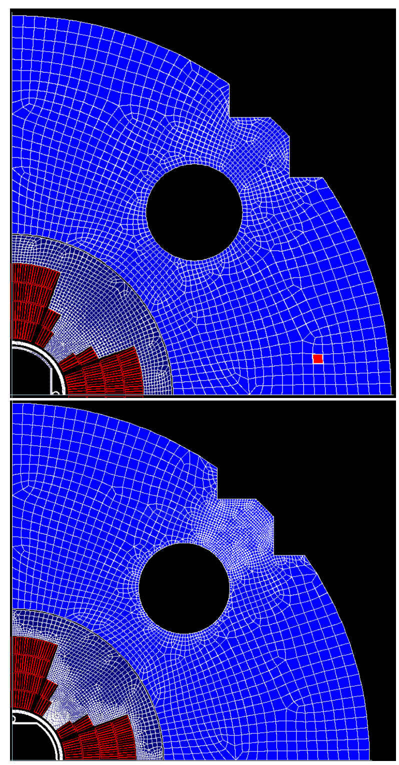

Figure 1: Cross-sections of the $Q_3$ magnet, the IP1 Right side (3R1, top) and the IP5 Left side (3L5, bottom) with their Beam Screen are shown.

The systematic values of the $b_4$, $b_8$, etc was supposed to come from an ovalization due to a dipole-like yoke assembly [4]. In order to simulate this ovalization in the Roxie magnetic model, the coil blocks have been displaced homogeneously by 50 µm (positive for the x-axis and negative for the y-axis) and the iron yoke elliptically deformed.

The design of the RE of the magnet is straightforward to generate in Roxie. Its dimensions were extracted from mechanical drawings with a precision of about 1 mm in the longitudinal position of each block. The Lead End (LE) of the magnet is more complex to reconstruct in Roxie. The

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB225

layer jumps, the internal splice due to the conductor grading in the second layer and the conductor leads have been carefully modeled. A specificity of the MQXA magnet is the use of normal and mirror coils that breaks the quadrupolar symmetry in the layer jump area and more generally all over the LE. This specificity is another source of $b_4$. Figure 2 shows the 3D reconstruction of the coil return and lead ends.

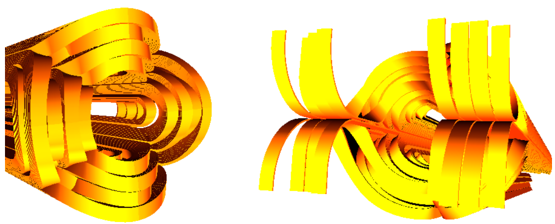

Figure 2: MQXA Return (RE, left) and Lead (LE, right) Ends.

## MQXA FIELD QUALITY

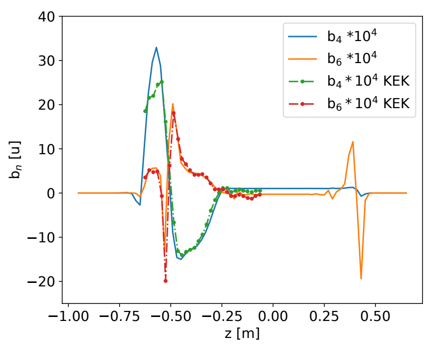


Figure 3: Comparison between the harmonics longitudinal profile of the Roxie 3D machine-like model and the longitudinal magnetic measurements performed at KEK. Courtesy of H. Nakamoto (KEK).

In Roxie, it is possible to compute Field Harmonics and, in particular, the longitudinal distribution of such Harmonics with the desired step in z. Figure 3 shows a comparison of the longitudinal $b_4$ and $b_6$ harmonics computed from the 3D magnetic model described in the previous section and the values for the LE, as measured at KEK with the rotating coil technique for steps of 2 cm. In order to speed up the computation, we have shorten the length of the central and constant field of the magnet. The model and the measurements agree pretty well in the case of $b_6$ harmonics. They show overall good agreement in the case of $b_4$ harmonics, with a visible difference in the region between −0.75 and -0.5 m.

