MAX IV AND SOLARIS 1.5 GeV STORAGE RINGS MAGNET BLOCK PRODUCTION SERIES MEASUREMENT RESULTS

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Abstract

The magnet design of the MAX IV and Solaris 1.5 GeV storage rings replaces the conventional support girder + discrete magnets scheme of previous third-generation synchrotron radiation light sources with an integrated design having several consecutive magnet elements precision-machined out of a common solid iron block, with mechanical tolerances of ±0.02 mm over the 4.5 m block length. The production series of 12+12 integrated magnet block units, which was totally outsourced to industry, was completed in the spring of 2015, with mechanical and magnetic quality assurance conforming to specifications. This article presents mechanical and magnetic field measurement results of 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 Solaris National Synchrotron Radiation Centre, located in Krakow, Poland, consists of a 1.5 GeV storage ring identical to the MAX IV 1.5 GeV ring, and a 600 MeV injector linac [2]. These 1.5 GeV rings have a double bend achromat (DBA) lattice, consisting of 12 achromats, with a circumference of 96 m.

Each DBA is realized as one integrated "magnet block" (example photo shown in Fig. 1) conceptually identical to the MAX IV 3 GeV ring magnets [3], so that the ring consists of 12 such units, containing a total of 156 magnet elements.[1] The different magnet element types that are present in the magnet blocks are listed in Table 1. Detailed magnet design was made using the Opera-3d FEM code [4], with a model of the full magnet block being simulated (see Fig. 2). The magnet design was iterated against the lattice design [5], with the final magnet design that went into production being the 4th iteration [6].

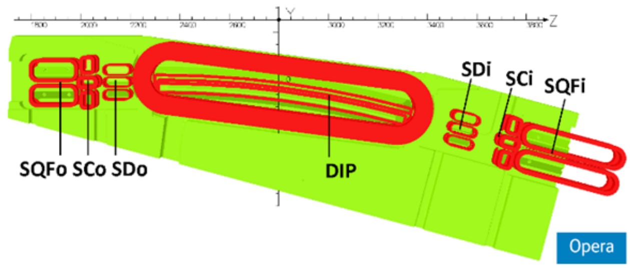

Figure 2: Opera-3d model "MAXIV1,5GeVmagnetblock, MJ130711-36.opc",with magnet element names indicated.

Table 1: List of 1.5 GeV Ring Magnet Elements, with Nominal Field Strengths from Design Lattice [5].

magnet	No [pcs]	l [m]	r_{pole} [mm]	B [T]	B' [T/m]	B''/2 [T/m^2]
DIP [2]	24	1.19	14	-1.310	6.749	
pfs					±5 %	
SQFo	24	0.2	17.5		-28.71	-219.5
SQFi	12	0.4	23.5		-25.03	-142.4
SDo	24	0.1	25.5			510.1
SDi	24	0.1	25.5			370.7
SCo	24	0.05	18.6			32.0
corr x				±0.25 mrad		
corr y				±0.25 mrad		
skew q					-3.6	
SCi	24	0.07	24.5			67.2
corr x				±0.25 mrad		
corr y				±0.25 mrad		
skew q					-2.145	

Specification and Procurement

The 1.5 GeV ring magnet block procurement was similar to the preceding MAX IV 3 GeV ring magnet procurement [3], with a supplier being responsible for mechanical tolerances and for performing field measurements according to MAX-lab instructions, and MAX-lab being responsible for field measurement results, but with

