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MAX IV 3 GeV STORAGE RING MAGNET BLOCK PRODUCTION SERIES MEASUREMENT RESULTS

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Abstract

The magnet design of the MAX IV 3 GeV storage ring replaces the conventional support girder + discrete magnets scheme of previous third-generation synchrotron radiation light sources with a compact (Ø25 mm aperture) integrated design having several consecutive magnet elements precision-machined out of a common solid iron block. The production series of 140 integrated magnet block units, which was totally outsourced to industry, was completed mid-2014. This article presents mechanical and magnetic field measurement results of the full production series.

INTRODUCTION

The MAX IV synchrotron radiation facility [1], consisting of two storage rings, 3 GeV and 1.5 GeV, and a full energy linac, is currently being installed/commissioned in Lund, Sweden. The 3 GeV storage ring [2] has a multibend achromat (MBA) lattice, consisting of 20 achromats, each consisting of 7 cells, with a circumference of 528 m. The integrated magnet design concept of the 3 GeV ring has each lattice cell realized as one "magnet block", consisting of several consecutive magnet elements in a common solid iron yoke (see Fig. 1), so that the whole lattice consists of 140 such magnet block units. A detailed presentation of this magnet design has been given previously in [3].

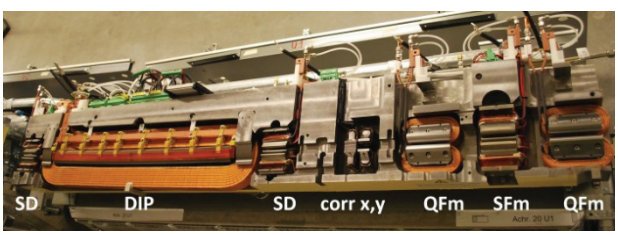

Figure 1: U1 magnet block bottom half.

There are 7 magnet block types per achromat (see Fig. 2). M1 and M2, 2.3 m long, are mirror identical. U1 and U2, 2.4 m long, are identical and U4/U5 are mirror identical to U1/U2. U3, 3.4 m long, has similar layout to the other U, but symmetric around its own midpoint.

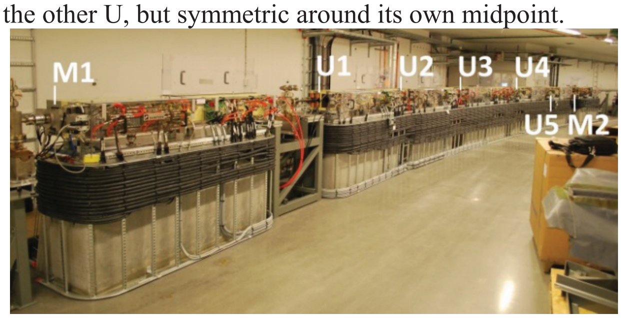

Figure 2: Achromat 04 in the 3 GeV ring, fully assembled.

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Mechanical Design Concept

The main structural parts of the magnet blocks are the yoke bottom and yoke top blocks (Fig. 3), which are each machined from a single block of iron[1].

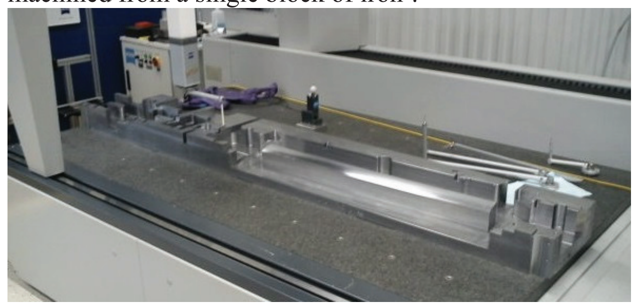

Figure 3: U4/U5 yoke bottom half undergoing 3D mechanical measurement.

