MAGNETIC FIELD CORRECTION OF THE BENDING MAGNETS OF THE 1.5 GeV HDSM*

F. Hagenbuck, P. Jennewein, K.-H. Kaiser

Abstract

Beam dynamics of the Harmonic Double Sided Microtron (HDSM), the fourth stage of MAMI, require a very precise magnetic field in the inhomogeneous bending magnets. By measuring the vertical field component B_y in and on both sides of the midplane, the complete set of field components B_x, B_y, B_z was determined in the whole gap. Starting from this the asymmetric pole surface current distribution necessary to correct both symmetric and antisymmetric field errors was calculated. Since tracking calculations showed that the influence of skewed field components on the beam deflection are negligible only symmetric field errors are taken into account for the final field correction. Nevertheless, in order to demonstrate the method, a set of asymmetric correction coils was built and successfully tested. The final symmetric coils are designed to reduce field errors to below $2 \cdot 10^{-4}$. Deflection errors in the fringe field region near the magnet corners, which cannot be corrected by surface currents, will be compensated by vertical iron shims in combination with small dipoles on each beam pipe.

INTRODUCTION

The Harmonic Double Sided Microtron (HDSM) [1, 2], which is presently under construction, will increase the end energy of the RTM-cascade MAMI from 0.855 to 1.5 GeV. The HDSM mainly consists of two linear accelerators and two pairs of 90° bending magnets. For the compensation of vertical edge defocusing due to the inclination of the magnet pole edges with respect to the beam direction a sophisticated pole profile was chosen leading to a relatively strong field gradient normal to the front edge, see Fig. 1. Unavoidable manufacturing errors of such an advanced magnet easily lead to a field inhomogeneity $\Delta B/B$ of some 10^{-3} and contain the risk for a distinct distortion of the midplane symmetry. Therefore, it is necessary to identify not only symmetric but also antisymmetric field errors and to extend the surface correction coil technology, developed for the homogeneous RTM dipoles of MAMI [3], to the inhomogeneous HDSM magnets.

In the presence of a strong vertical field component B_y (here the magnetic induction $\vec{B}$ is called magnetic field) in the order of 1 T it is experimentally not feasible to measure directly the horizontal components B_x and B_z which are expected to be in the range of a few Gauss only. However, the knowledge of the B_y distribution on both sides of the midplane allows to calculate the distribution of B_x and B_z in the midplane [4]. Having measured also B_y in the

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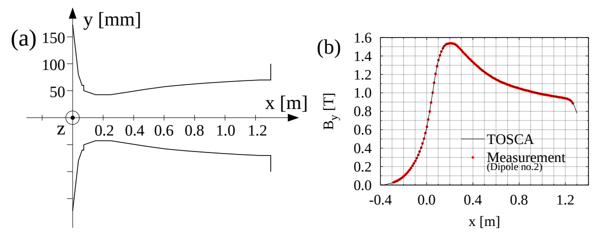

Figure 1: (a) Pole profile and (b) magnetic field B_y in the midplane of the HDSM magnets.

midplane all components of the magnetic field $\vec{B}$ are determined in the midplane and in principle the complete field distribution consisting of a symmetric and antisymmetric part can be calculated in the whole gap [4].

MAGNETIC MEASUREMENTS AND RESULTS

Field Mapping

Before starting the field mapping each magnet was subjected to a well defined cycling procedure providing a reproducability of about 10^{-5} for the nominal magnetic field of 1.53 T. The field distribution was measured using three high precision hall probes (MPT-141, Group 3 Technology Ltd.) moved by a precision positioning machine in a grid of 12 mm · 12 mm. The hall probes were installed in a Plexiglas cube to measure the vertical field component B_y in the magnet midplane as well as at a distance of 25 mm on either side of it. The cube itself slid on an air cushion on a precisely levelled Plexiglas plate. During the measurements the field stability was controlled by means of an NMR-probe. In view of a possible future increase of the maximum output energy the mapping has been done not only at the nominal field but also at 1.64 T and 1.71 T corresponding to end energies of 1.61 GeV and 1.67 GeV respectively. However, only the results for one dipole as a representative example for the four magnets with the nominal field of 1.53 T are discussed here.

