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HALL PROBE MEASUREMENTS OF 80 UNIT CELL MAGNETS FOR THE MAX-IV STORAGE RING

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Abstract

80 unit cell magnet segments have been manufactured by Scanditronix Magnet for the 3 GeV storage ring at MAX-IV in Lund, Sweden. All of the magnets have been approved by Max-lab after a large field measuring campaign using both a high precision Hall probe bench, as well as a new rotating coil system. Each unit cell magnet consists of one dipole, two quadrupole, three sextupole and one vertical and one horizontal corrector magnets. The Hall probe bench was used to measure the dipole magnet (with combined dipole and quadrupole component) as well as the quadrupole magnets. This paper will focus on the Hall probe measurements performed on the dipole magnets from the perspective of a manufacturer. E.g. the repeatability of the measurements and the relation between field performance and mechanical tolerances will be analysed.

MAX-IV

MAX-IV aims to be the new centre for synchrotron light in Sweden, and will be the replacement of the smaller MAX-II and MAX-III storage rings. The accelerator complex will consist of a linac and two storage rings (see Fig. 1), with the larger one having a circumference of 528 m and electron energy of 3 GeV. The concept is similar to that of the MAX-III accelerator, focusing on a compact magnet design, with combined function magnets. Also with separate magnetic elements built into the same iron block. This keeps the overall dimensions of the magnets down, as well as simplifies the alignment of the magnets [1].

The entire 3 GeV storage ring contains 20 achromats, with each achromat consisting of two matching cells and five unit cells. The cells contain one dipole magnet each which gives the storage ring the advantages of a multi-bend achromat lattice, which lowers the electron beam emittance. It also has the benefits of increasing the energy acceptance, as well as improves the dynamic aperture [2].

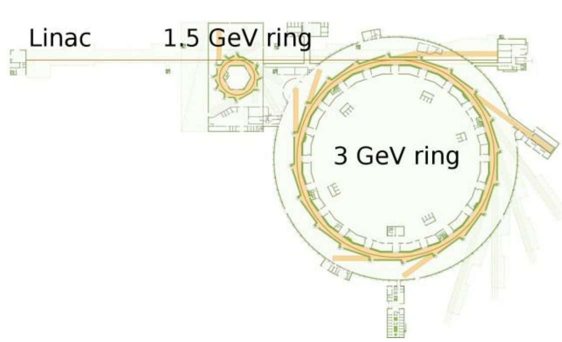

Figure 1: An overview of the MAX-IV accelerator complex. Courtesy of MAX IV Laboratory.

Scanditronix has produced four of the five unit cell families (U1, U2, U4 and U5) as seen in Fig. 2. The magnets contained in the U1 and U5 cells are identical, and U2 and U4 as well, the only difference is that the cells are mirrored versions of each other. However, all four families contain the same dipole magnet.

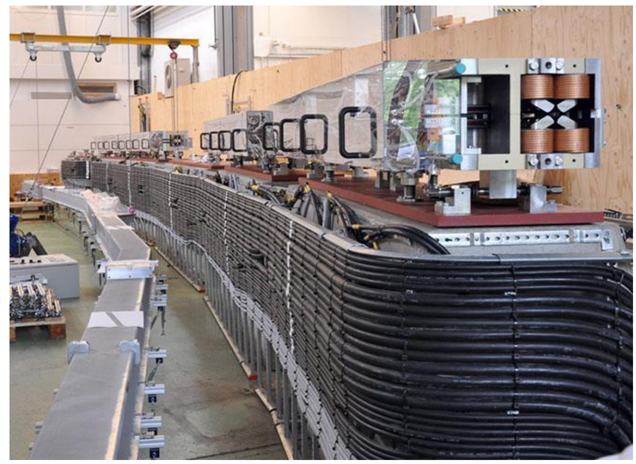

Figure 2: Image of one achromat (mock-up). Courtesy of MAX IV Laboratory.

Scanditronix Magnet selected two subcontractors for the machining of the iron blocks to keep the tight time schedule for the project. One company produced the U1 and U2 segments, and the other produced the U4 and U5 segments. It is seen from the results of the field measurements that there are no significant difference between the magnets machined at the two subcontractors.