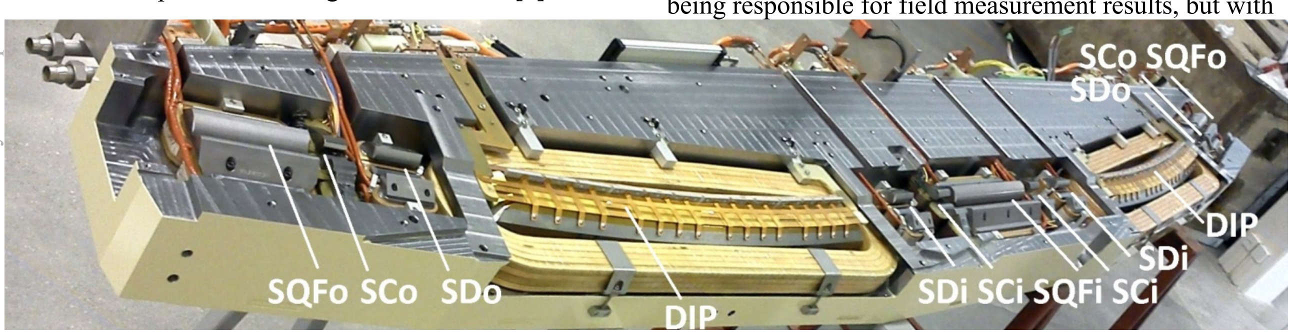

Figure 1: 1.5 GeV ring DBA magnet block #023 bottom half, with magnet element names indicated.

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[1] 300 elements if counting SCo/SCi x, y, and skew q windings separately.

[2] DIP is defined in the lattice as consisting of 30 longitudinal slices, total length = 1.19 m (effective l. = 1 m). Fields stated here are central slice.

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the difference that for 1.5 GeV the supplier did part of the mech. design (coil exits leads, cabling and cooling water distribution) and all manufacturing drawings, based on instructions in the technical specification [7] and intermediate drawings from MAX-lab defining all tolerances and yoke subdivision in parts. Another difference was that mechanical tolerances for quad and sextupole pole surfaces were defined in situ per yoke bottom/top block, instead of as separate pieces (with tolerance stack-up) for 3 GeV.[3]

The contracts for both MAX IV and Solaris were awarded to one supplier, Danfysik[4], so that the 12 + 12 magnet blocks for both facilities constituted one production series, completed in the spring of 2015.

YOKE MACHINING RESULTS

The manufacturing methods used were conventional 3-axis CNC milling for the yoke bottom/top blocks[5], and wire erosion for the quad and sextupole pole pieces. Each yoke half was 3D measured (see Fig. 3), verifying the mechanical tolerances over the whole 4.5 m block length.

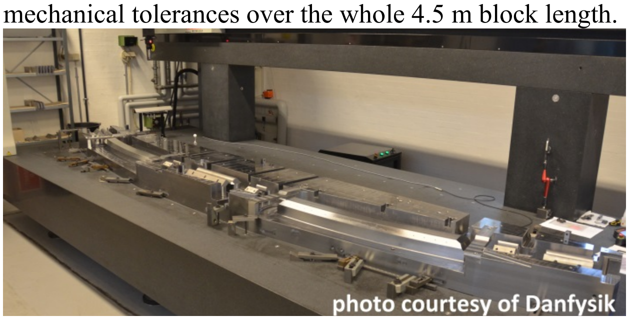

Figure 3: Yoke half in the 3D coordinate meas. machine.

Table 2: Summary of Mechanical Measurement Results, Per Function Critical Surface Category, for the Full Production Series of 48 Yoke Bottom and Top Blocks.

feature	No [pcs]	evaluation	tolerance [mm]	min. [mm]	max. [mm]	rms [mm]
midplane	48	flatness	0.05	0.021	0.049	0.037
SQFo	96	surface shape[6]	0.04	-0.020	0.020	0.010
SDo	94[7]	surface shape	0.06	-0.044	0.044	0.017
DIP	96	surface shape	0.04	-0.021	0.026	0.015
SDi	92[7]	surface shape	0.06	-0.038	0.042	0.018
SQFi	48	surface shape	0.04	-0.024	0.020	0.013

FIELD MEASUREMENT RESULTS

To provide the field meas. data required in the technical specification, the supplier used the same Hall mapping bench as was previously used for MAX IV 3 GeV ring magnets, and again like for 3 GeV chose the solution of several longitudinally spaced meas. coils in a common rotating shaft for rotating coil access inside magnet blocks [8]. No measurements were done at MAX-lab nor Solaris.

Spread in Field Strength

Measured spread in field strength is listed per magnet type in Table 3. A coarse estimate on expected spread of the main field component, given by taking Table 2 pole shape tolerances as max-min variation on the Table 1 pole radii, and calculating the corresponding spread in field strength by Ampere's law, is also listed for comparison.

