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MECHANICAL AND MAGNETIC PERFORMANCE OF COMPACT SYNCHROTRON MAGNET SYSTEMS FOR MAX IV AND SOLARIS

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Abstract

Compact magnet systems for ultra-low emittance, low-cost synchrotron light sources have been developed at MAX-Lab. Results of the test at Danfysik of 60 magnet systems produced for the MAX IV 3 GeV storage ring will be presented with focus on the long term stability and trends of the magnetic performance of the internal magnets. The test results are found to be in good agreement with the tight mechanical tolerances. A complete series of 12 magnet girder systems for both the MAX IV 1.5 GeV and the SOLARIS storage rings are also to be produced at Danfysik. With two combined function dipoles and 11 multipole magnets integrated into 4.5 m long iron yokes these magnet systems are significantly larger. New aspects of the magnetic test concept for multipole magnets placed deep inside the girder structure will be described.

INTRODUCTION

Danfysik has finished the production of 20 of each of the MAX-lab magnet girder types M1, M2 and U3. The top and bottom yoke of these complex magnet systems are machined out of single iron blocks including a combined function dipole. Up to 12 discrete multipole magnets are mounted into the yokes [1, 2]. The production concept and test system have previously been reported [3]. Here we will report the main test results for Hall probe field mapping of the dipole magnets and harmonic coil measurements of the multipole magnets.

The MAX IV 1.5 GeV and the SOLARIS synchrotron storage rings are to be constructed from conceptually similar magnet girder systems [4], which all are to be built by Danfysik. Both rings require 12 double bend achromats which each contains two dipoles and 11 separated multipole magnets. With a length of 4.5 m and a weight of 6 tons these magnet systems are significantly larger than the 3 GeV girders where the largest U3 girder is 3.3 m long with a weight of 1.6 tons. The size difference is illustrated in Fig. 1 which shows the mechanical layout, as designed by MAX-lab, of the U3 girder for 3 GeV compared to the 1.5 GeV girder magnet. It is a special challenge to machine such long complex structures to very tight mechanical tolerance requirements. The production of the prototype girder magnet for MAX-lab 1.5 GeV and SOLARIS has shown that this is possible even for such a large system. Magnetic test of multipoles placed deep inside such long structures is an extra complication. A relatively simple modification of our harmonic coil system does, however, allow high precision measurements to be performed on these internal magnets.

PRODUCTION STATUS

All 60 magnet girders for MAX IV 3GeV have been produced and the final magnetic testing is essentially finished. One third of the girders has been delivered to MAX-lab and the rest is about to be shipped. The main requirement for the yoke machining is a ±0.02 mm tolerance limit on critical parts, which is also the tolerance needed for the separately machined multipole pieces. This was a significant challenge, but based on previous experience the prototype 1.5 GeV magnet girder has been produced to the satisfaction of MAX-lab. This was made possible by an investment made by a sub-supplier in a new and larger precision CNC machine dedicated to this task. Machining of each of the 1.5 GeV yokes half part is a large task with 60 h spent on the initial rough machining and 150 h for the final machining.

Four of the 1.5 GeV magnets for trimming contain a total of four separate functions by including a trim sextupole, skew quad and x- and y-correction function which result in unusually complex coil windings.

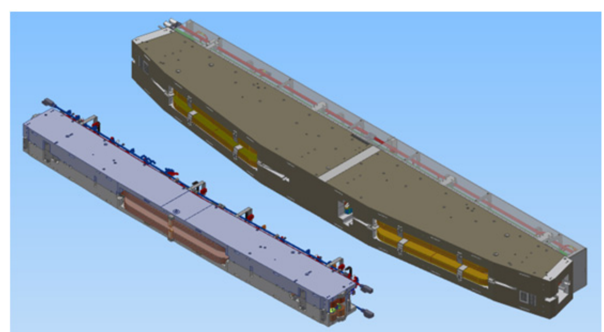

Figure 1: Mechanical layout for the U3 magnet girder for the MAX-lab 3 GeV ring compared to the larger girder for the 1.5 GeV MAX-lab and Solaris synchrotrons

RESULTS FOR THE 3 GeV GIRDERS

Hall Measurement of the Dipole

The C-type of dipole magnets has been Hall probe field mapped through a slot in the side yoke using a long precision field mapping bench. The field mapping was performed by precision alignment and on-the-fly measurements with interpolation to the required field points, as previously described [3]. The 3 GeV combined function M1/M2 dipoles are to bend the beam 1.5° while the longer U3 dipoles are made for 3° bend with a maximum center field of 0.53 T, a gradient of 8.7 Tm/m at a center pole gap of 28 mm. The dipoles are made with a soft end having a reduced magnetic field level [1].