The integrated value of $b_4$, considering the Ovalization of the Coils and Iron and the detailed description of the LE, is slightly lower with respect to the total integrated measured value, including its error (i.e. 1.30 $\pm$0.11 units). The Beam Screens impact the $b_4$ and $b_6$ harmonics as can be seen in Table 1. In order to quantify the impact of the longitudinal distribution on the beam based observables and on the non-linear corrector strengths a simple model of the magnet heads

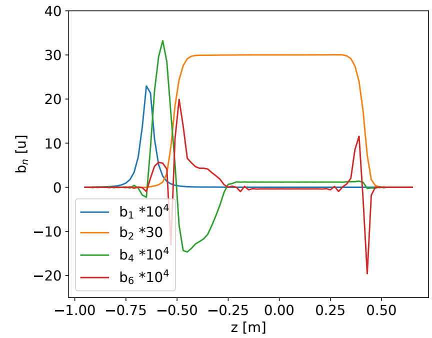


Figure 4: Longitudinal profile of the harmonics in the $Q_3$ magnet from the Left side of IP5.

is considered. According to this model (described in [3]), the magnet is divided into three regions: the central part with constant field harmonics, plus two additional kicks at the ends, that can have different magnetic lengths and strengths. This model is called HE+Heads and it is compared to the regular Hard Edge model (HE). The relation between the harmonics values over the whole magnet (TT) and in those sections is:

$$b_{n,TT} = \frac{b_{n,BD}L_{BD} + b_{n,LE}L_{LE} + b_{n,RE}L_{RE}}{L_{TT}} \quad (1)$$

with: $L_{TT} = L_{BD} + L_{LE} + L_{RE}$. Their values are reported in Table 1 together with the integrated values. The final longitudinal harmonics distribution, including the Beam Screen of the Q3 magnet, as oriented in IP5, is shown in Fig. 4. The BS contributions are close to the ones considered in the WISE database (i.e. $\pm$ 0.12 compared with +0.14 and -0.12 for IP5 and for IP1, respectively).

Table 1: Harmonics in the Different Sections of the MQXA Magnet. C+I Refer to the Magnet with Only the Iron, 3R1 and 3L5 Refer to the Beam Screen Type and Orientation

| Struc. | Roxie | L | $b_1$ | $b_3$ | $b_4$ | $b_6$ |
|---|---|---|---|---|---|---|
| C+I | Total | 6.37 | 0.30 | 0.02 | 1.05 | 0.03 |
| | Body | – | 0.00 | 0.00 | 1.03 | -0.28 |
| | LE | 0.41 | 4.68 | 0.38 | 1.33 | 4.45 |
| | RE | 0.20 | 0.00 | 0.00 | 1.01 | -0.19 |
| C+I+3L5 | Total | 6.37 | 0.30 | 0.02 | 1.19 | -0.05 |
| | Body | – | 0.00 | 0.00 | 1.17 | -0.36 |
| | LE | 0.41 | 4.68 | 0.38 | 1.44 | 4.39 |
| | RE | 0.20 | 0.00 | 0.00 | 1.21 | -0.30 |
| C+I+3R1 | Total | 6.37 | 0.30 | 0.02 | 0.93 | -0.05 |
| | Body | – | 0.00 | 0.00 | 0.90 | -0.37 |
| | LE | 0.41 | 4.68 | 0.38 | 1.48 | 4.68 |
| | RE | 0.20 | 0.00 | 0.00 | 0.82 | -0.30 |

The WISE total values for the $Q_3$ magnets are bigger than the total ones from our machine-like 3D model of 0.2 units (or more), as shown in Fig. 5.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB225



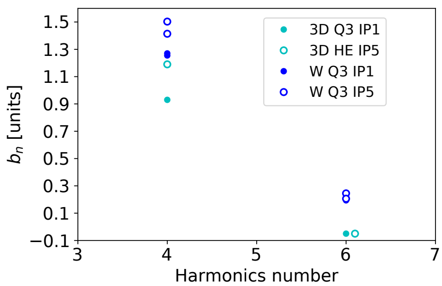


Figure 5: Total harmonics values from the WISE database and from the Roxie machine-like 3D model.

## EFFECT OF 3D MAGNETIC FIELD ON NON-LINEAR CORRECTOR STRENGTH

In LHC as in HL-LHC, there is one corrector on each side of the two high luminosity IP. The correction is computed following the method explained in Ref. [5]:

$$\begin{pmatrix} K_{n,L}L \\ K_{n,R}L \end{pmatrix} = -\begin{pmatrix} \beta_x^{n/2}\big|_L & \beta_x^{n/2}\big|_R \\ \beta_y^{n/2}\big|_L & \beta_y^{n/2}\big|_R \end{pmatrix}^{-1} \sum_{s\in IR} K_{n,s}L \begin{pmatrix} \beta_x^{n/2}\big|_s \\ \beta_y^{n/2}\big|_s \end{pmatrix} \tag{2}$$

$K_{n,s}L = K_{r,s}Lb_{n,s}$ corresponds to relative field errors in the different elements in the IRs. Figures 6 and 7 shows the correlation of the non-linear correctors strength (respectively octupole and dodecapole correctors) at both sides of the high luminosity IPs for 60 machine configurations (given by the $b_2$ random errors).

