Magnetic Measurement of the ELETTRA Transfer Line Magnets

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Abstract

The results of magnetic measurements of the dipole, quadrupole and steering magnets that will form the transfer line between ELETTRA 1.5 GeV linac and storage ring are presented.

1. INTRODUCTION

The injection system for the ELETTRA 1.5 GeV storage ring is a 1.5 GeV linac. In order to leave the whole of the experimental hall free for exploitation of synchrotron radiation beamlines the linac is located underground and tangential to the outside of the storage ring building . A relatively long (103 m) and complex transfer line is therefore required consisting of five 31.4^{o} dipoles (three horizontal and two vertical), two 15.7^{o} dipoles, 30 quadrupoles and 34 steering correction magnets. The design of the transfer line, which allows for an easy extension of the linac to 2 GeV in a future phase, is presented in ref. 1, while details of the magnet design are given in ref. 2. All of the magnets have been constructed by Tesla Engineering, England. In this report we present the results of magnetic measurements of the dipoles and the first quadrupole and steerer.

2. DIPOLE MAGNETS

The main parameters of the two bending magnet types are given in Table 1. The same laminations were used for both lengths of the parallel-edged dipoles, stacked along the arc of a circle with the nominal bending radius. The vertical magnets are identical to the horizontal ones apart from the orientation. Magnetic field measurements were carried out using the measuring system developed for the ELETTRA storage ring dipoles [3], which consists of an automated three-axis positioning bench with a probe containing a linear array of 15 Hall plates. Measurements of the vertical field component were made in the median plane, both linear scans in the centre of the magnet (x-direction) to confirm the 2D pole profile calculation [2] and field maps (x-z plane) to study the integrated field properties. Detailed measurements were not able to be carried out of the vertical dipoles, however a number of point measurements will be carried out to confirm the similarity with the horizontal magnets.

Table 1. Main parameters of the transfer line dipole magnets.

Bending angle	15.7^{o}	31.4^{o}
Nominal bending radius	4.4475 m.	
Field strength (2 GeV)	1.5 T	
Pole gap (at pole centre)	43 mm.	
Pole width	100 mm.	
Yoke length (mm)	1183.2	2373.2
Turns per pole	32	
Current (2 GeV)	833 A	

The uniformity of the field in the centre of the magnet is the same for both magnet types and typical results are shown in figure 1. Increasing saturation is observed above about 600 A, however at the 1.5 GeV (605 A) and 2 GeV (833 A) operating levels the field homogeneity is within ± 0.15 % for a ± 2.5 cm aperture. The measurements are in very good agreement with the results of 2D calculations made with POISSON [4], also shown in fig. 1. The central field values are also in good agreement with predictions, and at 2 GeV indicates a reduction in field of 3.4 % due to finite permeability, increasing to 8.7 % at 1000 A.

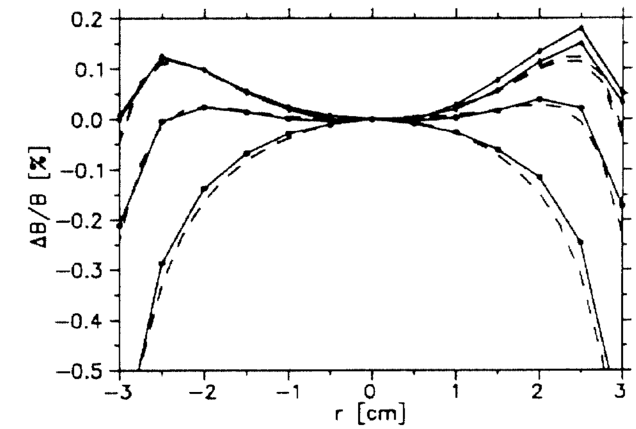

Fig.1 Field homogeneity in the centre of the dipole magnet at various current levels : 200 A (upper curves), 600 A, 800 A and 1000 A (lowest curves); solid lines - measurements, dashed lines - calculations.

Field maps were carried out at excitations corresponding to possible operating levels at 1.0, 1.5 and 2.0 GeV. The spacing of points in the x direction was that of the Hall plate separation, 1 cm, while in the z-direction it varied between 5 cm in the centre of the magnet and 2 cm in the fringe field region. In the case of the 31.4^{o} magnets the probe could be mounted in either of two positions in order to cover the required scan range (± 1.4 m) without the necessity of moving the magnet. The maps were analyzed by firstly determining the energy (E) and trajectory of the electron that starts from the centre of the magnet and exits with the correct bending angle (θ). Field values were then interpolated (cubic spline) at points lying on a series of curves that have a constant radial separation (r) from the central trajectory (i.e. concentric in the case of constant radius), r positive signifying radially inwards. The homogeneity is expressed as the difference of the field integrals along these curves with respect to the central trajectory. Table 2 presents a summary of the results of these measurements at different currents (I). L_{mag} is the magnetic length i.e. the field integral of the central trajectory divided by the central field (B_0), and ρ_0 is the bending radius at the magnet centre (L_{mag}/θ).

