MULTIPLE FUNCTION MAGNET SYSTEMS FOR MAX IV

F. Bødker, C.E. Hansen, N. Hauge, E. Krauthammer, D. Kristoffersen, G. Nielsen, C.W. Ostenfeld, C.G.T. Pedersen, Danfysik A/S, Taastrup, Denmark

Abstract

Danfysik is currently producing 60 magnet systems with discrete multipole functions integrated into yokes for the bending achromats of the MAX IV 3 GeV storage ring. The integration of up to 12 multipole magnets into individual yoke structures enables a compact, low emittance storage ring design where the elements are aligned with high precision inside the magnet girders. Testing of the compact magnet structures with yoke lengths up to 3.3 m has been a challenge which required development of new test equipment dedicated to this task.

INTRODUCTION

Danfysik is in the process of producing 20 of each of the MAX-lab magnet girder types M1, M2 and U3. Fig. 1 shows a mechanical layout of one of the magnet girders, as designed by MAX-lab [1]. The top and bottom magnet yokes, including the poles for a combined function bending magnet, are machined out of one single iron block. Separate, higher order multipole magnets are mounted into the yokes. The machining of the up to 3.3 m long yokes out of solid iron blocks to tight tolerances requires special attention and advanced machining procedures. This process is now fully implemented and the required tolerances have been achieved.

The dipole and quadrupole elements are magnetically field mapped on a precision Hall probe measuring bench with special attention to achieve the best possible position accuracy. All multipoles are measured on a slow rotating coil system developed for that purpose. Much effort has been put into automation in order to increase the reliability and reduce the measuring time. Testing of the first M1, M2 and U3 magnet girders is now completed.

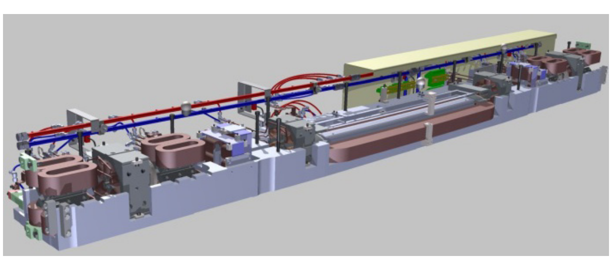

Figure 1: Mechanical layout for the U3 magnet girder.

PRODUCTION

Complete magnet girders of each of the three types have been produced together with iron yokes for the first 10 M1 girders. A picture of a finished M1 magnet girder is shown in Fig. 2. The main requirement on the yoke machining is a ±0.02 mm tolerance limit which is also the tolerance needed for the separately machined multipole pieces. In order to meet this tolerance and in addition to obtain magnets with uniform magnetic properties, the yoke parts are all made out of one batch of low carbon Armco steel and heat treated as part of the production.

Machining has been outsourced and is performed on a large scale CNC mill especially adjusted and calibrated for this task. To ensure the best possible precision the CNC machine is dedicated to machining of the MAX-lab girders during the whole production period. The high precision and small tolerances are achieved by using an iterative machining refinement process of rough machining and heat treatment followed by fine machining adjusted to 3D measurements.

After machining, 3D measurement campaigns, consisting of approximately 1300 point measurements, are performed for each top and bottom yoke. Results for the produced parts have been evaluated in cooperation with MAX-lab and the results were within specifications. Special attention was paid to the pole face geometry of the dipole integrated in each yoke. The mechanical tolerances of ±0.02 mm on e.g. the pole face geometry are referenced to the very large mating surfaces of the yoke halves and reference surfaces at each yoke end.

