ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOAD3

RELATIVE ALIGNMENT WITHIN THE MAX IV 3 GeV STORAGE RING MAGNET BLOCKS

J. Björklund Svensson*, M. Johansson, MAX IV Laboratory, Lund, Sweden

Abstract

Unlike the discrete magnet scheme of previous 3rd generation light sources, the magnet elements of the MAX IV storage rings are integrated in precision-machined magnet blocks. By analyzing the rotating coil measurements made by the magnet suppliers, we determined the relative alignment between consecutive magnet elements, which was found to be <10 μm RMS for all magnet block types in both horizontal and vertical direction. This article presents our analysis and results for the full magnet production series.

INTRODUCTION

The MAX IV synchrotron radiation facility [1], currently being built on the outskirts of Lund, Sweden, will house two electron storage rings; one smaller and one larger, at 1.5 and 3 GeV, respectively [2]. The magnet design concept [3], with magnet blocks containing several different magnets, will be used for both storage rings. The two halves of these magnet blocks are each CNC machined out of a single block of iron (2.3-3.4 m long), and together, they work as both supporting structure and return yoke for the magnets, see Figure 1. The different magnet block types for the 3 GeV ring are called M1, U1, U2, U3, U4, U5 and M2 and are placed in that order in the achromats. The production of these magnet blocks, including all field measurements, was entirely outsourced to industry[1], based on a technical specification and full set of drawings [4] provided by MAX-lab.

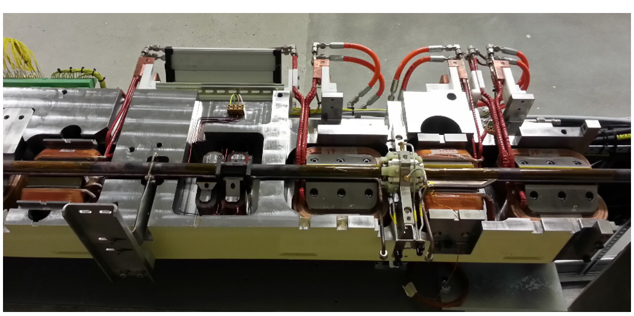

Figure 1: U3 bottom yoke half in achromat 16 with vacuum chamber in place, upstream side, viewed from the outside of the ring. Magnet elements from right to left (particle direction): QF, SFi, QF, Corr y/x, SD.

The MAX IV magnet block design assumes that the magnetic center location for each magnet depends only on the position of the pole surfaces [3]. This means that the alignment accuracy of individual magnets within each block is given by the mechanical tolerances of the top and bottom yoke halves (±0.02 mm over the whole block length), the loose quadrupole pole tips (±0.01 mm) and the sextupole and octupole yoke halves (±0.02 mm), as well as the respective assembly tolerances. Based on this assumption, no requirement of measuring magnetic center locations relative to the mechanical reference surfaces with high accuracy was made in the technical specification. However, from the provided field measurements, we could calculate the relative alignment between consecutive magnet elements within each magnet block.

The technical specification required measurement of the magnetic field strength as well as the harmonic content to characterize the magnets. Both magnet manufacturers decided to measure the harmonic content with rotating coils, and because of limited accessibility inside the magnet blocks they produced rotating coil shafts fitted with multiple coils placed at different positions along the shaft. These were used to measure several consecutive magnets, which then allowed us to evaluate the relative alignment since the magnets could be considered to have been measured within a common local coordinate system defined by the shaft. Several different rotating coil shafts were produced because of the differences in magnet layout between block types. A brief summary of the elements measured by each rotating coil shaft can be found in Table 1.[2]

Table 1: Elements Measured by Each Rotating Coil Assembly

Coil assembly	Magnet elements
"M1/M2 long"	OXX - QFe - OXY - QDe
"M1/M2 short"	OYY - SDe
"U3"	QF - SFi - QF - SD
"U1..U5 long"	QFm - SFm - QFm/
	QF - SFo - QF
"U1..U5 short"	SD

MAGNETIC CENTERS FROM ROTATING COIL MEASUREMENTS

Displacements from Harmonic Content

To calculate the displacement of the rotating coil axis from the magnet center, one can use the feed-down of the main magnetic field components. Eq. 9.72 in [5] relates the

* jonas.bjorklund_svensson@maxlab.lu.se

[1] Danfysik A/S, Taastrup, Denmark: 60 pcs M1, M2 and U3. Scanditronix Magnet AB, Vislanda, Sweden: 80 pcs U1, U2, U4 and U5.

