MAX IV 3 GeV STORAGE RING PROTOTYPE MAGNET

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Abstract

The MAX IV synchrotron radiation facility, currently under construction, will consist of a 3 GeV storage ring, a 1.5 GeV storage ring, and a full energy linac injector/SPF/FEL driver. The magnet design for the 3 GeV storage ring is conceptually identical to the MAX III storage ring magnets [1], with all magnet elements within each cell machined out of one solid iron block. A prototype of a matching cell magnet block has been manufactured and mechanical and magnetic field measurements have been performed.

THE MAX IV 3 GeV STORAGE RING MAGNET DESIGN

The MAX IV 3 GeV storage ring consists of 20 achromats. Each achromat consists of five unit cells and two matching cells. A schematic is shown in Fig. 1.

The different magnet types were designed using FEMM for 2D simulation and Radia for 3D simulation. [2] The 3D simulations were made for the dipoles and quadrupoles as standalone magnets (i.e. not in a common iron block). An example Radia model is shown in Fig. 2. The dipole simulation was evaluated as longitudinal slices, which were used as basis for iteration between lattice design and magnet design.

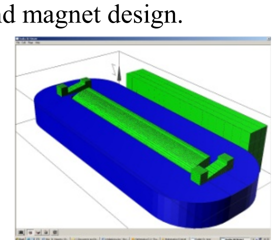

Figure 2: Radia model of the "DIPm" gradient dipole, located in the matching cells. Part of the pole is a soft end with an air gap beneath.

After lattice and magnet design had converged, 3D CAD models of the magnet blocks were made taking the FEMM/Radia models and extending the return yokes longitudinally to form a common yoke block, one for each cell. An example is shown in Fig. 3.

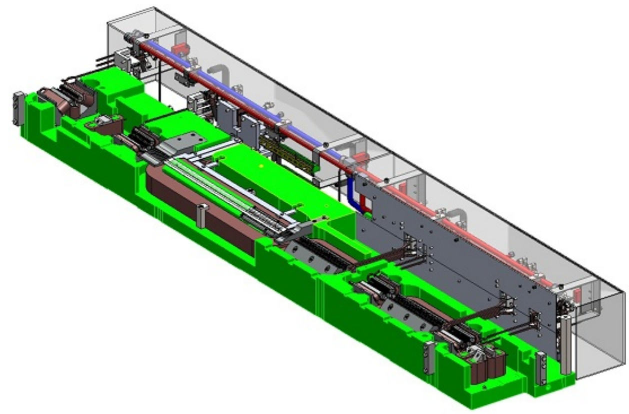

Figure 3: 3D CAD model of a matching cell magnet block, ca 2.3 m long. The yoke bottom, marked green, is machined from a single piece of iron.

THE PROTOTYPE MAGNET BLOCK

One prototype of the matching cell (mc) magnet block has been manufactured. A photo is shown in Fig. 4.

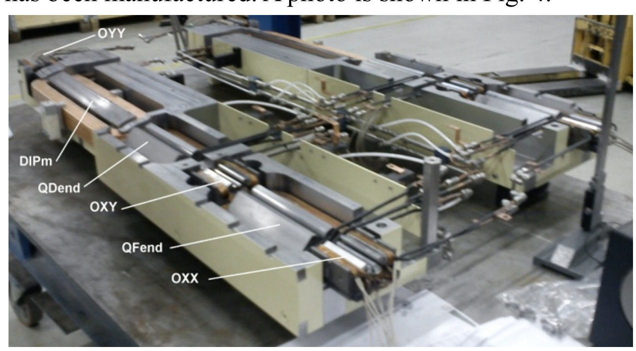

Figure 4: mc prototype magnet block, top and bottom halves disassemled. The prototype represents an earlier version of the mc magnet block design, without the SDend sextupole and the correctors.

The Yoke Block Halves

For the 3 GeV ring magnets, the most challenging parts are the bottom/top yoke halves. A photo of the prototype yoke bottom is shown in Fig. 5.

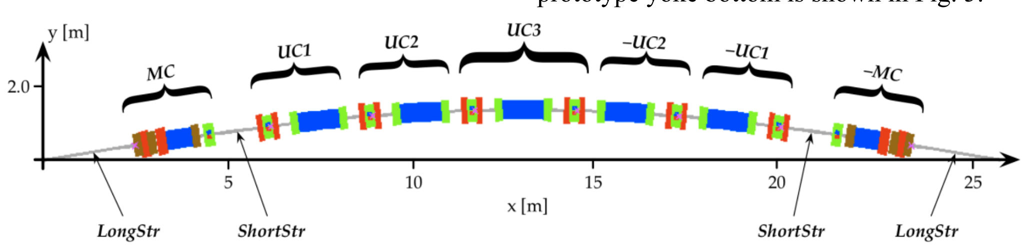

Figure 1: Schematic of one achromat of the MAX IV 3 GeV storage ring.