Table 3: Hall Probe (DIP) and Rotating Coil (others) Results, Integrated Strength Series Average and Spread at Nom.[8] Current, for the Full Series of 24 Magnet Blocks.

magn	No [pcs]	int. strength at nom. I	est. [%]	min. [%]	max. [%]	rms [%]
DIP	47[9]	-1.313 Tm	±0.14	-0.12	0.12	0.07
		6.768 T		-0.36	0.38	0.17
SQFo	48	-5.861 T	±0.23	-0.29	0.43	0.13
		-45.42 T/m		-0.69	0.56	0.27
SQFi	24	-10.14 T	±0.17	-0.14	0.16	0.08
		-58.04 T/m		-0.40	0.30	0.18
SDo	48	51.70 T/m	±0.35	-0.29	0.19	0.10
SDi	48	37.83 T/m	±0.35	-0.32	0.39	0.19
SCo	46[10]	5.08 T/m [11]		-0.81	0.63	0.36
x	48	1.18 Tmm				
y	48	-1.25 Tmm				
sk q	48	-0.183 T		-0.59	0.50	0.26
SCi	48	4.75 T/m		-0.96	0.82	0.46
x	48	1.17 Tmm				
y	48	-1.24 Tmm				
sk q	48	-0.147 T		-0.43	0.36	0.22

The measured min-max roughly agrees with the expected, meaning that we see no clear indication of additional spread in field strength from material properties.

Combined Function Magnets

For DIP, SQFo and SQFi, a key requirement is correct ratio of the main and combined function field terms.

Table 4: Results from Table 3 Scaled to Main Term = Nominal, Showing Combined Term Diff. to Nominal.

magn	No [pcs]	int. strength scaled	difference to nominal [%] avg.	min.	max.	σ
DIP	47[9]	6.756 T	0.09	-0.25	0.48	0.17
SQFo	48	-44.49 T/m	1.37	0.68	1.95	0.27
SQFi	24	-57.31 T/m	0.66	0.26	0.96	0.18

The series average indicates the level of agreement between the Opera-3d model and measurements. It can be noted that in these designs, in most of the pole volume, the magnetic field B is larger than 1 T, for DIP up to 1.7 T on the pole face [6]. The field meas. results from magnet block #001 were accepted as is[12] without any change to pole designs, meaning that all our results are the outcome

[3] Except SCo/SCi, with coarser tolerances, defined per pole piece.
[4] Danfysik A/S, Taastrup, Denmark, contract awarded fall of 2012.
[5] Raw yoke blocks, ARMCO Pure Iron grade 4 (C < 0.01%), 5 m long, were purchased in advance by us and free issued to the magnet supplier.
[6] The mech. tolerance called "surface shape" is defined as 2x amplitude of largest deviation within the tolerance zone, ie 0.04 means ±0.02 mm.
[7] Excl. yoke top #001 and bottom #024 which had outlier data points at edge of SDo/SDi tolerance zones, of up to +0.06 mm, that were accepted.

[8] At nominal current levels stated in [7], except DIP, adjusted after #001 measurements, and except SCo/SCi, updated to agree with [6].
[9] Excl. one outlier, magn. block #002 DIP2 with scaled Δint B' = +0.77 %
[10] Excl. two outliers, block #001 SCo1 and SCo2, at +2 % from average.
[11] Significantly stronger than lattice requirement (Table 1) due to magnet design using previous iteration values by mistake [6].
[12] The DIP average gradient deviation is well within the adjustment range of the pole face strip (pfs) circuit, and the SQFo/SQFi average sextupole deviation are assumed to be easily compensated by adjusting SCo/SCi.

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of a production series executed directly from Opera-3d modeling, without any intermediate prototyping.