The pole surface of the dipole is machined directly out of the block, whereas the quad and corr. pole tips are dismountable, to allow coil installation. Sextu- and octu-poles are designed as complete magnet halves, which are mounted in the yoke blocks (see Fig. 1). Mechanical tolerances for the different categories of function critical surfaces in the yoke bottom/top blocks are:

- Vertical mating planes for quad pole tips and sextupole/octupole yoke halves: distance to midplane ±0.02 mm.
- Sideways guiding slots for quad pole tips and sextupole/octupole yoke halves: distance to sideways ref. surfaces[2] ±0.02 mm.
- Midplane: flatness[3] tolerance 0.04 mm.
- Dipole: surface shape[4] tolerance 0.04 mm.

And tolerances for the other critical yoke parts are:

- Quad pole pieces: surface shape tolerance 0.02 mm
- Sextupole/octupole yoke halves with poles assembled: surface shape tolerance 0.04 mm.

Procurement

The production of the magnet blocks was outsourced as build to print-contracts, based on a technical spec. and full set of drawings [4] provided by MAX-lab, with suppliers being responsible for mechanical tolerances, and for performing field measurements according to MAX-lab instructions, and MAX-lab being responsible for the field measurement results. The contracts for the magnet blocks production were awarded in the fall of 2011, to two

[1] "ARMCO Pure Iron grade 4", C < 0.01%.
[2] Two outer corners on the yoke block together with the midplane define the mechanical reference frame in which all the tolerances are evaluated
[3] The mechanical tolerance called "flatness" is defined as peak-to-peak deviation between measured data points and a best fit-plane.
[4] The mechanical tolerance called "surface shape" is defined as the twice the amplitude of the largest deviation within the tolerance zone, ie 0.04 mm means ±0.02 mm.

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separate suppliers:

- 60 pcs M1, M2 and U3: Danfysik[5]
- 80 pcs U1, U2, U4 and U5: Scanditronix Magnet[6]

The production series were completed mid-2014.

YOKE MACHINING RESULTS

From the manufacturing point of view, the most challenging part of the 3 GeV ring magnet production was the yoke bottom and top blocks, with ±0.02 mm tolerances applying over the whole block length of 2.3-3.4 m. The manufacturing method used for all block types was conventional 3-axis CNC milling, performed by one subcontractor for Danfysik's 120 pcs M1-, M2- and U3-yoke halves, and by two subcontractors in parallel for Scanditronix's 160 pcs U-yoke halves. Following the technical specification, every tolerance < 0.1 mm was measured for every yoke block of the whole production series by 3d coordinate measurement machine (3d CMM), as part of the machining subcontractors' verification. For each yoke block a 3d CMM report, listing all measured values, was submitted to MAX-lab for approval.

Achieved Machining Accuracy

The outcome of the yoke bottom/top blocks production series can be presented by sorting the measured values from the 3d CMM reports in the different categories of function critical surfaces, for each type of yoke block. Example measurement data is shown in Figs. 4 and 5, and results for all categories/block types are summarized in Table 1.

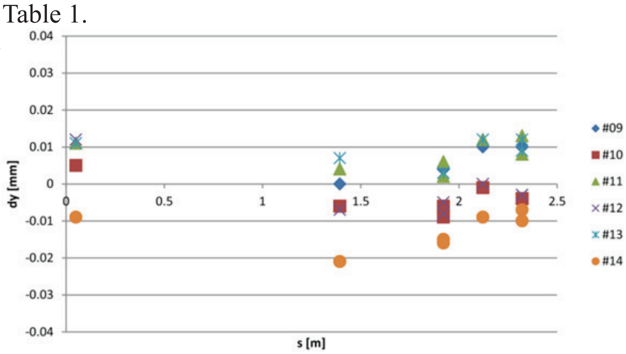

Figure 4: Vertical mating surfaces measured deviation, as function of longitudinal position in yoke block, for 6 example U4/U5 yoke bottom/top blocks.

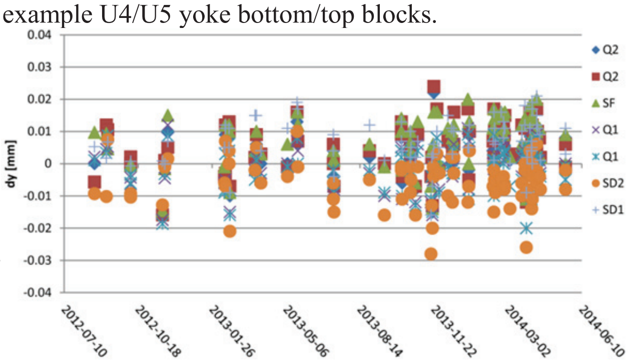

Figure 5: Vertical mating surfaces measured deviation, as function of meas. report date, for U4/U5 blocks [80 pcs].

