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

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Abstract

The MAX IV 3 GeV storage ring magnets are integrated "magnet block" units consisting of several consecutive magnet elements precision-machined out of a common solid iron block. In the 3 GeV ring, there are 140 magnet blocks containing a total of 1320 magnet elements. During the manufacturing phase of the project, a field measurement was performed for each magnet element, by Hall probe and/or by rotating coil. This article presents an overview of the magnetic field measurement results that were obtained for the full production series.

INTRODUCTION

The MAX IV Laboratory, located in Lund, Sweden, is a synchrotron radiation facility, consisting of two storage rings, 3 GeV and 1.5 GeV, and a full energy injector linac. [1] 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. Installation of the 3 GeV ring was completed in the summer of 2015 and ring commissioning started August 2015.

For the 3 GeV ring magnets, key aspects are the relatively small pole gap (Ø 25 mm) and the integrated magnet blocks concept (example photos shown in Fig. 1, 2), by which the magnet-to-magnet alignment within each block is given by the mechanical accuracy of CNC machining. For a more detailed presentation of this design, see [3].

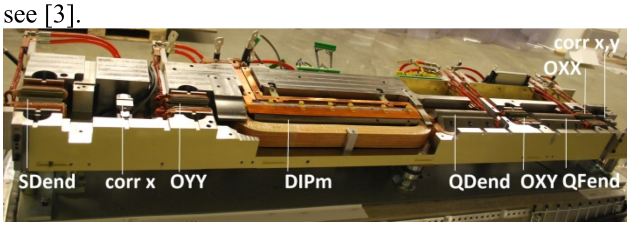

Figure 1: M1 magnet block bottom half.

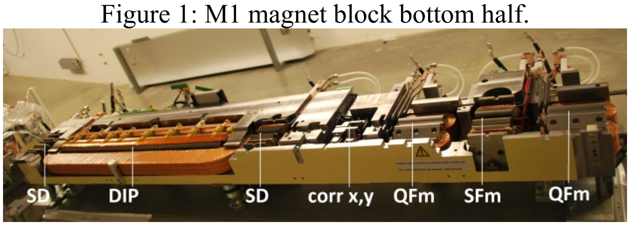

Figure 2: U1 magnet block bottom half.

There are 7 magnet blocks per achromat, each block corresponding to one lattice cell. They are named, in order of placement, M1, U1, U2, U3, U4, U5 and M2. With 20 achromats, there are 140 magnet blocks in the 3 GeV ring. The different magnet element types that are present in the blocks are listed in Table 1.[1]

Table 1: List of 3 GeV ring magnet elements, with nominal field strengths from design lattice [4].

magnet	No [pcs]	block	l [m]	r_{pole} [mm]	B [T]	B' [T/m]	B''/2 [T/m^2]	B'''/6 [T/m^3]
DIP [2]	100	U1-5	~1.22	14	-0.528	8.66		
pfs						±4 %		
DIPm [2]	40	M1,2	~0.75	14	-0.532	8.71		
pfs						±4 %		
QFend	40	M1,2	0.25	12.5		-36.57		
QDend	40	M1,2	0.25	12.5		25.06		
QFm	80	U1,5	0.15	12.5		-37.77		
QF	160	U2-4	0.15	12.5		-40.34		
SDend	40	M1,2	0.1	12.5			1701	
SFm	40	U1,5	0.1	12.5			-1701	
SD	200	U1-5	0.1	12.5			1167	
SFo	40	U2,4	0.1	12.5			-1742	
SFi	40	U3	0.1	12.5			-2076	
OXX	38[3]	M1,2	0.1	12.5				33000
OXY	38[3]	M1,2	0.1	12.5				-65459
OYY	40	M1,2	0.1	18				28429
corr x	200	all		12.5	±0.25 mrad			
corr y	178[4]	all		12.5	±0.25 mrad			
total =1320								

Procurement and Production

The production was outsourced as build to print-contracts for fully assembled and tested magnet blocks, with MAX-lab providing technical specifications and full sets of manufacturing drawings [6]. The contracts were signed in the fall of 2011, with two suppliers, Danfysik[5] and Scanditronix Magnet[6], and the production series were completed in mid-2014.

