SIMULATIONS OF FRINGE FIELDS AND MULTIPOLES FOR THE ANKA STORAGE RING BENDING MAGNETS*

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Abstract

ANKA is the synchrotron light source of the Karlsruhe Institute of Technology (KIT)[1]. With a maximum particle energy of 2.5 GeV, the storage ring lattice consists of 16 bending magnets with a nominal magnetic flux density of 1.5 T. For the beam dynamics simulations the consideration of the fringe fields and multipoles is essential. A reference measurement of the longitudinal magnetic flux density profile of a bending magnet exists for a current of 650 A, corresponding to a particle energy of 2.46 GeV. For lower beam energies where the magnets are no longer close to saturation, however, the exact density profiles may vary significantly. In order to derive fringe fields and multipole components for different beam energies, simulations of the magnetic flux density for different beam energies were conducted using a finite element method (FEM). We present the results of the simulations and demonstrate the improvements of the beam dynamics simulations in "Accelerator Toolbox for MATLAB (AT)" [2].

MOTIVATION

To obtain a better model of the ANKA storage ring, nonlinear effects in the magnetic fields have to be considered. We want to study the fringe fields and multipoles caused by bending magnets and implement them into an existing model. Non-linear effects are often determined by iterative matching of the simulation model to measurements. However we chose another approach, however: we want to calculate the fringe field integrals and multipoles from simulated field profiles and compare simulation results with measurements.

FRINGE FIELD INTEGRAL

The magnetic field does not end abruptly at the edges of a bending magnet, but extends beyond the magnet edges (shown in Fig. 1). Therefore, an effective magnetic length has to be considered in simulations. The field gradient in vertical direction caused by fringe fields influences the vertical beam optics. A quantity that describes this effect is so-called *fringe field integral*, which is defined by[3]:

$$F_{INT} = \int_{-\infty}^{\infty} \frac{B(s)(B_0 - B(s))}{G \cdot B_0^2} ds, \qquad (1)$$

where G is the gap of the bending magnet, B_0 is the maximum magnetic flux density (see Fig. 1) and $B(s)$ is the position-dependent magnetic flux density.

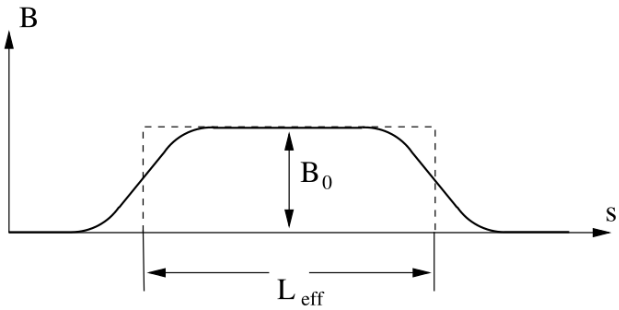

Figure 1: (Schematic diagram). B_0 is a maximum magnetic flux density. L_{eff} is an effective bending magnet length.

MAGNETIC FIELD PROFILES

The longitudinal magnetic field profile (shown in Fig. 2) was measured using a hall effect sensor. The measurement was taken at a current of 650 A which corresponds to a beam energy of 2.46 GeV.

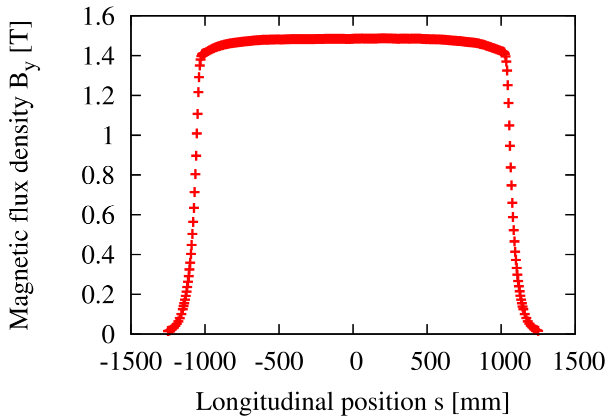

Figure 2: Measured vertical component of the magnetic flux density of an ANKA reference bending magnet along the beam orbit.