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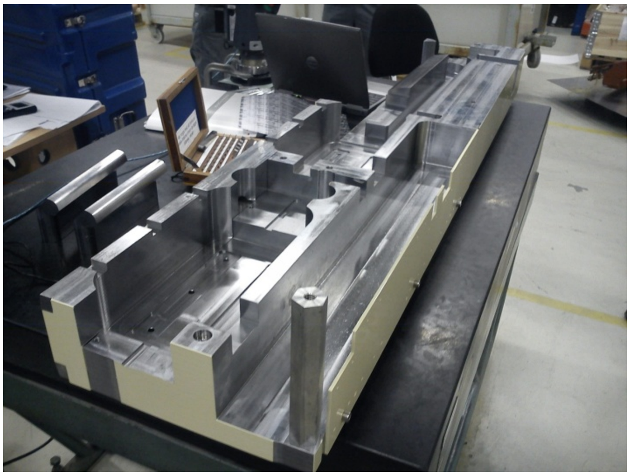

Figure 5: prototype yoke bottom.

The dipole poles are machined directly out of the iron block. The quad poles are loose pieces that are assembled into guiding slots in the yoke block. 6pole and 8pole magnets are designed as standalone magnets (see Fig. 6), with position in the block determined by guiding slots.

Figure 6: prototype octupole yoke half with three poles and one coil assembled. On the bottom side of the return yoke is a step that fits in a guiding slot in the yoke block.

The alignment in transverse and longitudinal direction of the top yoke block half to the bottom yoke block half is determined by reference surfaces on two outer corners of the blocks. It thus follows that the critical manufacturing tolerances for the yoke bottom and yoke top blocks are

- Transverse position of the guiding surfaces relative to the outer reference surfaces
- Vertical position of the guiding surfaces relative to the mid plane
- Flatness of the mid plane
- Dipole pole profile relative to outer reference surfaces/midplane.

since these features determine the alignment of the magnetic centres within the magnet block and also the field quality for each magnet element.

Manufacturing

The prototype yoke bottom and yoke top were CNC-milled out of low carbon steel blocks. The low carbon steel blocks were purchased to specified chemical composition and delivered flame cut to specified size, followed by heat treatment for magnetic properties. The blocks were then machined using a conventional 3-axis CNC mill. Prior to this, a dummy yoke block was machined out of regular mild steel to verify correct programming and for testing of the machining method.

For the above listed critical tolerances, a tolerance level of ±0.01 mm was specified in our manufacturing drawings, as representing what we believe to be the limit of what is achievable using conventional CNC milling.

Mechanical measurement results

Mechanical dimensions of the prototype yoke bottom and yoke top were checked using a 3D coordinate measurement machine. Results for the above listed critical surfaces are listed in table 1.

Table 1: prototype bottom/top yoke measured mech. deviation, peak to peak spread [mm] of all data points per surface category. Rep. twice for both yoke halves. [3]

feature		bottom meas#1	bottom meas#2	top meas#1	top meas#2
left guiding		0.031	0.035	0.041	0.021
right guiding		0.038	0.043	0.041	0.032
vert guiding		0.036	0.038	0.031	0.026
mid plane		0.026	0.052	0.031	0.027
DIPm pole[#],	entrance	-	-	0.026	0.023
	mid	-	-	0.023	0.019
	exit	-	-	0.018	0.014

[#] difference between top and bottom.

The tolerance that was specified on the prototype manufacturing drawings, ±0.01 mm, corresponds to 0.02 peak to peak. The measured is generally 100-200 % of this tolerance. We thus consider the prototype to be a demonstration that a ±0.02 mm tolerance level is feasible for the 3 GeV ring production series. This is also the tolerance level that was achieved in the MAX III production series of 8 magnet blocks. [4]

FIELD MEASUREMENT

The "DIPm" Gradient Dipole

The DIPm was measured by Hall probe, taking a map of B_y-points in the mid plane over ca 750 mm along the s-direction and ±15 mm in the x-direction. The map was evaluated in the same way as the Radia simulation – by calculating $\int B_y(x)ds$ within twelve longitudinal slices, followed by polynomial fit. Results are listed in table 2.

We see that the central (slice dm0) gradient is close to the Radia value, but the fringe slices differ by more. The measured slices were given to lattice design, resulting in a very minute change of the specified gradient in the dipoles. The resulting change to the DIP/DIPm pole profile is put directly into the series production drawings.

Table 2: magnet element DIPm, dipole and qpole content per slice, in Radia, prototype meas. and Opera3D. [3]

slice	Radia [T]	meas. [T]	Opera3D [T]	Radia [T/m]	meas. [T/m]	Opera3D [T/m]
dm6	-0.0078	-0.0037	-0.0043	0.0052	0.0675	-0.0623
dm5	-0.1871	-0.1748	-0.1769	2.9384	2.7146	2.7785
dm4	-0.2595	-0.2574	-0.2666	4.2438	4.2516	4.4078
dm3	-0.2698	-0.2626	-0.2639	4.3088	4.2560	4.2676
dm2	-0.4070	-0.3964	-0.4001	6.0952	5.8501	5.8890
dm1	-0.5211	-0.5236	-0.5225	8.5802	8.6908	8.6719
dm0	-0.5241	-0.5241	-0.5241	8.6868	8.6958	8.7104
df1	-0.5238	-0.5239	-0.5243	8.6979	8.6961	8.7140
df2	-0.5230	-0.5235	-0.5241	8.6904	8.7048	8.7213
df3	-0.3767	-0.3529	-0.3538	5.9359	5.5521	5.5625
df4	-0.0187	-0.0055	-0.0062	-0.0645	-0.1203	-0.1215
df5	-0.0054	-0.0003	-0.0003	-0.0012	-0.0019	0.0026

