Measurement and Correction of the ELETTRA Storage Ring Dipole Magnets

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Abstract

The results of magnetic measurement of the 24 gradient dipole magnets for the ELETTRA storage ring are presented. The method of correcting the variations in dipole, quadrupole and sextupole components using shims is described. Trajectory and path length effects are also considered.

I. INTRODUCTION

The ELETTRA storage ring [1] contains 24 gradient bending magnets with a nominal field of 1.2 T and field index of 13 at the final operating energy of 2 GeV [2]. A previous report dealt with the measurement of the prototype magnet [3] using the test system developed at CERN for the ELETTRA magnets [4]. The system has since been transferred to Trieste and used to measure the 25 series production magnets, constructed by Ansaldo Componenti, Italy.

II. FIELD MEASUREMENT AND ANALYSIS

The measurement system consists of an automated three-axis bench with a temperature stabilized probe containing a linear array of 15 SBV-585-S1 Hall plates, with 1 cm spacing. Field maps with a rectangular grid of points were measured in the median (x,z) plane of the magnet, with variable density along the longitudinal direction (z). A standard measurement (half magnet) contained 38 points in z, up to z=1.06 m, at which point the field was less than 0.25 % of its central value. The point spacing in z varied between 5 cm in the magnet centre and 1 cm at the edge. In the x direction there were 10 points with 1 cm spacing. All 15 plates were read at each point. Subsequent analysis consisted first in averaging the field values at each point. The number of points in x was such that there were at least 4 measurements of the field at each point in the region of interest.

The trajectory of the electron that starts from the magnet centre and exits with the correct angle (7.5°) was determined by iteratively tracking electrons with different energies. Field integrals were then evaluated along a series of curves parallel to the electron trajectory i.e. with constant radial separation, r. Interpolation between measurement points was carried out using a two dimensional cubic spline. The field integrals were fitted with a third order polynomial in order to determine the multipole field components defined as follows :

$$\int B\, dl = a_0 + a_1 r + a_2 r^2 + a_3 r^3$$

The rms relative error of the fit over ± 3 cm was 10^{-5}. Although this method results in a different energy for each magnet, the results are valid also at fixed energy since to a very good approximation small shifts in the x-direction (dx) produce a relative change in field integral, and hence energy, (for fixed bend. angle) given by $(G_o/B_o)dx$ without significant change in magnetic length or other field components.

Both halves of each magnet were measured at an excitation corresponding to initial operation at 1.5 GeV. A smaller number of magnets were measured at other currents. Linear scans were also carried out in the magnet centre (z=0) on each magnet.

III. MEASUREMENT RESULTS

Table 1 summarizes the average properties of the magnets while figure 1 shows the measured variations in the integrated field components, as well as the field (B_o) and gradient (G_o) in the centre of the magnets, at 1.5 GeV.