Symmetric field errors

In Figure 2 the contour plot of the measured vertical field component B_y in the midplane can be seen. It shows the difference between B_y and the central field profile in the midplane $\Delta B_y(x,0,z) = B_y(x,0,z) - B_y(x,0,0)$. Relative deviations with respect to the central field profile $\Delta B_y(x,0,z)/B_y(x,0,0)$ are only about 10^{-4} in the inner area of the gap. Much larger field decays exist, however, near the magnet corners. They have been predicted by TOSCA-simulations and lead to deflection errors of up

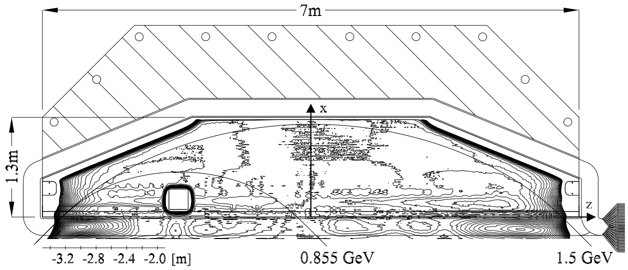

Figure 2: Field deviation $\Delta B_y(x, 0, z)$ in steps of 0.2 mT.

to 2.2 mrad at low electron energies. In addition, undulating field deviations can be seen in front of the pole edge. They can only be explained by a misalignment of the coil conductors of up to about 1 cm. The influence of all these fringe field errors to the beam will be compensated by the combined action of iron shims and small correcting magnets on each beam tube as described below.

Antisymmetric field components

The antisymmetric components B_x and B_z in the midplane were calculated from the measured B_y component on both sides of it. In the fringe field area the off-midplane components could not be measured precisely enough in our setup to extract the antisymmetric fields with the desired resolution. In order to get a solution for the inner region Ω of the gap, the calculation was performed under the assumption that the antisymmetric field components vanish in the fringe field region. To fulfill this (Dirichlet) boundary condition from each grid point of the boundary line of Ω an ideal fringe field decay was added numerically. The result for the antisymmetric field distribution is shown in Fig. 3. The undulations along the pole edge that can be seen in Fig. 3 (b) are produced by a 0.02 mm oscillatory instability of the milling head during the machining of the upper pole of the magnet. In general the transverse components are below 1 mT leading to vertical deflections of about 0.1 to 0.35 mrad. A rough estimation of the influence of such fields to the beam optics leads to an acceptable coupling of only a few percent between the horizontal and vertical phase spaces.

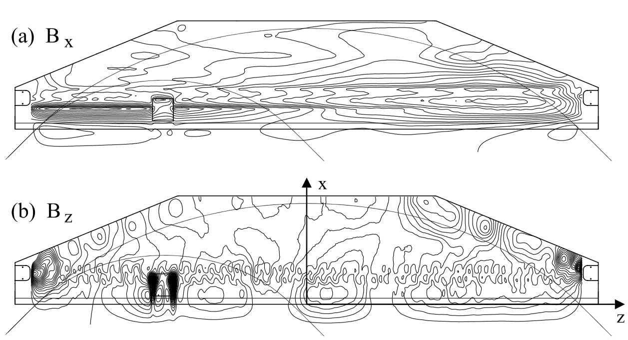

Figure 3: Lines of constant fields (a) B_x and (b) B_z in steps of 0.2 mT and 0.05 mT resp. in the midplane.

FIELD CORRECTION

For the correct functioning of the HDSM the beam has to be guided very closely to its ideal orbit. Therefore, the relative field errors in the bending magnets are reduced to below $2 \cdot 10^{-4}$ by means of surface correction coils.

