MODELLING THE MAGNET LATTICE OF DELTA

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Abstract

The Dortmund Electron Accelerator (DELTA) is a 1.5 GeV synchrotron light source. DELTA uses a strong focusing magnet structure. The distance of magnets is small and quadrupoles, steerers and sextupoles use the same magnet yoke. Magnet fields were measured taking into account the interference of different multipoles. The applied methods and preliminary results will be presented.

1 SURVEY

1.1 Introduction

The magnet lattice at the electron storage ring DELTA was designed for low emittance optics of about 5 nm rad at 1 GeV [1]. This involved a closely packed magnet structure, resulting in a minimal ullage for the neccessary amount of correcting and sextupole magnets (see Fig. 1). It was thus decided to add extra coils to the quadrupole yokes to provide required dipole- and sextupole components. Furthermore, separate sextupole magnets have been mounted directly to the quadrupole yokes with only about 7 cm of space between their yokes. Since the magnetic inductance depends on the level of saturation within the yokes, the resulting dipole and sextupole components of such a multifunctional magnet structure clearly inherits a nonlinear dependency of the quadrupole excitation current. Previously, these dependencies have only been measured in part, thus it is not surprising, that theoretical models of the DELTA optics have so far failed to reproduce observed machine parameters.

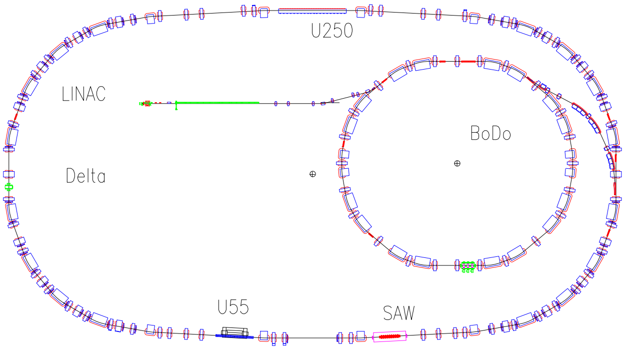

Figure 1: Close packed magnet structure at DELTA.

In order to improve the theoretical understanding of the storage ring optics, systematic multipole measurements and power supply calibrations have been undertaken.

1.2 Magnet Configurations

DELTA magnets comprise two types of quadrupole yokes, one having a length of 0.2 m (hereafter referred to as short quadrupoles), the other being twice as long (i.e. long quadrupoles). Both kinds are partly equipped with external sextupoles mounted to their face. The long yokes usually bear an extra pair of coils for the excitation of vertical dipole components, whereas the short yokes may bear either a pair for vertical or horizontal dipole excitation. Both types of quadrupoles may incorporate an extra set of coils for an additional sextupole field. Since latter reduce the width of the mechanical aperture required for the multipole measurement presented below, this configuration has been discarded for measurements.

Since DELTA is operative since 1995, it is not practical to perform measurements on each of its magnets. Rather we selected spare components of each quadrupole type, equipped with the additional coils as described above. Thus, the best we can do is to apply these limited results to all magnets of their kind operative at DELTA.

2 MULTIPOLE MAGNET MEASUREMENT

We employed the *Multipole Magnet Measuring System 692* by DANFYSIK, as owned by BESSY II, to analyse integrated multipole components of different magnet setups. This system is based on a planar coil, whose length shall exceed the fringe fields of the magnet to be measured and whose width is limited by the available aperture radius. This coil is inserted with a parallel offset along the magnetic axis of the magnet to be measured. By rotating the coil around this axis, a voltage is induced, which is proportional to the change of magnetic flux along the length of the magnet. Thus, by stepwise integration of the induced voltage, one may readily reconstruct the azimuthal dependency of the radial component of the magnetic induction by means of a Fourier Transformation. Obviously, this method allows only to analyse the integrated magnetic field along the length of the coil. For a more detailled description of the hardware involved and means of evaluation see [2] as an example.

2.1 Results

So far, only on-axis evaluations of multipole components have been performed. We will present selected results with respect to the peculiarities of the magnet combinations.

Quadrupoles At DELTA, quadrupole currents are set on the ascending branch of their hysteresis after performing a unipolar magnet massage. Fig. 2 shows the typical signature of saturation for a quadrupole yoke with increasing excitation. The art of fitting a continuous function to the data was subjected to a minimal number of fitted parameters while minimizing the residual function χ^2/ν. For the quadrupole excitation measured, this was done best by a function of the form