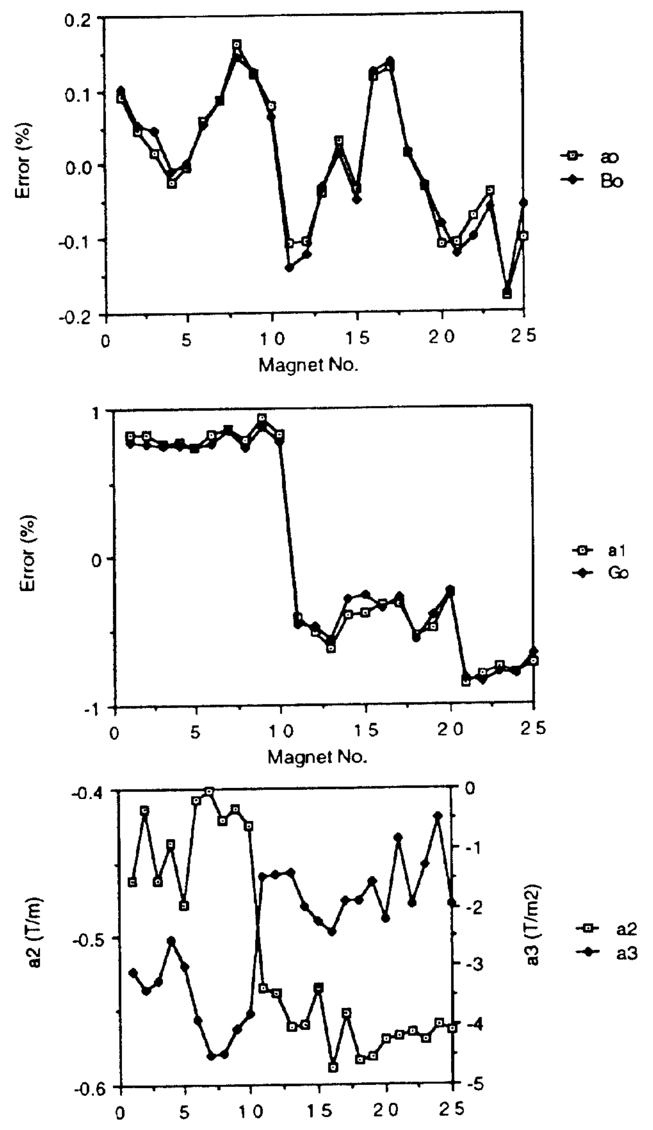

Figure 1. Variation in dipole (upper), quadrupole (middle), sextupole and octupole (lower) field in the dipole magnets.

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Table 1. Average magnetic properties of the dipole magnets, before shimming; a_1, a_2, a_3 values refer to 1/2 magnet.

I (A)	E (GeV)	B_o (T)	G_o (T/m)	L_{mag} (m)	a_1 (T)	a_2 (T/m)	a_3 (T/m^2)
700.0	1.0048	0.6018	1.496	1.4581	1.049	-0.32	-0.5
1050.0	1.5019	0.9008	2.240	1.4560	1.565	-0.51	-2.4
1420.0	2.0021	1.2067	2.993	1.4489	2.059	-1.10	-2.0
1950.0	2.4695	1.5086	3.640	1.4295	2.429	-2.62	-11.3

It is clear from the correlation between B_o and a_o, and between G_o and a_1, that the variations are caused by differences in the pole profile throughout the whole magnet. The dipole variation of 0.34 % (peak-to-peak) corresponds to a gap variation of 0.24 mm, while the 1.8 % gradient variation is equivalent to a 0.9° change in pole angle. By contrast the magnetic length variation is much smaller, 0.08 %, corresponding to 1.2 mm. It is evident that the errors are due to the final machining operation which was carried out on groups of 5 magnets : numbers 1-5, 6-10 etc. The largest changes occur between the first 10 and the remaining 15 magnets which corresponds to a gap of several months between the machining operations.

The effect of such dipole and quadrupole errors if uncorrected would lead to unacceptable closed orbit and β function errors [5]. The sextupole and octupole components are however small and within specification. The maximum values in fig. 1 correspond to relative field errors at the edge of the good field region (± 25 mm) of 5.8 10^{-4} and 1.1 10^{-4} respectively.

In order to overcome the dipole field variation the magnets will be displaced radially from their nominal positions by up to 0.68 mm. In order to correct the quadrupole (and also sextupole) variation it was decided to adopt the simplest and cheapest solution - a passive correction using shims.

IV. SHIMMING TECHNIQUE

Various attempts were made before arriving at a final solution that was sufficiently stable mechanically, and sufficiently independent of magnet current level to be effective over a range of ring energies. Solutions involving additional end plates and washers had to be rejected as being too dependent on magnet excitation, due to saturation in the end-field region. The final solution is illustrated in fig. 2.

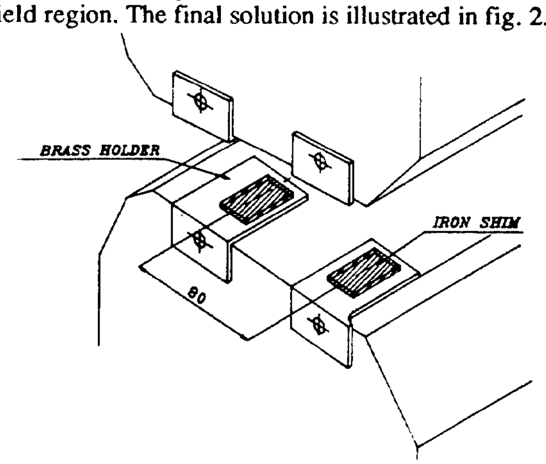

Figure 2. Position of shims for correcting the dipole magnets.