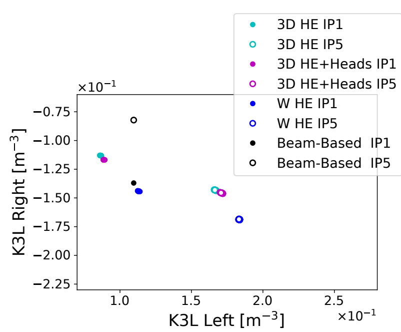


Figure 6: Integrated strength of the $b_4$ corrector computed for different models in IR1 and IR5, and 60 slightly different $b_2$ values.

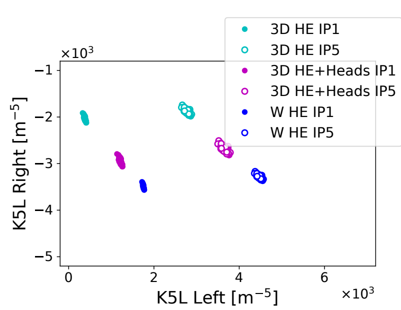


Figure 7: Integrated strength of the $b_6$ corrector computed for different models in IR1 and IR5, and 60 slightly different $b_2$ values.

Figure 6 shows the comparison between the beam-based estimations, the predicted values using the reference WISE total harmonics (W) and the predictions using our machine-like 3D model, reported in Table 1. The Roxie simulation with the smaller Beam Screen of the $Q_1$ magnet didn't converge, so the same values as $Q_3$ are used in this analysis. Its impact is expected to be less important than the $Q_3$ and the $Q_2$ (of type MQXB), due to the lower $\beta$-function in $Q_1$. Since we have no information of the MQXB Fringe Field, we use the WISE values for these magnets. With this approximation the 3D HE model predict values shift to the upper left, decreasing the accuracy for IP1 but improving for IP5. Taking into consideration the harmonics longitudinal distribution apply a small shift in the lower left direction so it cannot explained the discrepancy with the Beam-Based measurements.

In Fig. 7, the prediction for the HE and HE+Heads obtained by our 3D magnetic analysis are shown, together with the WISE predictions but without the beam-based values. There is no clear evidence of second order amplitude detuning from Beam-Based measurements in LHC. While, using the WISE values quite a strong correction should be needed in both IPs. In this respect, it is worth noticing that our 3D magnetic model gives a total $b_6$ which is significantly lower than the WISE values, going in the direction of the Beam-Based measurements. The HE+Heads model produce a shift in the same direction found for $b_4$ but bigger.

## CONCLUSION AND PERSPECTIVES

The 3D magnetic model of the MQXA type quadrupoles for the $Q_1$ and $Q_3$ LHC Inner Triplet reproduces the KEK measurements of the Connector Side (or Lead End). It appears that the LHC ellipsoidal Beam Screen not only add a $b_4$ harmonics along the magnet but also a $b_6$ one. Its contribution doesn't necessarily sum in the same way in the body and in the ends of the magnet. Our analysis goes in the direction of the Beam-Based measurements concerning the $b_6$ integrating values of the MQXA type quadrupoles. It shows that it is important to take into consideration all the possible sources of the high order harmonics in order to reproduce Beam-Based values with the model of the machine. It claims for very accurate magnetic measurements (i.e. $\leq 0.1$ units) of the Inner Triplet quadrupoles field quality.

## ACKNOWLEDGEMENT

The authors would like to thanks S. Izquierdo-Bermudez and E. Todesco for the help using ROXIE and discussions, and the KEK team through H. Nakamoto for finding and providing the MQXA drawing. We also would like to thanks the CERN OMC team through E. H. Maclean and R. Tomas for the LHC model and the discussions.

## REFERENCES

[1] E. H. Maclean *et al.*, "New approach to LHC optics commissioning for the nonlinear era", *Phys. Rev. Acc. B*, vol. 22, pp.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB225

061004, June 2019. doi:10.1103/physrevaccelbeams.22.061004

[2] FiDeL home page database: the Field Model of the LHC, CERN, https://lhc-div-mms.web.cern.ch/lhc-div-mms/tests/MAG/Fidel/.

[3] T. Pugnat *et al.*, "Computation of beam based quantities with 3D final focus quadrupoles field in circular hadronic accelerators", *Nucl. Instr. Meth. A*, vol. 978, pp. 164350, Oct. 2020. doi:10.1016/j.nima.2020.164350

[4] A. Yamamoto *et al.*, "Analysis of mechanical tolerances of a low-beta quadrupole magnet for the LHC", *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 131-134, Mar. 2000. doi:10.1109/77.828193

[5] M. Giovannozzi *et al.*, "Specification of a System of Correctors for the Triplets and Separation Dipoles of the LHC Upgrade", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper WEPEA045, pp. 2612–2614.