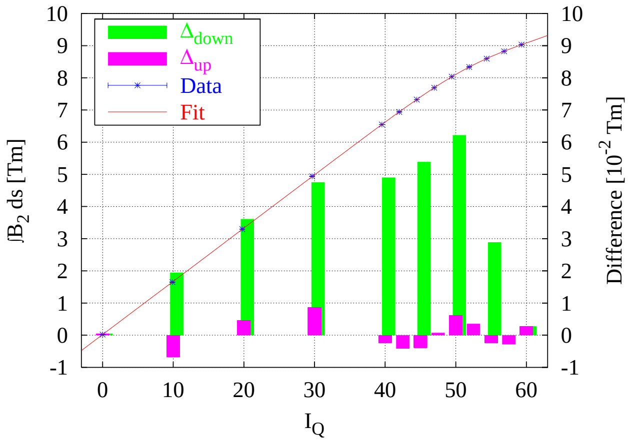

Figure 2: Amplitude of the quadrupole component B_2 upon ascending excitation of a long quadrupole with an externally mounted sextupole yoke. The bars represent the deviation of data points to the fitted curve for both branches of the hysteresis.

$$\int B_2(I_Q)\,\mathrm{d}s = \frac{t\,I_Q}{1+\left(\frac{I_Q}{I_S}\right)^{\alpha}} + \beta I_Q + \delta$$

for $0 \leq I_Q \leq I_{max} = 60$ A. It turned out that the measured data exceeds the formerly used function for the strength of a long quadrupole by up to 3%, whereas the data for a short quadrupoles give rise to an increase in strength by about 1%. Since saturation effects assert to short quadrupole yokes more clearly, the maximum averaged field gradient within a short quadrupole is measured to be 22.9 T/m opposed to 23.3 T/m for a long yoke, both evaluated at I_{max} without externally mounted sextupoles.

To analyse the influence of the external sextupole yoke, we studied the effective length of the quadrupole component, as defined by

$$l_{eff} = \frac{\int B_2(s,I_Q)\,\mathrm{d}s}{\bar{B}_2(I_Q)}, \quad \text{with} \quad \bar{B}_2(I_Q) = 2\mu_0\frac{nI_Q}{a^2}.$$

Here, $\bar{B}$ represents the idealized induction within a long quadrupole of $n = 188$ turns per coil, assuming $\mu_r \rightarrow \infty$ for its yoke of an aperture radius $a = 35$ mm. As can be seen in Fig. 3, the external sextupole yoke shortcuts the quadrupole fringe fields and thereby shortens its effective length by a constant 3 mm. This is also true for the short quadrupole yoke.

Corrector Magnets As the corrector coils are wound around the quadrupole yoke, their strength is highly dependend on the exciting quadrupole current, as can be seen from Fig. 4. With neglegible quadrupole excitation, the strength of both the horizontal correctors (HC) mounted on short and long yokes are about equal with their number of turns behaving as 240 to 150 respectively. However, since saturation effects become stronger for the shorter yoke, the decrease in strength becomes bigger for the shorter correctors. A similar drop is observed for the vertical correctors (VC), which are mounted on short yokes only. A function of the kind

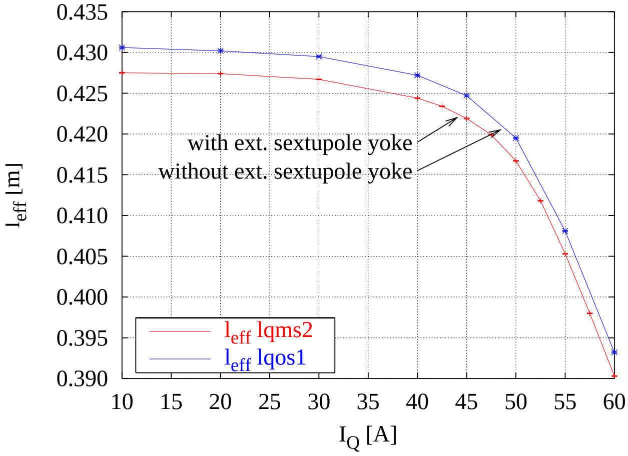

Figure 3: The effective length of the (long) quadrupole field is shortened by the externally mounted sextupole by about 7 ‰.

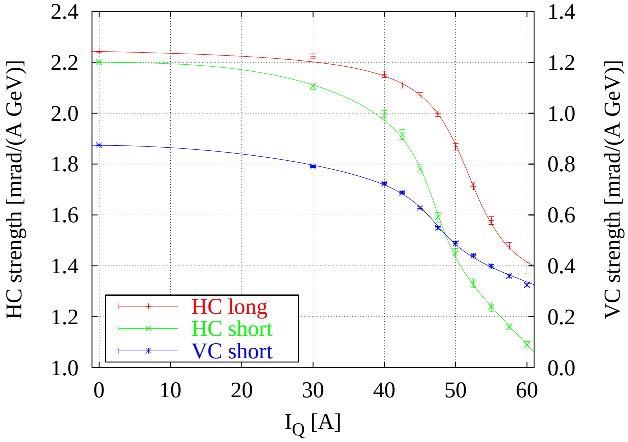

Figure 4: Steerer strength as a function of quadrupole excitation (data taken with external sextupole mounted).