Asymmetric Surface Correction Coils

Due to the fact that the complete field distribution in the inner part of the magnets can be calculated from the measurements it is possible to extend the correction to both symmetric and antisymmetric field errors [4]. In order to test the method, a pair of asymmetric surface coils was built covering about one square meter in the undulated field region, see Fig. 4 (a), (b). The coils were fabricated from 3 mm aluminium plates by water jet cutting. The number and shape of conductors of the combined correction coil set is dominated by the antisymmetric part. This is due to the fact that the generation of a compensating transverse field in a certain area requires a continous current density at the upper and lower pole faces, whereas the production of a vertical field only needs a current loop around this region. Field mapping after installation showed that in the midplane relative field errors of B_y could be reduced to about $\pm 1 \cdot 10^{-4}$, see Fig. 4 (c), (d). As can be seen in Fig. 5 also the field quality with respect to the antisymmetric field errors has improved significantly. In particular, the oscillations of the (off-midplane) antisymmetric vertical field component B_y^{as} and of the horizontal component B_z were removed. In spite of this success it was decided to do the complete correction only for the symmetric field errors. In view of the rather marginal effect of the transverse components to the beam it seemed not to be worthwhile to take the risk of using asymmetric coil sets which are much more complicated than symmetric ones.

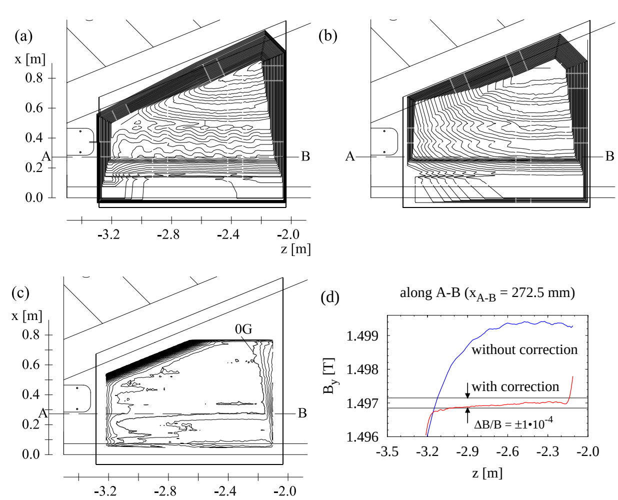

Figure 4: (a) Upper (b) lower test coils for asymmetric field correction. Coil current 15A. (c) $\Delta B_y(x, 0, z)$ in steps of 0.2 mT with asymmetric correction. (d) $B_y(x_{A-B}, 0, z)$ along A-B.

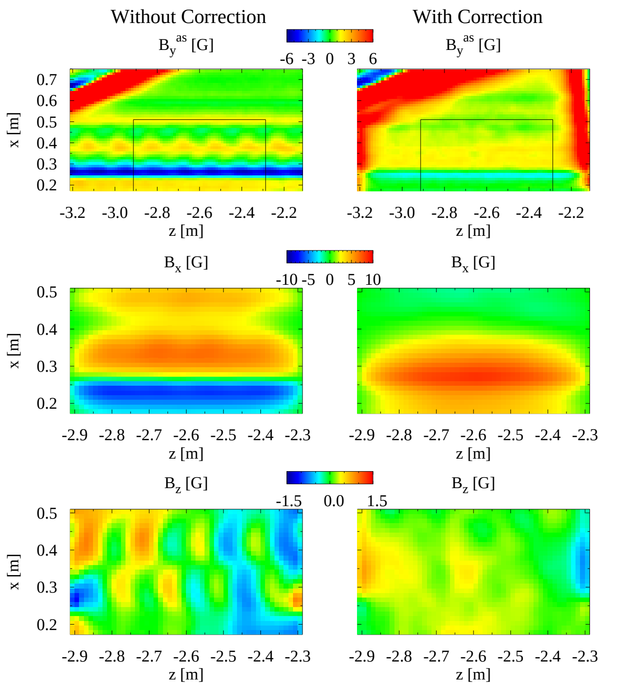

Figure 5: B_y^{as} measured 19 mm above and B_x and B_z (calculated in the indicated, see upper figures, sub-range of the measurement region) in the midplane.