[2] The corrector magnets present in some of these setups were also measured, but are not listed since they were not used for this evaluation. The "U1..U5 long" measurements also include a SD magnet, but since this rotating coil shaft has an extra bearing in the middle to counteract sag, the SD can not be considered as being in the same coordinate system.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOAD3

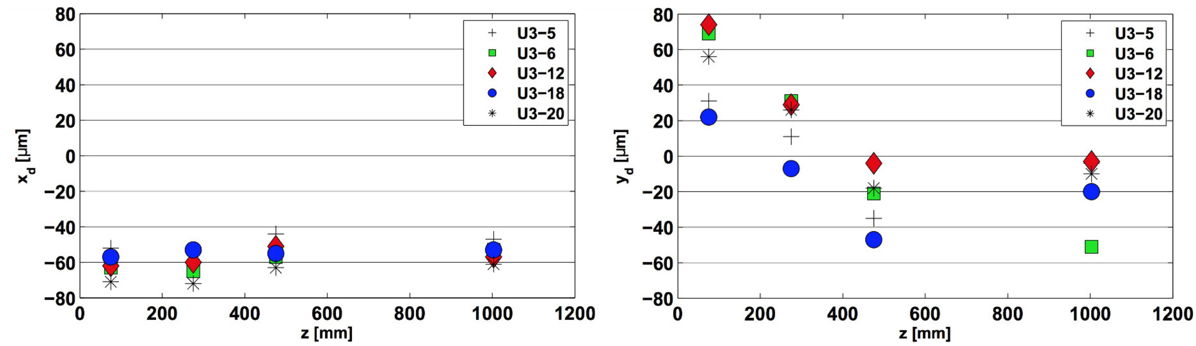

Figure 2: Displacements of the rotating coils axis with respect to the upstream magnets within five example U3 magnet blocks as a function of longitudinal position.

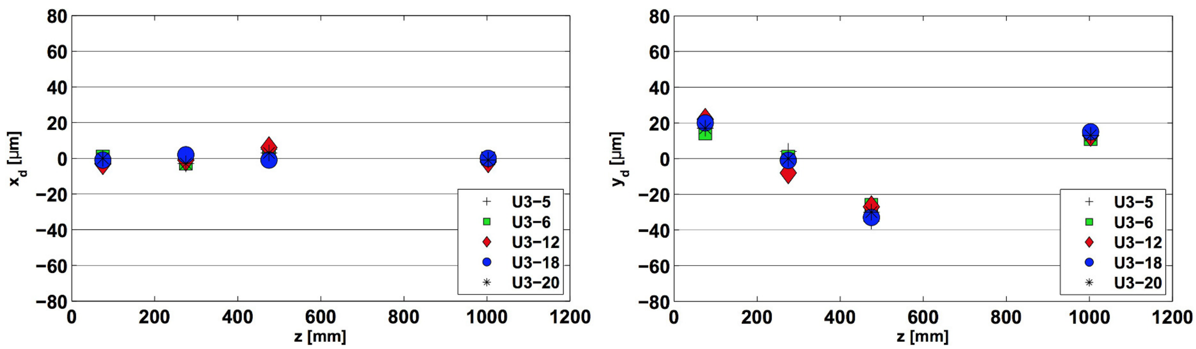

Figure 3: Relative displacements of the upstream magnets within five example U3 magnet blocks with respect to a linear fit of the displacements as a function of longitudinal position.