$$\frac{e}{p}\int B_1\,\mathrm{d}s = I_{HC,VC}\Big[a + b\tan^{-1}c(I_Q-d) - \frac{bc}{1+c^2d^2}I_Q + eI_Q^2 + fI_Q^3\Big]$$

minimizes the residual function χ^2/ν under the additional side condition that the first derivative with respect to I_Q

vanishes for $I_Q = 0$[1]. Just as the externally mounted sextupoles shortcut the quadrupole fringe fields, the dipole fields become shortened likewise. However, since the quadrupole field decays with r^{-4} and the dipole field with r^{-3}, the effect on the corrector fields is expected to be stronger. Indeed, by dismounting the sextopole yoke, the effective length of the dipole fields of the short quadrupole increases by 8.7%, whereas the increase for the long HC field measures about 4.6%. Within their operational range of ± 10 A, the strength of the dipole correctors have been measured to depend linearly on their exitation currents within $\pm 5\%$. This holds independently of the quadrupole excitation.

The observed dependencies become crucial for the correct interpretation of beam response matrices.

Sextupoles External sextupoles show no sign of yoke saturation within their operational range of ± 15 A. Thus, a linear dependency on their excitation current is observed. Even more, their sextupole component is not significantly dependend on the quadrupole excitation. However, DELTA also uses internal sextupoles [3], four of whose pole shoes are supplied by the quadrupole pole shoes. Thus, upon an increase in quadrupole excitation, the multipole amplitudes of their embedded sextupoles shift progressively from a sextupole component to a dipole component [3].

3 POWER SUPPLY CALIBRATION

Using a temperature stabilized Wolf Shunt of a nominal resistance of 2.5 m$\Omega \pm 0.03\%$ and a high precision digital voltmeter by *Prema*, calibrations of all 31 quadrupole power supplies for DELTA have been performed, see Fig. 5. Most strikingly, a set of five power supplies provide a current of about 3.5 % above the set value. The corresponding quadrupoles are located in the northern matching section, which currently bear the maximum betafunctions in both directions, underlying the delta optics 'del-008' [4]. Thus, their effect on the overall phase advance might become significant when modelling the machine.

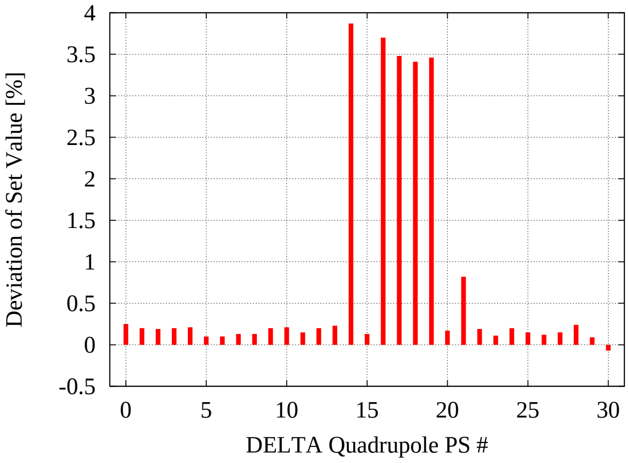

Figure 5: Current deviations for all 31 DELTA quadrupole power supplies.

4 MACHINE MODELLING

Early attempts at DELTA to set up the theoretically designed optics yielded into a heuristic machine setup, which allowed for storage and accumulation of beam current. When applying the formerly valid magnet calibrations – based on prototype magnet measurements performed by F. Brinker [3]– to this experimental setup, the horizontal tune differed by about 1.0 below the experimentally verified value of about 9.3. Likewise, crucial machine parameters such as beta functions and regions of stability for operating points differed inacceptably. On the other hand, DELTA encompasses a supersymmetry of only 2, exploiting a total of 24 quadrupole families and 11 families of sextupoles. Certainly, this complex setup results in a high number of degrees of freedom, which make it difficult to fit for magnet errors in order to obtain a more accurate model of the machine. Employing the results of recent magnet measurements, as have been partly presented above, the integral parameter of the machine's tune now fits quite well for both transverse directions. Yet, the comparison of the predicted orbit response matrix with its experimental counterpart shows significant differences in local parts of the matrix. Now that we have considerably amended our understanding on the strength of corrector magnets at DELTA and simultaneously improved our means of beam based calibrations of DELTA beam position monitors (see [5]), the next step may be to analyse the orbit response matrix with respect to currently unidentified differences between simulation models and the existing machine setup.

5 CREDITS

We wish to thank the scientific staff at BESSY II for allowing us to use their multipole magnet measuring system and for generously helping us out with hardware and experience. In particular we like to mention D. Krämer, J. Feikes, T. Knuth and U. Strönisch.

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[1] This was done in an attempt to sensibly compensate for the lack of data points at low currents I_Q