FIELD MEASUREMENTS AND SORTING OF THE HERA E-RING DIPOLES

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1 Abstract

In the HERA electron storage ring and its injection channels, currently approaching completion, a total of 454 dipoles, 716 quadrupoles and 420 sextupoles is needed for beam transport. This contribution focusses on both the hardware and software used for determining the field parameters of the 400 main bending magnets. The results of the measurements and their statistical evaluation as well as the sorting strategy used to minimize the perturbation of the β -function are presented.

2 Fundamentals

Inside the air gap of a common beam transport magnet with constant cross section the field shows no dependence on the z-coordinate (i.e. along the beam) and the current density is zero. The magnetic field may therefore be described by a two-dimensional scalar potential $V(r, \phi)^{-1}$ that obeys the Laplace equation

$$\nabla^2 V(r,\varphi) = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 V}{\partial \varphi^2}$$
(1)

The potential V can be expanded in a Fourier series

$$V = V_0 + \sum_{n=0}^{\infty} r^n [a_n sin(n\varphi) + b_n cos(n\varphi)]$$
(2)

and the components of the field are given by

$$B_r = \mu_0 \frac{1}{r} \frac{\partial V}{\partial \varphi} = \sum_{n=1}^{\infty} n r^{n-1} [a_n \cos(n\varphi) - b_n \sin(n\varphi)] \quad (3)$$

$$B_{\varphi} = -\mu_0 \frac{\partial V}{\partial r} = -\sum_{n=1}^{\infty} n r^{n-1} [a_n sin(n\varphi) + b_n cos(n\varphi)] \qquad (4)$$

Because the wavelength of the betatron oscillations $(\lambda \approx 140m)$ exceeds the length of the magnets by far and because the field errors are small, only the integral of the field

$$J(r,\varphi) = \int_{-\infty}^{\infty} B(r,\varphi) \, dz \equiv \langle B(r,\varphi) \rangle \, l_{F\epsilon} \tag{5}$$

is relevant to the beam optics. For the rest of this article we will - without the risk of confusion - simply refer to $B(r,\varphi)$ rather than the mean value $\langle B(r,\varphi) \rangle$.

3 Technique of Measurements

The relative strength and homogeneity of the magnetic field are measured using a rotating and a linearly moving coil respectively. Provided that the length of the coil exceeds the combined lengths of the iron yoke and the fringe fields, this method yields integrated values of the dipole and higher order components of the field.

3.1 Dipole Component

The principal layout of the system used to measure the dipole component of the field is shown in Fig.1 . The general idea is to complement the serial magnet to be tested by a reference magnet of the same type and to excite both magnets in series by the same current. The measuring coils are rotated synchronously and are connected so as to form a bucking circuit. In this way we measure directly the deviations of the serial magnet from the reference magnet and avoid problems with possible current fluctuations and drifting instrumentation amplifiers. The rotating coils ($10m \times 25mm\emptyset \times 5$ turns) inside the air gaps are driven at both ends by stepping motors. Precision gears reduce the speed of rotation by a factor of 10 to 0.75 cps and provide a resolution of 4000 steps per revolution. An angle encoder attached to the coil inside the reference magnet triggers 8192 successive analog to digital conversions (12 bit resolution) per revolution. The relative deviation d of the series magnet from the reference magnet is readily shown to be

$$d = a \left[\cos(\varphi) + a/2 \sin^2(\varphi) \right]$$
(6)

with $a = U/U_r$ and U, φ = amplitude and phase of the differential voltage, U_r = amplitude of the reference coil voltage.

All values are extracted by means of discrete Fourier analysis from the raw data. The determination of φ and U_r requires an extra measurement concerning the reference magnet alone. The overall relative accuracy proved to be $\pm 1.5 \cdot 10^{-4}$ and was regularly checked by remeasuring the same magnet.



Fig. 1 General layout of the $\int B dl$ measuring equipment

3.2 Multipole Components

The multipole distribution of the field is measured with a coil moving in the plane of symmetry of the magnet. A rotating coil is not suitable for this task, because

(a) in this case it is essential for the coil to follow the particle orbit, and

(b) the region of interest spans ± 40 mm in the horizontal direction, whereas the gap height of 51.5mm limits the diameter of the rotating coil to the aforementioned value of 25mm.