One of the key requirements for which the suppliers were responsible was the mechanical tolerances for the yoke bottom and top blocks, ±0.02 mm for function critical surfaces over whole 2.3-3.4 m block length. Summarized results for the full production series 3D measurements were presented in [7], with RMS results being within, or well within, these tolerances.[7]

FIELD MEASUREMENT SPECIFICATION

The contracts included field measurements of all magnet elements in all magnet blocks, which are a total of 1320 magnet elements (see Table 1 above). The concept was that the specification [6] listed what field measure-

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[1] Some of the nominal fields stated in Table 1 differ slightly from [3] and [6], since the dipole slices resulting from the prototype measurements [5] had not been fully implemented until the lattice update presented in [4].

[2] DIP and DIPm are defined in the lattice as consisting of 12 longitudinal slices. Lengths stated here are sum of slices, and fields are central slice.

[3] +2 OXX and 2 OXY in achromat 01 (injection) with pole radius 18 mm.

[4] +2 vertical correctors in achromat 01 with pole gap = 2*18.5 mm.

[5] Danfysik A/S, Taastrup, Denmark: 60 pcs M1, M2, U3.

[6] Scanditronix Magnet AB, Vislanda, Sweden: 80 pcs U1, U2, U4, U5.

[7] All other function critical yoke parts, like quad pole tips and sextupole/octupole yoke halves, were also verified by 3D CMM, but for these we have not made a statistical treatment like in [7].

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ment data should be provided for each magnet element, given some basic instructions and performance requirements, with the suppliers responsible for solving how to perform the measurements, and with MAX-lab being responsible for the results, as it was our design and drawings. No field measurements were done at MAX-lab, this was totally outsourced to the magnet suppliers.

Briefly stated, the measurements to be provided were,

- Hall probe,
  - Dipole field map at nominal current.
  - Dipole field map at nom I. + pole face strips at max I.
  - Quadrupoles transverse lines at nom I.[8]
- Rotating coil,
  - Quadrupoles, sextupoles, octupoles and correctors at nom I.
  - Sextupole and octupole trim coils at max I. for each connection mode.[9]
- Extended with more current levels and repeatability tests for a few magnet blocks of each type.

MEASUREMENT SETUP

Both suppliers chose to procure both new Hall mapping benches and rotating coil systems for this project [8] [9],

- Hall probe, Danfysik: an insertion device mapping bench with an in-house developed Hall probe.
- Hall probe, Scanditronix Magnet: a 3D CMM with a commercially available Hall probe integrated.
- Rotating coil, Danfysik: ceramic rotating shaft with tangential measurement coils, with a commercially available integrator.
- Rotating coil, Scanditronix Magnet: carbon fibre rotating shaft with radial measurement coils, with an in-house developed integrator.

For rotating coil access inside the magnet blocks, both suppliers chose the solution of several longitudinally spaced measurement coils in a common rotating shaft.[10]

SERIES MEASUREMENT RESULTS

The outcome of the field measurement campaign for the 3 GeV ring magnet block production series can be presented as statistics for different categories of results,

- Alignment
  - Between different magnet elements within magnet blocks was indicated to be < 10 µm RMS by rotating coil, see [3] and [10]
- Strength
  - Series average per magnet type are listed in Tables 2 and 3 below.
  - Series spread around these averages were presented in [7], typically 0.1-0.3% RMS.
- Field quality - see following two subsections.

[8] Each quadrupole has 2 or 3 small inspection ports through the yoke outside for Hall probe access.

[9] All 3 GeV ring sextupoles and octupoles have trim coils, one per pole, individually wired to terminal strips at the back of the magnet block.

[10] Some further description of this is given in [3] and [10].