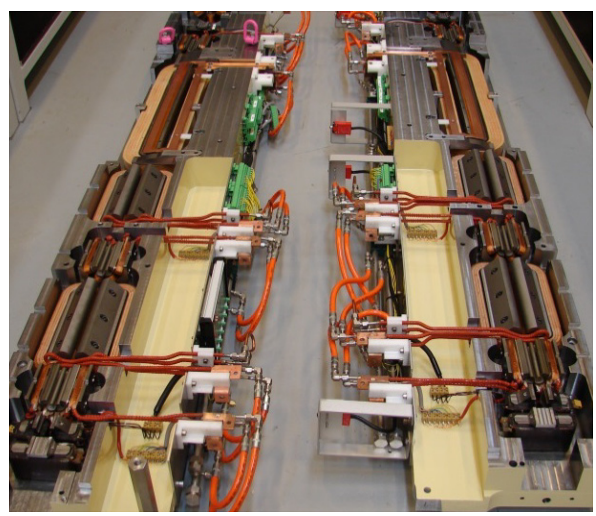

Figure 2: Top and bottom parts of an M1 magnet girder.

Meeting the tolerances on the sextupole and octupole magnets, which are kinematically mounted into precision machined slots of the yokes, required a special functional machining to avoid the build-up of the tolerances on individual iron pieces.

A special coil winding concept was developed in order to minimize the risk of internal water leaks, in particular in the well hidden coils of the multipole magnets. This concept omits the need for internal joints inside the girder for the sextupole and octupole coils and it further facilitates simplified and faster coil production including large scale impregnation of multiple coils.

FIELD MAPPING WITH HALL PROBE

Hall Measurement Setup

Field mapping of the combined function dipoles is performed through dedicated slots in the side yoke, as seen in Fig. 3. For quadrupole magnets the field gradients are measured at three longitudinal positions through small holes in the side of the yoke. Our Hall probe is mounted on a sled which rests on a long granite beam with an overall flatness of 37 µm. The sled is moved along the z direction by a servo motor with feedback from a laser, and the probe is moved by stepper motors using the feedback from linear encoders with an accuracy of 3µm.

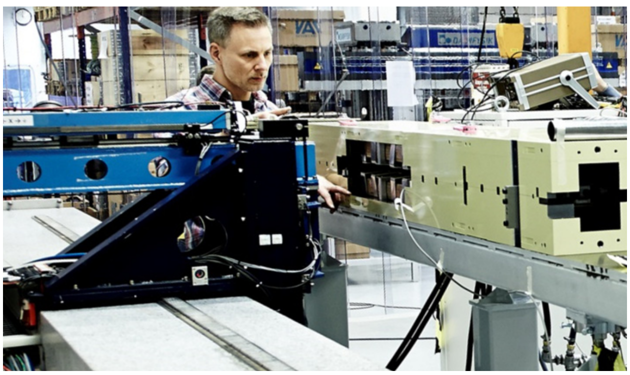

Figure 3: Field mapping with a Hall probe mapper on a granite bench with longitudinal axis along the beam axis.

The relations between bench and girder coordinate systems were found by scanning the probe over magnetic pins at mechanically known girder positions. Repeated scans over the same pin found the same pin position within 2.2 µm. We have seen position drift of less than 10 µm during a period of several days.

Accurate on-the-fly field measurements were possible using a Hall probe measuring system made at Danfysik based on a concept adapted from GSI [2]. The Hall element is placed in a non-metallic keeper including a temperature sensor and calibrated against field and temperature to field accuracy better than 1 G. The probe is supplied by a current supply with 30 ppm long term stability.

Software routines for fully automated control and logging of environmental parameters minimize user interaction and hence reduce the risk of errors in the relative complex field mapping. In addition, they ensure efficient, failure safe and reproducible measurement conditions for the entire production series.

Hall Measurements

The bending dipoles are to be field mapped along lines transverse to the nominal orbit with 5mm spacing and along the curved orbit with a transverse spacing of 1 mm, resulting in a total of up to 7600 points. If this was realized by step-and-go measurement, it would take more than 10 hours. Instead the dipoles are mapped on-the-fly on a rectangular grid, and the required data obtained by interpolation. The resulting measurement time was only 1.5 h, minimizing errors due to thermal drift.

The raw field values of the measured grid are shown in Fig. 4, with the soft dipole end [1] to the right. The map is made by on-the-fly measurements along straight lines in the z-direction with 0.25 mm between samples and 1 mm line spacing. This grid forms the basis for interpolation on transverse lines and along the orbit, as shown in Fig. 5.