[5] Danfysik A/S, Taastrup, Denmark.
[6] Scanditronix Magnet AB, Vislanda, Sweden.

Table 1: Summary of Yoke Bottom/Top Block Mechanical Measurement Results, per Block Type and Category, for the Full Production Series of 280 Yoke Blocks

yoke block type	surface category	min. [mm]	max. [mm]	rms [mm]
M1/M2, [80 pcs]	vertical	-0.030	0.037	0.012
	sideways	-0.030	0.031	0.009
	midplane	0.011	0.039	0.021
	dipole[7]	0.011	0.033	0.018
U1/U2 [80 pcs]	Vertical	-0.031	0.029	0.009
	sideways	-0.024	0.047	0.016
	midplane	0.019	0.040	0.032
	dipole[7]			
U3 [40 pcs]	Vertical	-0.032	0.038	0.013
	sideways	-0.023	0.024	0.010
	midplane	0.014	0.037	0.028
	dipole[7]	0.016	0.026	0.020
U4/U5 [80 pcs]	Vertical	-0.028	0.024	0.009
	sideways	-0.030	0.038	0.013
	midplane	0.012	0.040	0.026
	dipole[7]			

The Fig. 4 data is typical in that deviations are usually correlated along the length of the yoke block. Fig 5 is typical in that there was no clear trend over time in the measured deviations. As seen in Table 1, the achieved accuracy is within, or mostly within, the ±0.02 mm tolerance level. In cases where measured dimensions outside tolerance were accepted by MAX-lab, a consequence analysis was made, indicating if the deviation could be accepted as is, or if corrective action had to be taken by the supplier.

FIELD MEASUREMENT RESULTS

To provide the specified set of magnetic field measurement data, the suppliers performed:

- Hall probe mapping - in on the fly-mode using an insertion device mapping bench (Danfysik) or in point to point-mode using a 3d CMM as mapping bench (Scanditronix Magnet) – taking full field maps in the dipoles and single transverse lines in the quadrupoles.
- Rotating coil measurements - using several longitudinally spaced measurement coils in a common rotating shaft inserted into the magnet blocks, to be able to access the different magnet elements inside (both suppliers[8]) – for quadrupoles, sextupoles, octupoles and corrector magnets.

For the dipoles, measured field was presented as a grid of B_y-values in an x,s curvilinear coordinate system, with 1x5 mm spacing, over a width of x=±15 mm and a length of 754.24 or 1223.78 mm (DIPm or DIP), corresponding to the length of all 12 slices representing the dipoles in the

[7] For the dipoles, the value stated here is "surface shape"/2 = the amplitude of the largest deviation on the pole surface.
[8] Both using indepently developed test setups.

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lattice model. The rotating coil data was presented as harmonic content, normal and skew terms, at a reference radius = 10 mm. Example Hall and rotating coil data are shown in Fig. 6 and 7, for two magnets for which a repeat measument was made (3 months apart, after magnet block dis-/re-assembly), which gives an indication on repeatability.

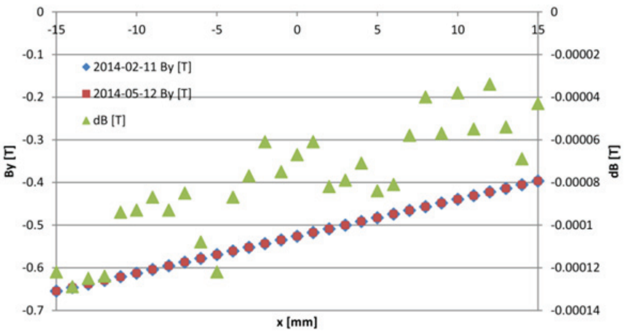

Figure 6: Hall probe data, $B_y(x)$ at dipole center, at nominal current, from two separate Hall maps of the same magnet block, U2#07. Difference between 2nd and 1st measurement, dB, is plotted on secondary axis.