Dipole Hall Probe Field Maps

The dipole Hall probe field maps were presented as an x,s grid of B_y field values over x = ± 15 mm and s = 0 - 1223.78 or 754.24 mm (for DIP or DIPm) with 1x5 mm spacing, following a simplified nominal beam trajectory: a straight line going into the dipole, constant radius through the dipole[11], and a straight line out from the dipole. The field map area for DIP is shown in Fig. 3 and an example field map is shown in Fig. 4 below.

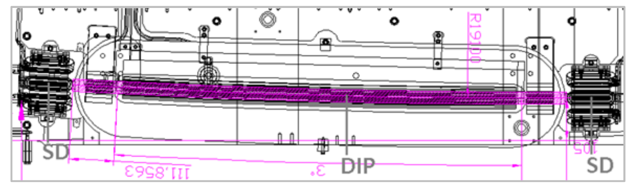

Figure 3: U1 magnet block 3D cad model transparent view from above (cf. Fig. 2), close-up on DIP, with field map area sketched in place (purple).

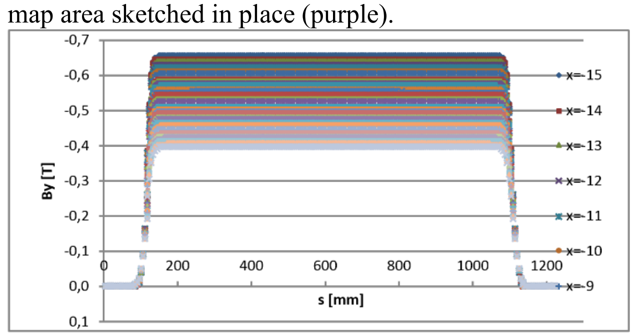

Figure 4: U1#03 DIP Hall probe measured $B_y(s)$ for x = -15, -14, …, +15 mm (total 7688 data points), at nom. I.

The field maps were analyzed by subdividing into 12 longitudinal slices and calculating slice average $B_y(x) = \mathrm{int}B_y(x,s)ds/\text{slice length}$, then applying a 3rd order polynomial fit[12] over x = ±11 mm for each slice. Sum of slices results per type are listed in Table 2 below, and an example plot of slice longitudinal distribution is shown in Fig. 5. What this plot shows is that the DIP average deviation in focusing strength comes mainly from that the bulk gradient differs from nominal. The total difference (listed in Table 2) is however well within the adjustment capability of the pole face strips (see Table 1).

Table 2: Hall probe results per magnet type, integrated strength series average at nom I.[13], and int. B' difference[14] to nominal [4], series spread.

magnet	No [pcs]	block	int B [Tm]	int B' [T]	int B' diff. to nom. avg. [%]	min. [%]	max. [%]	rms [%]
DIP	80	U1,2,4,5	-0.522	8.529	0.20	-0.07	0.43	0.11
DIP	20	U3	-0.523	8.529	0.22	-0.24	0.44	0.15
DIPm	40	M1,2	-0.263	4.244	0.31	0.13	0.51	0.09

[11] Or in the case of DIPm, constant radius through the bulk part and another constant radius (double) through the soft end part.

[12] Residual between measured and fit is generally < 1 G, ie. there is no significant higher order content above n = 4.

[13] With nominal current levels adjusted after preliminary measurements on first magnets produced, then kept the same through whole series. Ie, not identical to the specified nominal current levels in [6].

[14] With measured values scaled to series average int B = nom. bend angle.

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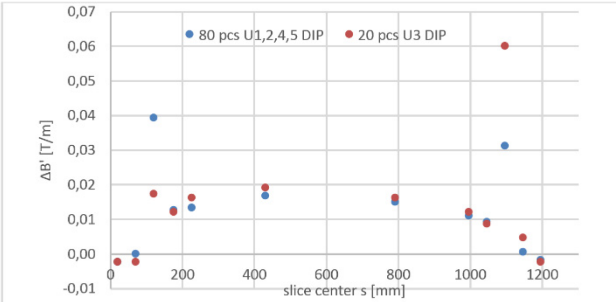

Figure 5: DIP Hall probe meas. series average[14] difference to nominal B' per slice, as function of slice long. position. Differences are largest in the fringe slices (cf. Fig. 4).