Each shim consists of a piece of magnet lamination, 1.5 mm thick and 20 mm wide, embedded in a brass holder which is bolted onto the magnet end plate so that the lamination lies flat on the pole surface. The centre-to-centre spacing of the shims was a compromise between maximizing the effect on the gradient and minimizing the effect on higher order field components.

Pairs of shims on the open side of the magnet decrease the gradient while those on the closed side increase it; both sets increase the sextupole field. Initial measurements showed that the effect was linear with shim length and that the effects of two pairs of shims added. Shim lengths were then calculated for each magnet to reach a common gradient and sextupole value, chosen in order to minimize the maximum required shim length (61 mm). Shims with similar length were then grouped to obtain an acceptable number of types of shim (7) and magnet groups (5). A prototype was constructed of each pair, and all 5 groups tested on one magnet (no. 16) at excitations corresponding to 1.5, 2.0 and 2.4 GeV. Two shim groups which gave the largest effects of the gradient were also tested on a second magnet (no. 8) with different gradient from the first magnet.

The measured effect of the shims agreed very well with the expected results, with the exception of the shortest shim (10 mm), for which an adjustment of the length was required. The results also demonstrated that the effects were the same for either magnet, and so could be applied to the whole group without the need to test each magnet.

The expected performance of the magnets based on the shim measurement data is shown in fig. 3. It can be seen that the gradient dispersion has been reduced to 0.2 %, within the desired 0.4%. The variation in sextupole value has also decreased significantly. The variation in octupole field has increased, but is considered acceptable.

V. PERFORMANCE AT HIGHER ENERGIES

The limited number of measurements that were made at higher energy (7 magnets at 2.4 GeV) are sufficient to show the good correlation between integrated and central field and gradient, as at 1.5 GeV. The *additional* variation at 2 GeV (0.2 %) and 2.4 GeV (0.5 %) with respect to 1.5 GeV is very similar for both field and gradient, and is clearly an effect due to saturation.

Measurements of the shims at different energies show a systematic reduction in the average gradient due to shim saturation, however the maximum variation introduced is only 0.02 % at 2 GeV and 0.08 % at 2.4 GeV, which are therefore small compared to the effects of magnet saturation.

Figure 4 shows the estimated dipole and gradient variations at different energies, taking into account both magnet and shim effects, and assuming a perfect correction of the dipole errors at 1.5 GeV by means of radial positioning.

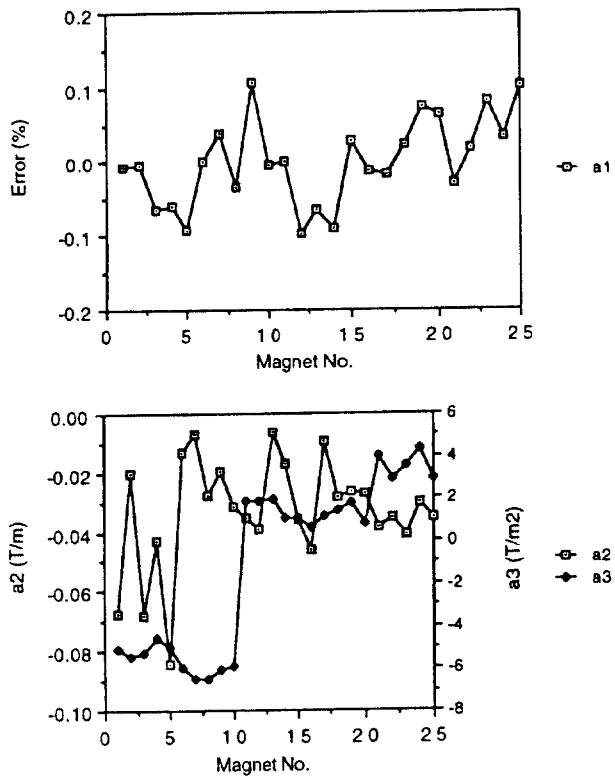

Figure 3. Estimated quadrupole (upper) and sextupole /octupole (lower) field variations at 1.5 GeV after shimming.