Symmetric Surface Correction Coils

The current distribution for the correction of symmetric field errors $I_c^s(x,z)$ was calculated (assuming infinite relative permeability within the magnetic iron) from the difference between the mean of the off-midplane measurements of B_y at a distance $h = 25$ mm and the mean of the off-midplane central field profiles according to

$$I_c^s(x,z) = \frac{1}{\mu_0}\left[\overline{B_y}(x,\pm h,z) - \overline{B_y}(x,\pm h,0)\right] y_P(x)$$

with $y_P(x)$ the variable half distance of the air gap. The resulting correction coil consisting of 10 A and 20 A windings can be seen in Fig. 6. Field mapping shows, see Fig. 7, that the desired field accuracy of $2 \cdot 10^{-4}$ is also achieved with symmetric correction coils.

Iron Shims in the Fringe Field

For the higher field deviations in the fringe field region near the magnet corners that cannot be compensated at the same location with surface coils two correction elements are needed to correct both, the angle and the displacement of the beam. Therefore, the correction magnets placed on

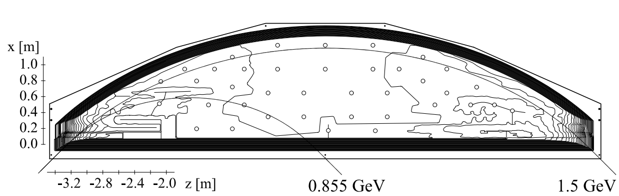

Figure 6: Surface correction coil for symmetric field errors.

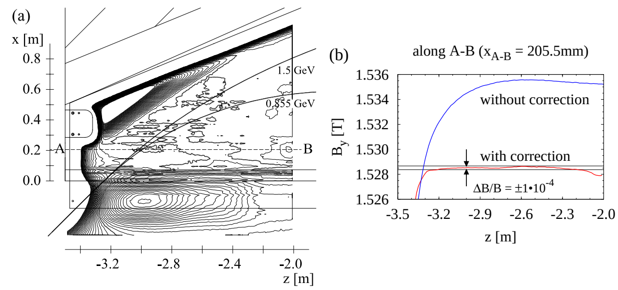

Figure 7: (a) $\Delta B_y(x,0,z)$ in steps of 0.2 mT with symmetric correction. (b) $B_y(x_{A-B},0,z)$ along A-B.

the return paths and on the linac axes will be completed by vertical iron shims attached to the front face of the HDSM-dipoles reaching more or less deeply into the free space of the Rogowski profile. Since the shims are almost completely saturated in the area where they do not touch the front face, they essentially add their magnetic flux to the fringe field, see Fig. 8 (a), (b). The field distribution and the electron path for the complete correction by means of a pair of shims and a correction magnet is shown in Fig. 8 (c)-(e).

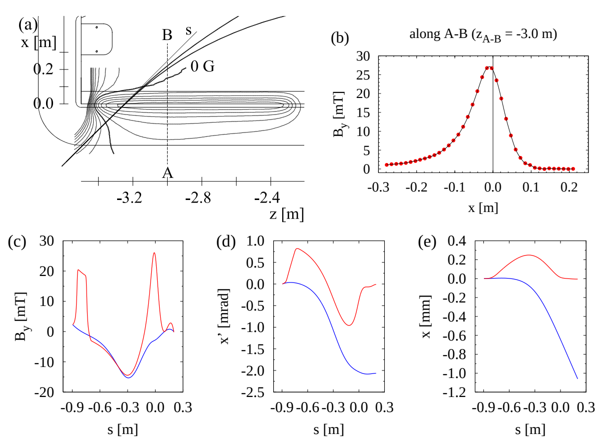

Figure 8: (a) Lines of constant field $B_y(x,0,z)$ in steps of 5 mT produced by 3 mm shim. (b) $B_y(x,0,z_{A-B})$ along A-B. (c) Magnetic field B_y, (d) beam angle x' and (e) displacement x at 855 MeV along the linac axis s counted from its intersection with the dipole front face (blue lines without, red lines with correction).

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