HALL PROBE BENCH

Scanditronix Magnet acquired a new state-of-the-art Hall probe mapping bench (see Fig. 3) to meet the high precision in measurements that was required by Max-lab. This is located in a temperature controlled room where the magnets were stored until correct measuring temperature was achieved. The base of the measurement system is a 3D coordinate measuring machine (CMM) of portal type from Hexagon Metrology. This is built on a flat table of solid granite, to ensure a horizontal placement of the magnets, as well as a good resistance against vibrations.

The CMM has been equipped with a Hall probe and teslameter from Group3, with an absolute accuracy of ±0.01% of reading ±0.006% of range [3].

The CMM has a volumetric measuring range of 3000x1200x1000 mm, and an accuracy of about 5 μm per

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meter, which makes it very suitable for the measurements of the over 2.4 m long magnet block.

Figure 3: The Hall probe mapping bench.

After machining of the iron the five fiducial spheres on the yoke top surface were measured by the subcontractor in the coordinate system of the magnet block. Prior to the field mapping, the fiducial spheres where measured with the mechanical probe of the Hall probe bench, which then performed a standard best fit algorithm to align itself to the magnet block. This made it possible to measure the field using the same fiducials that are then used for the actual installation of the magnet in the storage ring.

The original idea was to measure directly on the fiducial surfaces located on the sides of the iron block, which were used as reference for the machining and the measurement of the spheres at the sub-contractor. However, this would have introduced another source for error when comparing the coordinate system used for the field measurements to the actual alignment of the block in the storage ring.

OFFSET MEASUREMENTS

The offset between the mechanical probe and the Hall probe is determined by measurements over a fine machined magnetic cone (see Fig. 4). The actual cones are machined out of low carbon steel to increase the precision in the machining. These are then fitted to a strong permanent magnet as the source for the field. This approach was chosen since it is more difficult to machine the ceramic magnet than the steel.

To ensure that the results were reliable, a number of tests have been performed; among others a rotation of the entire stand to see that there was no tilt that would affect the measurements. During each offset measurement, the cone is also rotated 360° with steps of 90° and the result is then averaged to eliminate specific errors that could be caused by the shape and magnetisation of the cone.

The results were then analysed by fitting a polynomial over the data, and finding the zero of the derivative. This turned out to be much more accurate and faster than to simply look for the point with highest field strength.

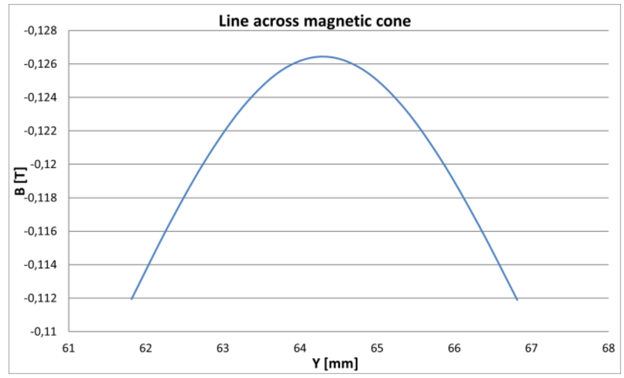

Figure 4: The field across the magnet cone in Y direction.

The final results are very repeatable, and the short term variation lies in the range of < 5 µm in any direction (see Table 1), which is well below the requested accuracy of the measurements.

Table 1: Repeated Offset Measurements

Measurement	X [mm]	Y [mm]	Z [mm]
1	519.103	63.912	-105.789
2	519.104	63.915	-105.789
3	519.103	63.916	-105.789

The customer did not set any demands on how often this procedure should be repeated, but to not risk having to re-measure too many magnets if something would change the offset, it was internally decided to perform the measurements once a week.

MEASUREMENTS OF THE GRADIENT DIPOLE

An additional magnetic cone was also placed on top of the magnet block before the measurements started. After aligning the Hall probe bench, the field was measured along two lines in the horizontal plane above the cone to find the coordinates of the centre. This was then repeated after the field measurements to verify that neither the magnet nor the Hall probe had moved during the measurements.

Scanditronix also made a zero-field chamber out of mu-metal in which the Hall probe was zeroed before each magnet block was measurement, and then controlled afterwards to verify that there had been no significant drift of the readings.

The dipole in each magnetic segment is a combined function magnet with a quadrupole component, with a cross section shown in Figure 7. It is measured in a curved linear coordinate system and is presented as a complete field map with a transverse step size of 1 mm and a longitudinal step size of 5 mm. From this data, the integrated fields and central fields are calculated using polynomial fits.