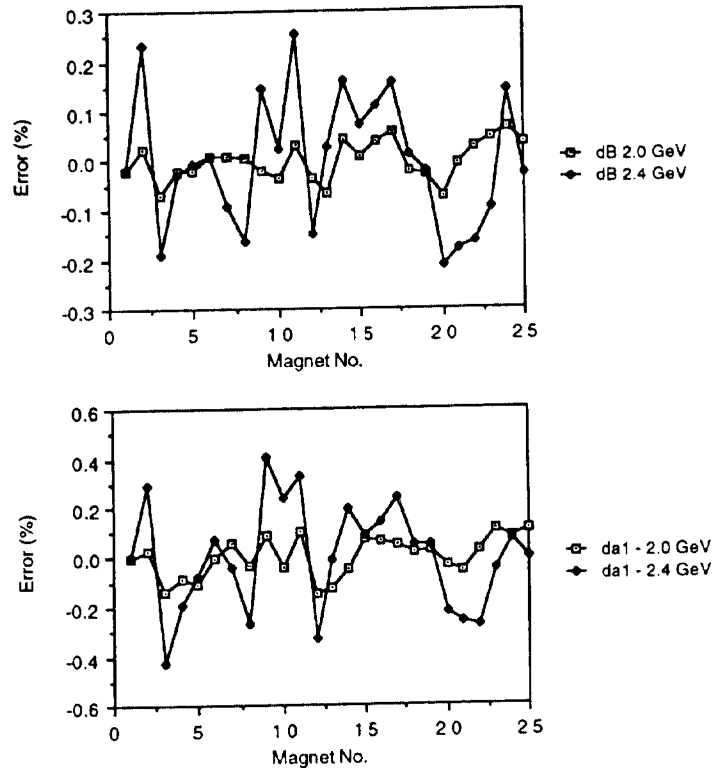

Figure 4. Estimated dipole (upper) and quadrupole (lower) field variations at 2 GeV and 2.4 GeV after shimming.

At 2 GeV there is little difference to the situation at 1.5 GeV : the dipole variation is 0.14 % and the gradient 0.26 %. At 2.4 GeV however there is a significant increase due to saturation : 0.47 % in field and 0.83 % in gradient. In order to provide for a possible future operation at high energy, it has been decided therefore to distribute the magnets in such a way as to minimize the effects on the optics [6].

VI. TRAJECTORY EFFECTS

The actual electron trajectory in the magnet deviates significantly from the ideal circular arc with nominal bending radius (5.5 m) due to the fact that the magnetic length and hence the radius of the electron trajectory are slightly greater than the nominal values, and also due to the effect of the fringe field. The result is that the trajectory is displaced in the x-direction (Δx) and also that the path length is different (ΔL) with respect to the hard-edge case. These quantities have been found to be equal for all magnets and are Δx = - 0.86 mm, ΔL = -0.089 mm, at 1.5 GeV. The shims have a negligible effect on both quantities.

The effect of the displacement in x is that due to the gradient, the field and hence current required for a given energy would be different to the measured values. This could be acceptable, however will be corrected along with the path length effect. The total path length error is 4.3 mm, corresponding to a momentum deviation of 1 %, given the ring circumference (259.2 m) and momentum compaction factor (1.6 10^{-3}). To overcome this effect all ring components will be displaced outwards with respect to their nominal positions by $\Delta L/\sin(\theta)$ = 0.68 mm, θ=7.5°. To take into account both effects, the dipoles will be displaced inwards by 0.86-0.68 = 0.18 mm, in addition to individual displacements to account for the dipole field variations described above.

VII. ACKNOWLEDGEMENTS

The contributions of G. Petrucci and other CERN staff to the successful transfer of the test system to Trieste is gratefully acknowledged. Magnetic measurements were carried out by A. Gubertini, R. Ciuch and P. del Giusto. D. Tommasini contributed significantly to the mechanical design of the shims and A. Wrulich to discussions on the implications of field errors and trajectory effects.

VIII. REFERENCES

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