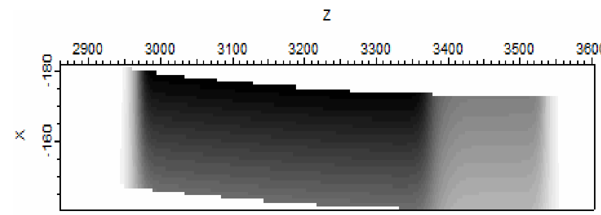

Figure 4: Magnetic field map of an M2 dipole. Darker color indicates higher field level.

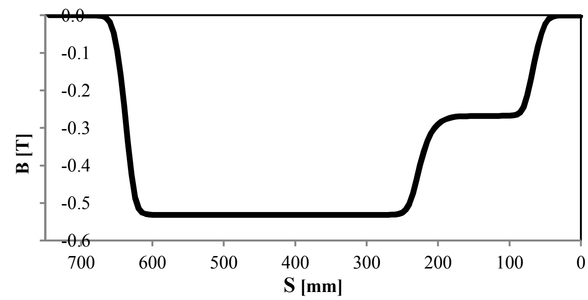

Figure 5: Magnetic field on the main orbit trajectory obtained by interpolation from the measured grid data.

Repeated interpolated field maps show that the results are very stable with relative standard deviations of $7{\cdot}10^{-5}$ on the field integral levels and deviations of only $2{\cdot}10^{-5}$ on obtained effective magnetic dipole lengths.

Step-and-go field measurements were made on a transverse line in the center region of an M2 dipole with a magnetic field gradient of 8.7 T/m, making the measurement strongly position sensitive. In Fig. 6 these results are compared with interpolated results obtained from three repeated full field maps of the dipole. The relative deviation is less than $1.6{\cdot}10^{-4}$, validating the interpolation scheme using on-the-fly measurements.

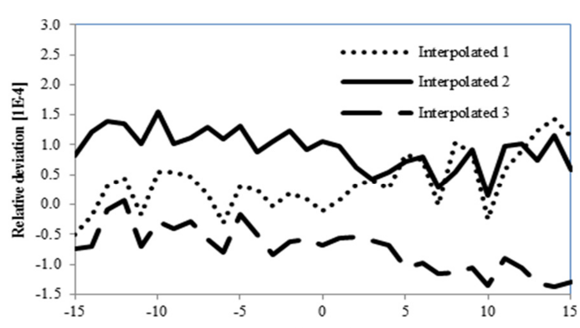

Figure 6: Relative deviation between discrete step-and-go measurements and interpolated field values on a transverse line of a combined function bending magnet.

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HARMONIC COIL MEASUREMENTS

The challenges of harmonic coil measurements of small aperture multipole magnets are discussed by Buzio in [3]. Several measurement techniques were considered, including multilayer PCB coil measurements. Inspired by work on Linac4 [4], we opted for a non-compensated tangential coil design using a 40 turn Litz-wire at an opening angle of 15° in order to obtain adequate sensitivity for the higher harmonics. The Litz-wire is placed in precision grooves machined into a support rod with at a measuring radius of 10.7 mm, which is optimized for the pole radius of 12.5 mm. A total of 13 harmonic coil segments are made, one for each individual magnet, with 3 to 5 individual coils on each support rod. The lack of compensating windings meant that accurate mechanical rotation of the coil was required, which was achieved by using high precision ball bearings. The harmonic coil system is inserted from a girder end (see Fig. 7) relying on mechanical positioning. By calibrating each coil segment separately, we could determine the individual phase differences between the coils, as well as the integrated strength transfer function. The coil signal is recorded via a Metrolab integrator using a LabVIEW program adapted from GSI in Darmstadt, Germany.

The measurement program has been modified to contain all relevant calibration and test values and to fully automate the measurement series, including current pre-cycling and measurements at a range of current values. This is particularly important with the need for continuous switching between many multipole magnets of different types using different coil segments.