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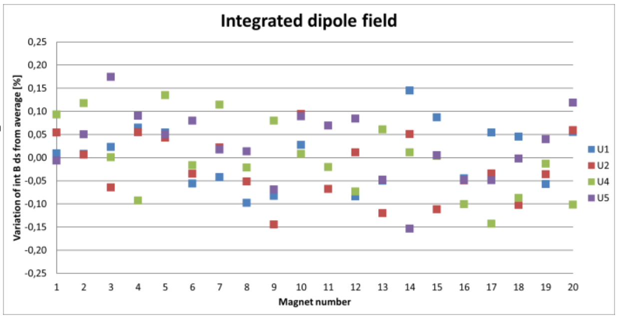

Figure 5: The variations from the average integrated dipole field for the 80 magnets.

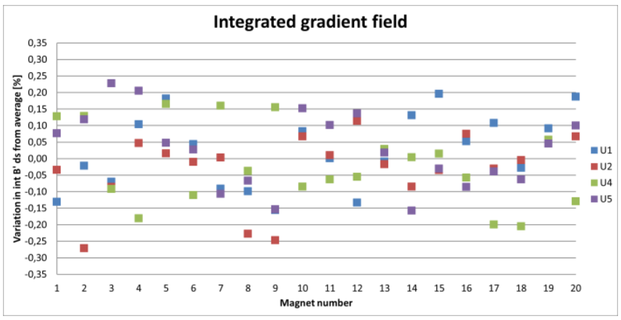

Figure 6: The variations from the average integrated quadrupole field for the 80 magnets.

The integrated dipole field has a variation of ±0.16% over all magnets as can be seen in Fig. 5, with a standard deviation of 0.07%. The field at the centre of each magnet has almost an identical variation and standard deviation, which could indicate that this is caused by the pole profiles. We can estimate the variation in pole gap that would result in a change of field similar to this since the nominal gap is known to be 28 mm, and the field strength should be linear to the pole gap. By using simple calculations, we can estimate that the variation of ±0.16% could be caused by a change in pole gap of ±0.04 mm, resulting in a variation of each pole face of ±0.02 mm. This conforms to the actual surface profile tolerance of 0.04 mm on the entire pole face with relation to the mating surface between the upper and lower half of the yoke.

Other possible reasons for the variation in measured field strength would be a misalignment due to either the measurements of the spheres, or the offset measurements. A transverse error in position of approximately 0.1 mm would result in similar changes in dipole field due to the field gradient. An error of this size is however unlikely because of the tough tolerances on the machining, as well as the high repeatability of the alignment and offset procedures.

The variation in integrated quadrupole component is ±0.25% as can be seen in Fig. 6, with a standard deviation of 0.11%, which is also very close to the variation of the field strength in the centre of the magnets. To estimate the variation in gradient from the tolerance of the pole profile, a FEMM [4] model was prepared based on the official 3D model of the magnet.

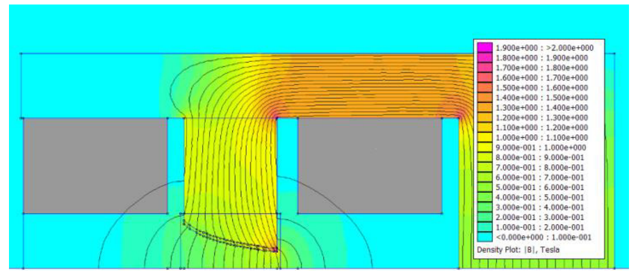
Figure 7: The cross section used for the FEMM calculations. The colour scale goes from 0 to 2 T.

The profile tolerance of 0.04 mm on each pole would allow for a rotation of the pole faces of ±0.7 mrad. By applying these mechanical variations to the FEMM model, and then evaluating the field components using a linear fit over x = ±11 mm, the gradient changed with ±0.32% from the average.

CONCLUSION

All 80 of the unit cell magnets produced by Scanditronix Magnet for the 3 GeV storage ring at MAX-IV have been approved after the field measurements.

It has been shown that both the dipole field as well as the gradient of all the combined function dipole magnets has a variation in strength below what could be expected from the mechanical tolerances placed on the pole profiles.

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