¹This is actually the z-component of the general vector potential $\vec{A}(x, y, z)$

Fig.2 displays the layout of the measuring machine. The curved coil ($10 \text{m} \times 10 \text{mm} \times 250$ turns, $\mathbf{R} = 610.4 \text{m}$) is actuated by a stepping motor connected to a 10:1 worm-gear and a subsequent eccentric drive with a stroke of $\pm 45 \text{mm}$. In this way the driving force becomes sine-like and the excitation of natural vibrations in the rig is reduced to a minimum. The data acquisition parallels that used for the rotating coils. In the present case the field is analyzed just in the plane of symmetry, and hence the Fourier expansions (3),(4) reduce to a polynomial $B_y(x) = \sum_{n=0}^{\infty} B_n(x) = \sum_{n=0}^{\infty} a_n x^n$. The normalized voltage induced in the coil is given by

$$U_{ind}/(L\cdot N\cdot v(x)) = \sum_{n=0}^{\infty} u_n x^n = B(x) - B(x+dx) \qquad (7)$$

with L, dx, N and v(x) =length, width, number of turns and local speed of the coil.



Fig. 2 General layout of the multipole measuring equipment

A polynomial fit of the data yields the voltage coefficients u_n and after evaluation of a set of recursive linear equations the field coefficients a_n . From (6) it can be seen, that the coil does not respond to the dipole component of the field. Thus the system gain can be high and the sensitivity for higher order components improved. Fig.3a shows a typical field cross section of a regular HERA e-dipole, run at a current of 6778A corresponding to $E_e = 30 GeV$. It is reasonable to disregard the n=2,3-components of the field error, because they will be



Fig. 3 Field profile, complete (a) and without mean n=2,3-components (b)

compensated by the quadrupole- and sextupole lenses, that are part of the HERA optical cell. Fig.3b gives an impression of the field after such correction. It is flat to $\pm 1 \cdot 10^{-4}$ in a region of $\pm 40mm$.

4 Results and Statistical Evaluation

The online software used for processing of the data emerging from the measurements is written in FORTRAN 77 and comprises full screen as well as graphical routines for displays on a separate high definition video terminal. The raw data are kept for safety reasons and the characteristics of the individual magnets are appended to a statistics file. Regular inspection of this statistics file was essential for keeping track of the quality of the incoming magnets.

Fig. 4 shows the distribution of the dipole strength at an exciting current of 6778A ($E_e = 30 GeV$). The comparatively high rms-width of $\sigma = 1.2 \cdot 10^{-3}$ reflects two problems encountered during the series production of the magnets:

(a) As with most of the HERA magnets, the regular dipoles are stacked of laminations of 5mm thickness, stamped using fine blanking techniques. The stamping process turned out to be sensitive to structure changes in the cutting zone (cold deformation). As a result the nominal gap height of 51.5mm



Fig. 4 Dipole strength distribution

varied by $\pm 0.06mm$ corresponding to $\Delta B_1/B_1 = \pm 1.2 \cdot 10^{-3}$. (b) Fluctuations of the relative magnetic permeability μ_τ of the soft iron sheets led to an estimate of $0.6 \cdot 10^{-3} \leq \Delta B_1/B_1 \leq 3 \cdot 10^{-3}$. The fact that the value based on the measurements amounts only to $1.2 \cdot 10^{-3}$ might originate from a correlation between mechanical and magnetic properties of the iron.

In addition, both (a) and (b) give rise to varying field gradients B_2 , because (a) changes the slant of the pole faces and (b) modulates the influence of different path lengths of the field lines inside the iron yoke. As can easily be seen, both effects act in the same direction. Fig.5 exhibits the strong correlation between increasing field strength B_1 and decreasing quadrupole component B_2 .

Table 1 summarizes the results of the measurements carried out on the whole series of 405 specimens.