Rotating Coil

The presence of higher order harmonic content error terms is exemplified by Fig. 6, showing series spread for one magnet type. This distribution is typical in that the error terms directly above the main term are the largest, and that the "allowed" terms can be seen ≠ 0. The values of the largest higher order term per magnet, series min/max and rms, are listed per magnet type in Table 3. The min/max are generally within expected for worst case displacements of the individual poles within the mechanical tolerances, given the pole radius of 12.5 mm.

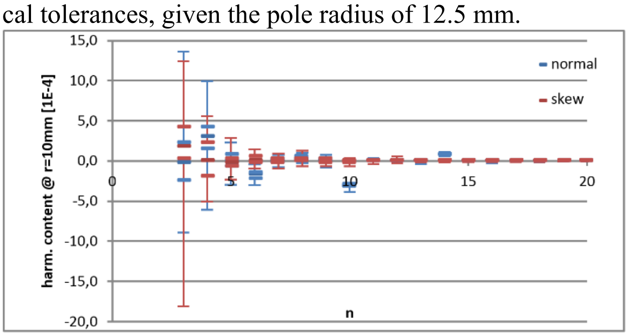

Figure 6: harmonic content higher order terms, boxplot of rotating coil meas. data for 80 pcs U2/U4 QF at nom I.

Table 3: Rotating coil results per magnet type, strength of main term series average, and largest higher order term (in 1E-4 of main term at r = 10 mm) series min/max/rms.

magnet	No [pcs]	block	int. strength at nom I.	harm. cont. [1E-4] min	max	rms
QFend	40	M1,2	-8.209 T	-10.4	7.3	3.0
QDend	40	M1,2	6.032 T	-9.6	8.0	3.1
QFm	80	U1,5	-5.918 T	-16.0	11.0	4.2
QF	80	U2,4	-6.117 T	-18.1	13.6	4.4
QF	80	U3	-6.250 T	-8.4	8.5	3.1
SDend	40	M1,2	182.1 T/m	-17.5	17.6	6.5
SFm	40	U1,5	-180.0 T/m	-19.6	23.9	10.9
SD	160	U1,2,4,5	126.8 T/m	-42.2	35.5	9.8
SD	40	U3	130.0 T/m	-19.4	18.3	6.2
SFo	40	U2,4	-187.1 T/m	-25.4	44.5	12.3
SFi	40	U3	-211.7 T/m	-17.2	8.4	5.5
OXX	38	M1,2	3230.9 T/m^2	-22.4	29.4	9.3
OXY	38	M1,2	-6497.1 T/m^2	-26.8	34.6	9.0
OYY	40	M1,2	2793.2 T/m^2	-13.3	14.5	4.7
corr x	200	all	3.8 Tmm			
corr y	178	all	-3.7 Tmm			

Additional Field Measurements

After production series completion, a few magnet blocks were kept at the supplier's for extra characterization, mainly

- Cross talk tests – levels generally agreeing with [5]
- Hall probe – re-measuring magnet blocks from one supplier at the other supplier's mapping bench.

This concluded the 3 GeV ring magnets field measurement campaign.

STATUS

3 GeV storage ring installation followed through fall of 2014 to spring 2015, with magnet subsystem testing completed mid-2015. Ring commissioning then started in August, with early highlights being

- Aug 11 beam through transfer line
- Aug 25 first turn
- Sept 15 stored beam 0.1 mA
- Oct 8 stacking 4 mA
- Jan 31 120 mA

From the magnet point of view, these milestones were noteworthy in that first turn was achieved without using any correctors (all set to 0 A), and with all other magnets set to lattice nominal current levels calculated from the field measurements made by the suppliers.[15] More turns and then stored beam were achieved with correctors manually adjusted but other magnets still at the calculated current levels.

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[15] without any cross-calibration between the two suppliers (although additional measurements exist from which this could be done). And without any shunting (see [3]) of individual magnet strengths.

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