AT uses two values for the fringe field integral, one for the entrance of the bending magnet, another for the exit. The magnetic flux density is not constant inside an ANKA

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bending magnet in regular user operation, since iron is saturated at around 1.5 T. Therefore, fringe fields have to be considered not only outside of a bending magnet, but also inside of it. Fringe field integrals are calculated for the entrance in the range of $(-\infty; 0]$ mm $F_{INT} = 0.791$, and for the exit in the range of $[0; +\infty)$ mm $F_{INT} = 0.751$. The calculated values are not identical, because the coil is not exactly symmetric, due to a connection for a power supply at the entrance. Therefore, the entrance field integral is higher than the exit field integral.

Simulated vs. Measured Field Profile

A bending magnet was modelled using a finite element method (FEM) software[5]. Magnetic field profiles for different coil currents were also simulated. At first, we simulated a field profile according to the measurement at the coil current of 650 A, and compared it to the measurement (see Fig. 3) to estimate the accuracy of our model. As a first step, we used a model with a symmetric coil without connection for a power supply, since the modelling the exact geometry of the connection is difficult. Therefore, only one half of the bending magnet is shown in Fig. 3. The comparison between the simulation and measurement shows a good agreement, thus we used this model for further studies.

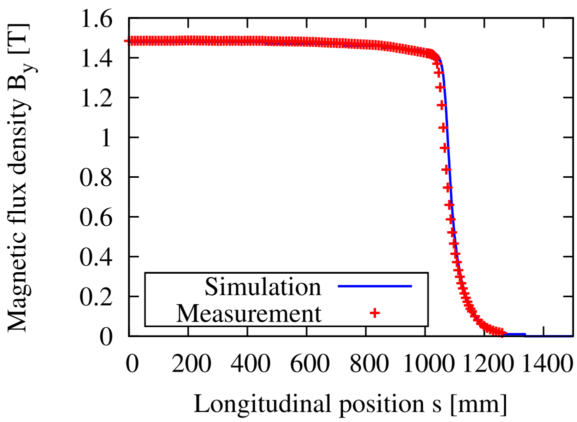

Figure 3: Simulated and measured vertical component of the magnetic flux density of a bending magnet along the beam orbit.

Field Profiles for Different Beam Energies

Using the model for a bending magnet mentioned above, we simulated field profiles for different coil currents corresponding to beam energies that are used in certain operational modes.

Figure 4 shows clearly that the field profiles at beam energies below 2.5 GeV are constant inside the bending magnet. Since iron becomes saturated at around 1.5 T (for 2.5 GeV), the corresponding field profile is slightly curved. This effect is essential for the fringe field integrals (see Tab. 1) and it also influences the magnetic optics. As shown in Tab. 1 fringe field integrals do not depend on the absolute strength of the magnetic flux density, but on the relative change. Therefore, fringe field integrals at low beam energies are nearly identical, but the value corresponding to 2.5 GeV differs.

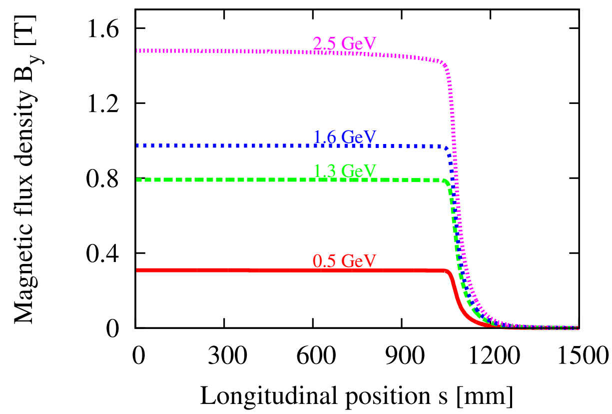

Figure 4: Simulated vertical component of the magnetic flux density of a bending magnet along the beam orbit for different beam energies.

Table 1: Fringe Field Integrals for Different Beam Energies

Beam Energy [GeV]	B [T]	Fringe Field Integral
0.5	0.3	0.533
1.3	0.8	0.536
1.6	1.0	0.541
2.5	1.5	0.750

Effects of Fringe Fields on Beam Optics

To demonstrate the effect of the fringe fields on the magnetic optics, we calculated the tunes (Q_x, Q_y) and chromaticities (Q'_x, Q'_y) at a beam energy of 2.5 GeV using the Accelerator Toolbox for MATLAB (AT). In the simulation the fringe field integral of 0.75 was used for both the entrance and the exit of the bending magnet. Table 2 clearly shows that fringe fields change the vertical tune and vertical chromaticity, since they cause a vertical magnetic field gradient.