Fig. 5 Correlation of the dipole and quadrupole components

E,	Ι	$J = \int B dl$	$\sigma(J/J_{ref})$	$ B_2/B_1 $	$ B_3/B_1 $
14	3156	0.7038	0.83	2.22	0.27
3 0	6778	1.503	1.19	2.22	0.21
50	11551	2.480	1.71	2.29	0.19
[GeV]	[A]	[T·m]	[10 ⁻³]	[10 ⁻³] @40mm	[10 ⁻³] @40mm

Table 1 Characteristics of the HERA e-ring dipoles

5 Sorting Scheme

The anticipated quality parameters of the machine impose certain limits to the acceptable variance of the magnetic data of the beam transport elements. One important task is to run with a low (half-integer) stopband width. The stopband width Δ_{rms} ($=1/\pi \cdot \Delta\beta/\beta$) [1] is given by

$$\Delta_{rms} = \frac{\sqrt{N}}{\pi} \cdot \qquad (8)$$

$$\sqrt{\frac{(\hat{\beta}\hat{k}\hat{l})^2}{2} \left(\frac{\Delta\hat{k}}{\hat{k}}\right)_{rms}^2 + \frac{(\check{\beta}\tilde{k}\tilde{l})^2}{2} \left(\frac{\Delta\tilde{k}}{\hat{k}}\right)_{rms}^2 + \left(\frac{\theta\bar{\beta}}{r_0}\right)_{rms}^2 b_1^2}$$

with

Ν	<u></u>	number of dipoles	=	400
$\hat{oldsymbol{eta}}$	=	eta in focussing quadrupoles	\approx	40m
$\check{oldsymbol{eta}}$	-	eta in defocussing quadrupoles	\approx	14m
$\bar{\beta}$		eta in the centre of the dipoles	\approx	24m
\hat{k}	=	$-\check{k} = ext{quadrupole strength}$	=	$0.12m^{-2}$
î		$\tilde{l} = $ quadrupole length		0.76m
θ	=	deflection angle	\approx	0.015 rad
r_0	=	reference radius		40mm
$\Delta \hat{k}/\hat{k}$	=	variance of foc. quad. strength		$1.2\cdot10^{-3}$
$\Delta \dot{k}/\dot{k}$	=	variance of def. quad. strength	=	$1.2 \cdot 10^{-3}$
b_1	-	variance of the dipole gradient	\approx	$2\cdot 10^{-4}$

The resulting value of $\Delta_{rms} \approx 0.03$ exceeds the specified maximum value by a factor of 2. This situation was greatly improved by splitting the distribution of the magnetic lengths of the quadrupole lenses ($\sigma \approx 0.8 \cdot 10^{-3}$) and by installing the dipoles in an ordered sequence according to their individual quadrupole component. The actual stopband width could be reduced to $\Delta_{rms} = 0.013$.

The second advantage to be gained by sorting the magnets is that one can cancel the individual deviations of the dipole strengths in order to minimize the orbit errors. This helps to keep the excitation of the correction dipoles moderate at the injection energy and eases the commissioning of the machine. The orbit error is found in a way similar to the one above to be

$$x_o^{rms} = \frac{8mm}{2sin(\pi Q)} \sqrt{2.25 \left(\frac{b_0}{0.001}\right)^2 + 0.507 \left(\frac{\Delta x}{0.1mm}\right)^2}$$
(9)

with $0 \leq Q \leq 1$ (stunes)

The first term under the root sign is contributed by the dipole error $b_0 = \Delta \int Bdl / \int Bdl$. The second term is due to the expected alignment errors of the quadrupole lenses: $\Delta x \geq$ 0.1mm. The somewhat high value of $b_0 = 0.83 \cdot 10^{-3}$ at $E_e =$ 14GeV (see Table 1) causes the first term to dominate, but this situation can also be improved by sorting.

Fig. 6 shows the evolution of the stopband width (a) and the orbit amplitude (b) due to the sorting process in one quadrant.



Fig. 6 Evolution of the stopband width (a) and orbit amplitude (b) in the SW-quadrant of the HERA e-ring. Without sorting: $\Delta_{rms} = 17 \cdot 10^{-3}$, $x_o^{rms} = 10mm$. SS denotes a straight section. Errors and misalignments of the quadrupoles disregarded.

6 Summary

The measurement of the 405 HERA e-ring dipoles provided the informations for monitoring the mass poduction of the magnets and helped to keep the variance of the integrated dipole strength at $1.2 \cdot 10^{-3}$ at $E_e = 30$ GeV. A sorting strategy for the dipoles improved the β -beat and thus the stopband width of the machine by one order of magnitude.

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References

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