field components in the reference frame (center of the measurement coil), C'_n, to the coefficients in the magnet frame, C_n:

$$C'_n = \sum_{k=n}^{\infty} C_k \binom{k-1}{n-1} \left(\frac{z_d}{r_0}\right)^{k-n},$$

where $C_n \equiv B_n + iA_n$, B_n and A_n are the normal and skew field components, respectively, $z_d = x_d + iy_d$ are coordinates in the complex transverse plane and r_0 is the reference radius. The subscript d indicates displacement. Defining the magnet frame as the frame where $A_{m-1} = B_{m-1} = A_m \equiv 0$ and using the approximation that the feed-down to a field component only comes from the component directly above (first order feed-down), we obtain

$$x_d \approx \frac{r_0}{m-1}\frac{B'_{m-1}}{B'_m}, \qquad y_d \approx \frac{r_0}{m-1}\frac{A'_{m-1}}{B'_m}, \tag{1}$$

where m indicates the main component. With these expressions, we obtained the displacements for all magnets. As an example, the displacements of a few of the U3 magnet block magnets can be seen in Figure 2.

Relative Alignment

Displayed in Figure 2 are the "raw" displacements of the rotating coil axis calculated directly from the measured field components. As seen in the figure, these displacements are within ±0.08 mm for these U3 magnet blocks, which is consistent with the specified positioning accuracy of the rotating coil shaft, ±0.1 mm. This uncertainty in location of the rotation axis relative to the mechanical reference surfaces is given by a tolerance chain consisting of mounting slots on the block yokes and bearing seat parts. What can also be seen in Figure 2 is that although there are large absolute offsets, the measured offsets within each magnet block appear to lie around a common line, especially so in the horizontal direction (left-hand plot). So, to calculate the relative alignment, we consider the magnets measured with the same rotating coil shaft in the same setup as having been measured in a common local coordinate system, and subtract a linear fit from the measured "raw" displacements as function of longitudinal position. Example calculated relative alignment for a few U3 magnet blocks (Figure 2 data with linear fits subtracted) is shown in Figure 3. As seen in this figure, relative offsets in the horizontal direction (left-hand plot) are within ±0.01 mm, and appear random, but vertical displacements are larger and appear to be systematically negative for the middle magnet and positive for the magnets at the ends of the rotating coil shaft. The same tendency is seen for all U3 measurements (and to smaller degree also for the "M1/M2 long" and "U1..U5 long" measurements). This is discussed further in the next subsection of this report.

As seen in Table 1, different numbers of magnets were measured with the different rotating coil shafts. Since the calculation of relative alignment includes subtracting a linear fit, using two magnets or less does not yield a meaningful result. Thus, the "M1, M2 short" and "U1..U5 short"

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOAD3

Table 2: Summary of the final results of the described evaluation for all magnets. The U3 values were compensated for sag since the coil shaft was the longest used; the RMS values for the other types were <10 μm even without this compensation.

Block	Elements	Eval. [pcs.]	Rel. align.	Min [μm]	Max [μm]	RMS [μm]	Comment
M1, M2	OXX-QFe-	39/40	dx	-10	12	3.2	
	OXY-QDe		dy	-24	18	9.1	Including sag
U1, U2,	QFm-SFm-QFm/	79/80	dx	-16	12	4.3	
U4, U5	QF-SFo-QF		dy	-24	30	6.4	Including sag
U3	QF-SFi-	20/20	dx	-10	13	4.7	
	QF-SD		dy	-21	19	7.6	Compensated for sag

measurements could not be used for this purpose. For the other rotating coil setups, the relative alignment within each group of magnets measured with the same rotating coil shaft has been calculated as described above for the whole production series of 3 GeV ring magnet blocks. The results are summarized in Table 2[3].