Quadrupoles and Octupoles

Rotating coil measurements of the quads and 8poles did not indicate any showstoppers. Hall probe $B_y(s)$ indicated 8pole $L_{eff} \approx 101$ mm, i.e. close to the nominal 100 mm, but for the quads, the measured $L_{eff} \approx 244$ mm differs more than we had expected to the nominal 250 mm. No subsequent change of the magnet design has been made.

Cross Talk

The mc prototype magnet block was tested for cross talk by powering one magnet element at a time from 0 to max to 0 while logging stationary Hall probes located in the adjacent magnet elements. The only cases for which we saw a correlation between applied current and measured field were QDend(DIPm) and OYY(DIPm). Both were ca 6 G at DIPm nom. I. QDend was also measured with rotating coil indicating the cross talk to be a dipole field of ca 10 G, plus a weak 6pole content of ca 2 T/m^2. These cross talk fields were considered to be acceptable, since they are static [5], so no resulting changes has been made to the magnet design.

OPERA3D FIELD SIMULATION

An Opera3D model of the mc prototype magnet block has been made, by importing the 3D CAD file of the yoke and adding the coils in the Opera 3D modeller. The model is shown in Fig. 7. Field simulation has been performed for the DIPm, QDend and QFend magnet elements. The DIPm field has been evaluated in the same way as the Radia simulation and the prototype measurement data. Results are listed in table 2. As shown in Fig. 8, the Opera3D simulation is quite close to the measured in the exit fringe region. In the soft end slices there is a larger difference, but not in the same trend as the Radia difference. We have noted that in Opera3D that part of the pole is completely saturated (see Fig. 9).

For the quads, simulated $L_{eff} \approx 244$ mm, i.e close to the measured.

Cross talk has also been tested in Opera3D. The simulated QDend(DIPm) cross talk is 4 G dipole plus 3 T/m2 sextupole, which is order of magnitude consistent with the prototype measurements.

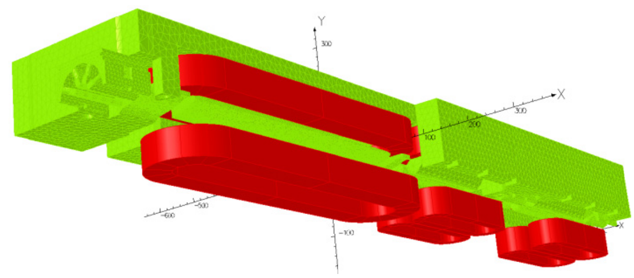

Figure 7: mc prototype Opera3D model.

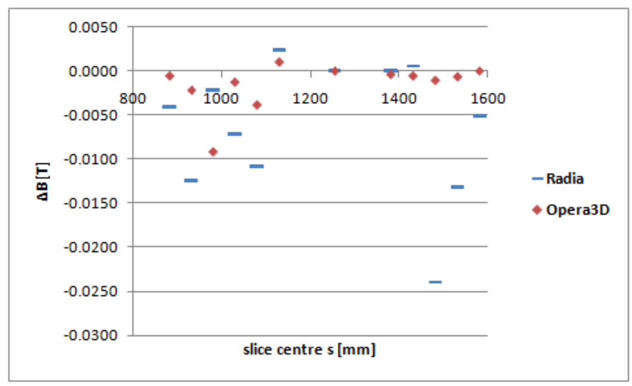

Figure 8: From the table 2 data, measured - simulated dipole content per slice, as function of slice longitudinal position. (dm6 at s=881 to df5 at s=1581).

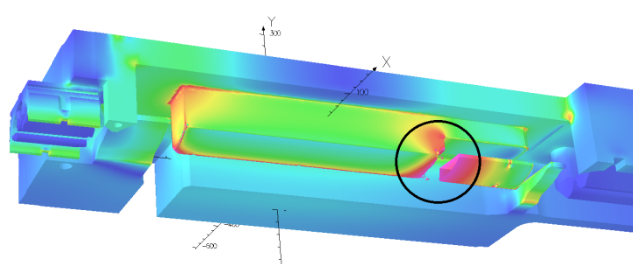

Figure 9: Opera3D, B field in the iron surface. Colour scale: 0-2 T. At the soft end, part of the iron is above 2T.

REFERENCES

[1] M. Sjöström et al. Nucl. Instr. & Meth. A 601 (2009)
[2] MAX IV Detailed Design Report, http://www.maxlab.lu.se/maxlab/max4/index.html
[3] MAX-lab internal report "mc prototype project - results summary, MJ110629"
[4] B. Anderberg (private communication).
[5] P. Fernandes-Tavares (private communication)