Field Quality

For the dipoles (DIP), the Hall probe field maps were analyzed by subdividing into 30 longitudinal slices and applying a 4^{th} order polynominal fit to each. The integrated strength results listed in Table 3 are sums of slices, and this analysis also provided higher order terms series (48 pcs) min-max = -0.13–1.65 T/m, -127.9–0.6 T/m^2 and 5629–8666 T/m^3, which agree nicely with Opera-3d = 1.16 T/m, -89.6 T/m^2 and 8070 T/m^3 [6], respectively.[13]

For the other magnet elements, measured by rotating coil, we summarize series harmonic content in Table 5 by listing the largest higher order term σ, indicative of average mechanical deviations, and largest min/max, resulting from both worst mechanical deviations and systematic error terms. The Fig. 4 example is typical in that the error terms directly above the main have the largest spread, and that the average values agree fairly well with Opera-3d.

For the sextupoles the Table 5 min/max are dominated by larger systematic error terms in the design. Especially for SCo/SCi, where relative field purity was traded for design compactness, since these are weak magnets.

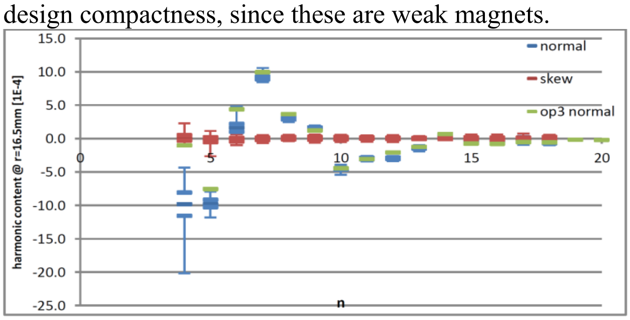

Figure 4: harmonic content higher order terms, boxplot of rotating coil measurement data for 48 pcs SQFo at nominal current, together with Opera-3d values [6].

Table 5: Rot. Coil Results, Largest Higher Order Term Series Min/Max/σ (in 1E-4 of Main Term at r_{ref}).

magnet	No [pcs]	at r_{ref} [mm]	harmonic content [1E-4] min.	max.	σ
SQFo	48	16.5	-20.2	10.6	2.7
SQFi	24	22	-10.7	7.2	2.4
SDo	48	24	-48.1	16.6	3.6 [14]
SDi	48	24	-51.3	19.5	4.2
SCo	48	16.5	-277.9	156.7	16.3
SCi	48	22	-132.0	110.4	18.1

Alignment

Magnet to magnet alignment within the blocks has been evaluated in the same way as for MAX IV 3 GeV [9], but the results are less conclusive since the SCo/SCi appear to have a systematic sideways shift[15] of ca -0.05 mm, giving large dx values in Table 6. If the SCi are ignored, the relative alignment accuracy is similar to 3 GeV.

[13] These error terms, mainly fringe fields, were accepted at design stage.
[14] Excluding skew n=6, which is present as a remanent field of opposite sign for SDo1 and SDo2, of ca ±10 1E-4. Unknown if real or artifact.
[15] Unknown if real or artifact, but we did not prioritize investigation, since if real, impact is anyway negligible (SCo/SCi are weak magnets).
[16] Includes rotating shaft sag under own weight, cf [9].

Table 6: Rotating Coil Results Per Group of Consecutive Magnet Elements (cf. Fig. 1), Relative Alignment.

elements	length [mm]	No [pcs]	rel. align.	min. [µm]	max. [µm]	rms [µm]
SQFo-SCo-SDo	250	24	dx	-71	38	25
			dy	-22	23	9
SDi-SCi-SQFi-SCi-SDi	880	24	dx	-67	45	60
			dy[16]	-45	47	37
SDi–SQFi–SDi	*880*	*24*	*dx*	*-14*	*26*	*12*
SQFo-SCo-SDo	250	24	dx	-75	40	30
			dy	-42	22	12

Cross Talk

We did not specify any thorough characterization of cross talks in these magnet blocks. Attempting a coarse check by hand held Hall probe in situ at MAX IV, for one example case SDo(DIP) we measure ca +3 G at magnet center, which is same sign but much weaker than Opera-3d +22 G [6], so as of yet results are inconclusive.

STATUS

Solaris ring commissioning began May 2015 [10] and scheduled user operation will begin Jan 2017.

MAX IV 1.5 GeV ring commissioning is a few weeks in progress and at the time of writing (late Sept) 1.6 mA stored beam has just been achieved.

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