Compensating for Shaft Sagging

The vertical displacements in the right-hand plot in Figure 3, discussed previously, can be ascribed to a sagging of the rotating coil shaft under its own weight. This deflection, u, can be described by a 4$^{\text{th}}$ degree polynomial, found e.g. in [6],

$$u(x) = \frac{qL^3}{24EI}\left(\frac{x}{L} - \frac{2x^3}{L^3} + \frac{x^4}{L^4}\right), \quad u_{\max} = \frac{5}{384}\frac{qL^3}{EI},$$

where q is the distributed load on the shaft, L is the distance between the supports, E is Young's modulus and I is the area moment of inertia. x is here the coordinate along the shaft, with $u_{\max} = u(L/2)$. q, L and E were given by the magnet manufacturer and I depends on the geometry and can be deduced from pp. 100 in [6].

After compensating for the sag in the "raw" values obtained by Eq. (1), one can make a new linear fit in the same way as before. The result of this compensation can be seen for a few example magnet blocks in Figure 4.

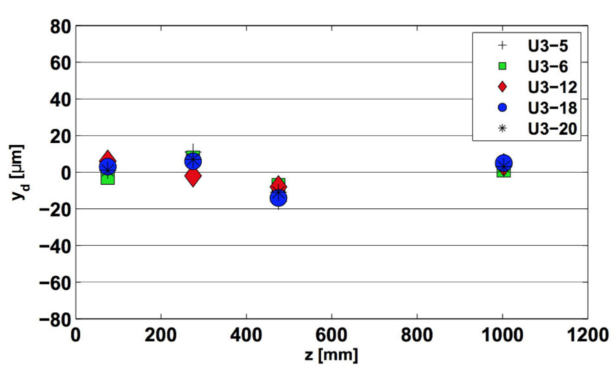

Figure 4: Vertical relative displacements of the upstream magnets within five example U3 magnet blocks as a function of distance along the block, compensated for sag.

[3] M2-19 and U2-2 were left out of the evaluation because some magnets were measured on separate occasions.

SUMMARY AND CONCLUSIONS

All magnets for the MAX IV 3 GeV storage ring have now been produced, and by means of harmonic data obtained by the magnet manufacturers, the relative alignment between consecutive magnet elements has been evaluated. By utilizing several longitudinally spaced measurement coils on a common shaft, a local coordinate system was established for the measurements and the relative displacements could be calculated, even though the absolute position of the measurement coils was not known.

The results were that all relative alignments were <10 μm RMS. Looking back at the original assumption that magnetic centers coincide with mechanical centers, we can conclude that the values in Table 2, the combined effect of mechanical tolerance stack-up, as well as any effects from inhomogeneous magnetization properties of the material, can be regarded as an upper bound on any disagreement. [3]

As the measurements are only covering a limited part of the totalt length of the magnet blocks, a safe estimate of the total relative alignment over the whole block length would be the values in Table 2 plus the mechanical tolerance over the full length of the blocks, ±0.02 mm. This would be roughly equal to the requirement of 25 μm RMS with a 2σ cutoff [7], indicating that from the perspective of magnet-to-magnet alignment, we are on track for achieving the design performance for the MAX IV 3 GeV storage ring.

REFERENCES

[1] M. Eriksson et al., "Challenge of MAX IV towards a multi purpose highly brilliant light source", TUOBS4, Proc. PAC2011
[2] P. F. Tavares et al., "The MAX IV storage ring project", J. Synchrotron Rad. 21, (ISSN 1600-5775, 2014)
[3] M. Johansson et al., "Magnet design for a low-emittance storage ring", J. Synchrotron Rad. 21, (ISSN 1600-5775, 2014)
[4] B. Anderberg et al., "MAX IV 3 GeV storage ring magnets - technical specification", unpublished
[5] S. Russenschuck, *Field Computation for Accelerator Magnets*, ISBN 978-3-527-40769-9, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germay (2010)
[6] G. Wihlborg, *Hållfasthetslära*, Compendium, KFS i Lund AB, Lund, Sweden (2006)
[7] S. C. Leemann, "MAX IV Detailed Design Report", ch. 2.1-2.4, https://www.maxlab.lu.se/maxlab/max4/index.html