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The long-term stability of the Hall probe was not as good as expected and therefore a daily correction is now performed in a reference magnet which reduces the drift to below 100 ppm. Figure 2 shows the variation of the measured on-axis field integral relative to the average dipole strength. The standard deviation of this variation is 0.07% for all three girder types. In comparison the ±0.04 mm tolerance on the 28 mm pole gap due to the allowed ±0.02 mm mechanical tolerance on the top and bottom poles corresponds to a field variation of ±0.14%. For a few of the first measured dipoles before the Hall probe drift correction the variation is larger, but with the correction all are within. This result shows that it is possible, with careful functional machining [3], to avoid the buildup of additional tolerances due to tolerances on the yoke. Similar results are obtained for the field gradient variation.

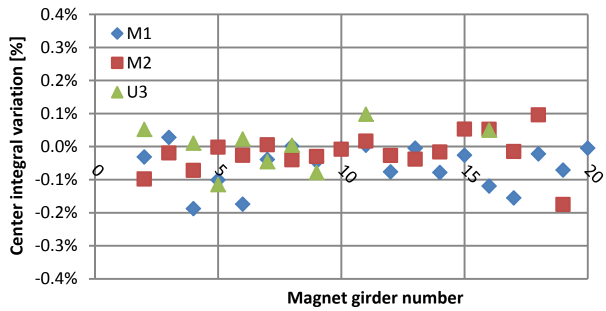

Figure 2: The relative field integral strength deviation from the average strength for the M1, M2 and U3 dipoles.

Harmonic Coil Multipole Measurements

The multipole magnets are measured by rotating coil measurements using short tangential pick-up coils at a measuring radius of 10.7 mm on a rod inserted from the entrance or exit end. The short term stability of this system is very good [3]. Long term stability of the main gradient strength and magnet rotation angle were harder to maintain with re-installation on each new girder magnet, but good stability was obtained by avoiding any changes in the coil installation and rotation concept. Fig. 3 shows the relative variation of the measured gradient strength for the four U3 quadrupoles at nominal excitation level. The standard deviation on this variation is 0.07% with a maximum of 0.16%. For the M1/M2 quadrupoles the standard deviation on the gradient variation is 0.16%. In comparison a 0.02 mm displacement of the four poles of the quadrupole can give gradient variations up to 0.3%. The higher harmonic content has for the M2 QDE been obtained by Opera-3D calculations and the relative amplitudes are in Table 1 compared to the measured values averaged over the M2 quadrupoles of both the QDE and QFE type (as they are mechanically similar). The measured average values are also shown for the U3 quadrupole. The harmonics terms up to n=20, which are not shown, are all below 0.1 unit indicating a high performance transverse pole profile and high performance of the wire eroded poles. The systematic n=6, 10 and 14 harmonics agree quite well with the 3D calculation for M2. The 9.3 unit n=6 term on the M2 quadrupoles is for U3 reduced to 2.1 unit by chamfering of the pole ends. The calculated 3.9 unit octupole is expected mainly to be due to differences in the horizontal/vertical return yoke path length but is slightly overestimated compared to the measured 2.5 unit. The standard deviation on the measured harmonics is also shown in Table 1. The highest harmonic error term on any of the quadrupole magnets is 9 unit. In comparison a sextupole of up to 11 units or 8 unit octupole can be generated by the allowed ±0.02 mm position tolerances on the pole placements. This shows that both the gradient variation and the harmonic error content is within what could be expected for the allowed mechanical tolerances without any issue of tolerance build-up.

Table 2 and 3 show the higher harmonic error content calculated with Opera-3D for the sextupoles and octupoles in the M2/M1 girders. The average and standard deviation of the measured values are also shown, except for the terms up to n=20 which are below 0.4 unit. If needed the n=9 and 15 terms for the sextupole and n=12 for the octupole could have been reduced by chamfering of the pole ends.

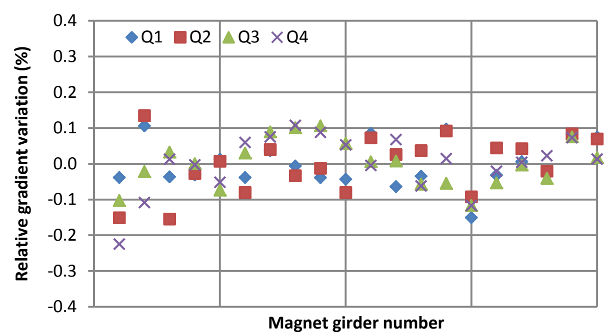

Figure 3: The relative integral gradient strength deviation from the average strength for the four U3 quadrupoles.

Table 1: Calculated higher harmonic for the M2 QDE quadrupole compared to the measured average values and standard deviation in units for the M2 quadrupoles. The test results for the U3 quadrupoles are also shown.