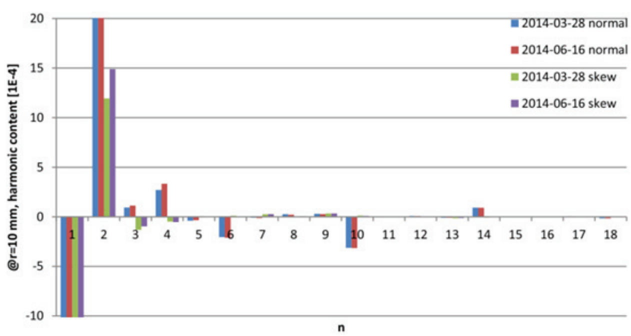

Figure 7: rotating coil data, U3#002 QF1 at nom. current.

Achieved Spread in Field Strength

A coarse estimate (by Ampere's law) on expected spread in field strength is ±0.4, ±0.6 and ±0.8%, for quads, sextupoles and octupoles, assuming ±0.025 mm on pole radius 12.5 mm. Measured variation in field strength at nominal current for the full production series is shown for one example magnet element type in Fig. 8, and summarized for all types in Table 2.

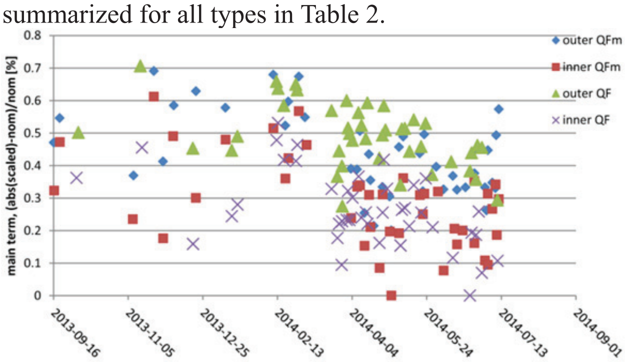

Figure 8: rotating coil data, U1,U2,U4,U5 quadrupoles.

[6] For magnet elements that are common to U3 and other U, U3 results have been calculated separately here, so that cross calibration factors between Danfysik and Scanditronix Magnet data have no impact.

spread in strength as function of measurement date.

Table 2: Spread in Strength at Nominal Current, per Magnet Element Type for the Full Series of 140 Magnet Blocks

magnet element	No [pcs]	in magnet blocks[6]	min. [%]	max. [%]	rms [%]
DIP B_0	80	U1,2,4,5	-0.15	0.17	0.07
DIP B_0	20	U3	-0.41	0.19	0.16
DIPm B_0	40	M1,2	-0.13	0.14	0.06
DIP B'	80	U1,2,4,5	-0.27	0.23	0.11
DIP B'	20	U3	-0.46	0.23	0.15
DIPm B'	40	M1,2	-0.18	0.20	0.09
QDend	40	M1,2	-0.45	0.48	0.19
QF	80	U2,4	-0.38	0.32	0.16
QF	80	U3	-0.41	0.43	0.25
QFend	40	M1,2	-0.38	0.35	0.14
QFm	80	U1,5	-0.36	0.33	0.15
SD	160	U1,2,4,5	-0.57	0.79	0.25
SD	40	U3	-0.37	0.25	0.16
SDend	40	M1,2	-0.46	0.39	0.17
SFi	40	U3	-0.38	0.77	0.21
SFm	40	U1,5	-0.50	0.68	0.27
SFo	40	U2,4	-0.41	0.54	0.21
OXX	38	M1,2	-0.57	0.58	0.29
OXY	38	M1,2	-0.24	0.93	0.27
OYY	40	M1,2	-0.33	0.38	0.15

CONCLUSIONS

- Our assessment is that a tolerance level ±0.02 is the lowest that can be set for yoke blocks of similar size/complexity.
- The resulting measured spread in field strength (Table 2) agrees with expected. Ie, we see no clear indication of additional spread in strength caused by material properties, etc.
- Since quads and sextupoles are series connected per achromat, the spread in field strength is further reduced in installation.

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