To compensate the natural chromaticity, 24 sextupole magnets are installed at the ANKA storage ring. The strengths of the sextupole magnets were calculated using the polynomial obtained from earlier measurements [6].

MAGNETIC MULTIPOLES

Not only fringe fields, but also magnetic multipoles inside a bending magnet influence the beam optics. Therefore they have to be considered in AT. To estimate magnetic multipoles we simulated 5 longitudinal magnetic field

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Table 2: Influence of Fringe Fields on Beam Optics

	no Fringe Field	**incl. Fringe Field**
Q_x	6.784	6.784
Q_y	2.853	2.811
Q'_x	2.810	2.810
Q'_y	2.858	3.057

profiles with horizontal distances of 10 mm to each other. Figure 5 shows the magnetic flux density in the center of a bending magnet along the horizontal plane.

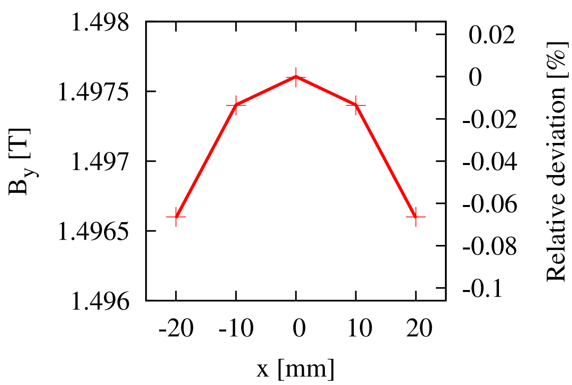

Figure 5: Simulated vertical component of the magnetic flux density in the center of a bending magnet along the horizontal plane.

To calculate multipole components, we considered the magnetic flux density expansion of the vertical component B_y in the proximity of the beam orbit[4]:

$$\frac{e}{p}B_y(x) = \frac{e}{p}B_y + \frac{e}{p}\frac{dB_y}{dx}x + \frac{1}{2!}\frac{e}{p}\frac{d^2B_y}{dx^2}x^2 + \cdots, \quad (2)$$

where e is the electric charge and p is the momentum of the particle. The first term defines the dipole component with a constant magnetic flux density. The second term describes the quadrupole component, where $\frac{e}{p}\frac{dB_y}{dx} = k$ is the quadrupole strength. The third term defines the sextupole component, where $\frac{e}{p}\frac{d^2B_y}{dx^2} = m$ is the sextupole strength. We obtained for $k = 0.0027\,\mathrm{m}^{-2}$ and for $m = -0.5\,\mathrm{m}^{-3}$.

To show the influence of multipoles on the magnetic optics, tunes and chromaticities were calculated at a beam energy of 2.5 GeV (see Tab. 3). This model also considers fringe field integrals.

FINAL RESULTS

We implemented the calculated fringe field integrals and multipole components into the 2.5 GeV AT model and compared the simulated results with measurements (see Tab. 4). The comparison shows clear improvements for both chromaticities, especially for the vertical one. Also

Table 3: Influence of Multipoles in Addition to Fringe Fields on Beam Optics

	no Multipoles	**incl. Multipoles**
Q_x	6.784	6.794
Q_y	2.811	2.697
Q'_x	2.810	2.522
Q'_y	3.057	6.880

the vertical tune could be improved, but the horizontal tune is overestimated by AT which provides a good motivation for further studies.

Table 4: Comparison of Model and Measurements. AT* model without fringe field integrals and multipole components, AT model including both.

	AT*	**AT**	**Measurement**
Q_x	6.784	6.794	6.782
Q_y	2.853	2.697	2.694
Q'_x	2.810	2.522	2.507
Q'_y	2.858	6.880	6.939

CONCLUSION AND OUTLOOK

Fringe field integrals and multipole components were successfully implemented into the AT model. The simulation results show an improved agreement with the measurements (see Tab 4). The non-linear effects were successfully predicted by FEM simulations, therefore no iterative matching was needed.

The next step is an implementation of fringe field integrals and multipole components into the AT model for other beam energies and a cross check of the simulation results with measurements. Furthermore, fringe fields of quadrupole and sextupole magnets will be considered in the AT model to make the model more realistic.

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