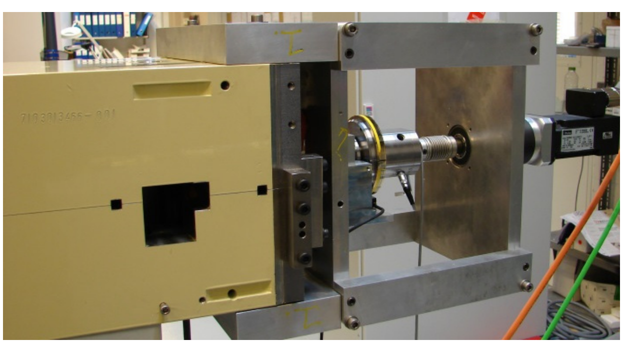

Figure 7: Rotating harmonic coil measuring system mounted on an end section with inserted pick-up coil.

The stability of the harmonic coil system was evaluated by making repeated measurements on two quadrupoles and two octupoles at their nominal field strength. These short term repeatability tests gave on average a standard deviation of 0.4 units on the main field gradient strength (unit=10^{-4}), a negligible change on the determined magnet center position and 0.01 mrad variation on the magnet rotation value. The variations on higher harmonic terms between repeated measurements were in all cases below 0.1 units. A simple thermal test where the harmonic coil was locally heated indicated quite modest thermal drifts of -0.03 mrad/°C for the magnet rotation angle and 0.2 unit/°C on the main harmonic gradient strength.

Extended harmonic coil measurement campaigns have been performed for the first M1, M2 and U3 magnet girders at a range of current settings for each of the 9 to 13 built-in magnets spanning from corrector, quadrupole, sextupole to octupole magnets. Measurements were repeated after repositioning of the test jig and again after disassembly of the top and bottom yokes. These repeated test jig mountings were a challenge for the measurement reproducibility. Variation on the magnetic center position with disassembly of the test jig and magnet is typically below 0.01 mm. The magnetic center was found to be within 0.1 mm of the harmonic coil rotation center, which is the combined limit on coil and magnet misalignments. The obtained variation of measured main harmonic gradient is for quadrupoles on average within ±2 units. For higher order terms it decreases from 0.4 to 0.05 units with increasing order of the harmonics. Generally, higher harmonic repeatability is well within 1 unit.

Higher harmonics of the other measured multipole magnets show similar trends. Besides the allowed terms, they are dominated by the first two higher harmonics. The remaining higher harmonics are typically below 1unit which shows that the pole profile is well performing. Fig. 8 shows sextupole and octupole harmonics as a function of excitation current for an M2 quadrupole. The octupole terms are nearly constant while the sextupole terms show some variation. It seems like the variation is a result of different yoke flux return paths in combination with excitation dependent permeabilities. Similar trends are observed for the sextupole and octupole magnets.

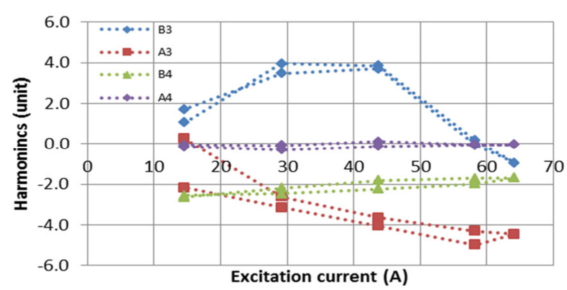

Figure 8: Measured normal and skew sextupoles (B3, A3) and octupoles (B4, A4) harmonics as a function of current for a focusing quadrupole on the M2 girder.

CONCLUSION

The first M1, M2 and U3 magnet girders have been produced and tested at Danfysik and found to fulfill both magnetic and mechanical specifications. The measuring systems perform very well with high stability and accuracy and our results are in general in good agreement with model calculations by MAX-lab.

REFERENCES

[1] M. Johansson et al., IPAC 2011, p. 2427.
[2] F. Klos, GSI Darmstadt, Germany, personal communication.
[3] M. Buzio, "Magnetic measurement of small-aperture quadrupoles at CERN", PSI Villigen, 15 April, 2010.
[4] M. Buzio, personal communication.