	C_n for QDE	C_n for M2 quads		C_n for U3 quads	
n	Calculated	Measured	St.Dev.	Measured	St.Dev.
3	0.6	3.1	1.7	2.9	1.6
4	3.9	2.5	1.6	3.1	1.8
5	0.1	0.6	0.3	0.5	0.3
6	8.8	9.3	0.5	2.1	0.4
7	0.1	0.2	0.1	0.2	0.1
8	0.1	0.2	0.2	0.4	0.1
9	0.0	0.2	0.1	0.2	0.1
10	1.8	1.5	0.1	3.2	0.1
14	0.9	0.8	0.1	0.9	0.0
18	0.2	0.2	0.1	0.2	0.1

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Table 2: Calculated and measured average harmonics and standard deviation for the 20 M2 sextupoles in units.

n	Calculated	Measured	St.Dev.
4	0.2	9.4	6.0
5	4.0	3.6	2.3
6	0.1	1.4	0.7
7	0.5	1.3	0.7
8	0.0	1.3	0.4
9	15.6	16.7	0.3
14	0.1	0.5	0.1
11	0.1	0.4	0.2
15	3.7	3.3	0.1

Table 3: Calculated and measured average harmonics and standard deviation for M2 OXX/OXY octupoles in units.

n	Calculated	Measured	St.Dev.
5	0.0	5.9	2.7
6	2.6	7.2	4.5
7	0.0	2.3	1.5
8	0.0	2.4	1.3
9	0.1	0.9	0.4
10	0.1	0.8	0.5
11	0.0	1.9	0.8
12	29.1	28.2	0.3

THE 1.5 GeV GIRDERS MAGNETS

The two combined function dipole magnets of the prototype girder have been Hall probe field mapped by means of our long field mapping bench (see Fig. 4) using the same concept as for the 3 GeV [3]. Minor deviations between the measured field and Opera 3D calculations performed by MAX-lab were observed but found to be acceptable.

Figure 4: Picture of the prototype 1.5 GeV girder magnetic at our Hall probe field mapping bench.

Harmonic coil measurement of the 3 multipoles at the entrance and exit ends are to be performed using a short end-coil system mounted at the girder ends. This is similar to the concept used for 3 GeV. A longer center-coil system has been developed for the measurement of the 5 internal multipoles placed between the two dipoles. The space needed for these measurements requires that they take place before the dipole coil and field clamps are installed. The coil rotates in high precision ball bearings driven by an external motor via a belt. Both concepts are illustrated in Fig. 5. The measuring radius of the tangential pick-up coils range between 16.5 and 24 mm. The harmonic strength and rotation angle of the 8 coil segments are calibrated against a calibration magnet in a separate setup. The short-term stability was measured as the standard deviation on the main gradient, higher harmonic error terms, magnet rotation angle and center offset. The test was repeated with removal and replacement of the harmonic coil between each measurement. The standard deviation average over the 3 or 5 coil segments are given in Table 4. Even with the use of a drive belt the results are more than adequate.

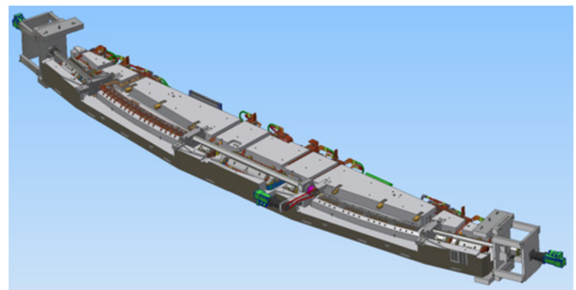

Figure 5: Harmonic coil measurement system shown without the top yoke for demonstration.

Table 4: Short term stability was measured for the short end-coil and long center-coil by making five repeated measurements with no changes in between (fixed). The test was also performed with replacement of the rotating coil between each measurement (replace).

Standard deviation on 5 measurements		Short end-coil		Long center-coil	
		Fixed	Replace	Fixed	Replace
Main gradient	unit	0.01	0.09	0.03	0.16
Higher harmonic	unit	0.04	0.04	0.06	0.09
Magnet rotation	mrad	0.002	0.05	0.01	0.09
Center x-offset	mm	0.000	0.009	0.001	0.002
Center y-offset	mm	0.000	0.001	0.002	0.003

CONCLUSION

The compact M1, M2 and U3 magnet girders for MAX-lab 3 GeV have all been produced. High performance magnetic field measurements show that the magnet performance is in agreement with the required ±0.02 mm tolerance limit without any further issue with additional tolerance chain build-up. The prototype 1.5 GeV girder has been produced and the two internal dipoles have been field mapped successfully. A harmonic coil system has been developed that allows high precision measurements even for the multipoles deep inside the magnet girder.

REFERENCES

[1] M. Johansson et al., IPAC 2011, p. 2427.
[2] M. Eriksson et al., IPAC 2011, p. 3026.
[3] F. Bødker et al., IPAC 2013, p. 34.
[4] M. Johansson et al., IPAC 2011, p. 2430.