Table 2. Results of integrated field measurements for the two dipole magnet types.

I (A)	θ	B_0 (T)	L_{mag} (m)	E (GeV)	ρ_0 (m)
400. 0	15.7	0.746	1.2251	0.9995	4.4709
605.4	15.7	1.126	1.2242	1.5086	4.4678
833.0	15.7	1.502	1.2210	2.0060	4.4558
400. 0	31.4	0.746	2.4411	0.9964	4.4543
605.4	31.4	1.127	2.4400	1.5045	4.4522
833.0	31.4	1.504	2.4338	2.0029	4.4409

It can be seen that the smaller dipole has a slightly larger magnetic length and hence bending radius compared to the nominal value, however the resulting trajectory deviation is not large enough to influence the field homogeneity. The length of the 31.4^o dipole was adjusted following the measurement of the first 15.7^o magnet and it can be seen that the correct bending radius is obtained between the main operating levels of 1.5 and 2 GeV as required.

Small differences between the entrance and exit of the magnets were noted of about 1.4 mm in magnetic length, corresponding to 0.02^o in bending angle, due to the asymmetry of the coil geometry which arises from the location of the coil connections. Differences between the magnets were sufficiently small, within 1.9 10^{-3} for the integrated field of the three large dipoles at the same current level.

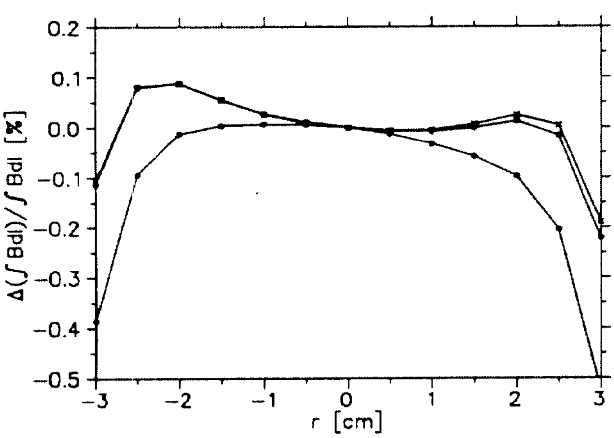

Fig.2. Integrated field uniformity of the 31.4^o dipoles at 400 A (upper curve), 605 A and 833 A (lower curve).

The homogeneity of the integrated field is very similar for all magnets and typical results are shown in fig.2. The average slope may be interpreted as a small reduction in end-angle of between 1.39^o and 1.75^o, depending on current, for the 31.4^o magnets; for the smaller magnets the homogeneity is very similar, implying an end-angle change of 0.6-0.8^o. When this is taken into account, the integrated field uniformity is within ± 0.15 %, which is acceptable.

3. QUADRUPOLE MAGNETS

The main parameters of the quadrupoles are summarized in Table 3. The prototype quadrupole was measured using the rotating coil system set up for the storage ring quadrupoles and sextupoles [3]. A special coil assembly was constructed, similar to those used for the storage ring magnets, with an outer radius (23.67 mm) as close as possible to the magnet inscribed radius in order to maximize the sensitivity to the higher harmonics. The assembly includes a second coil with half the radius in order to distinguish between real harmonic field components (scaling as r^n, for a 2n-pole field) and errors introduced by rotational inaccuracies (scaling as r).

Table 3. Main parameters of the transfer line quadrupoles

Inscribed radius	25 mm
Yoke length	482 mm
Pole width	48 mm
Maximum gradient	22 T/m
Turns per pole	47
Maximum current	116 A

The results of measurements made at the nominal maximum excitation (116 A) are presented in Table 4, scaled to a reference radius of 25 mm, and after correction of the sextupole and octupole errors. The average of nine measurements is shown; the reproducibility for a single measurement was in the range 0.002-0.004 % rms.

Table 4. Harmonic content of the tranfer line quadrupole.

Component, n	Harmonic content (%)
3	0.010
4	0.005
5	0.006
6	0.090
7	0.005
8	0.006
9	0.006
10	0.017
> 10	< 0.005

The results are within the tolerances specified for the magnet. The harmonic content does not change appreciably with excitation level, despite the onset of saturation which reduces the integrated field strength by about 2.2 % at 116 A.

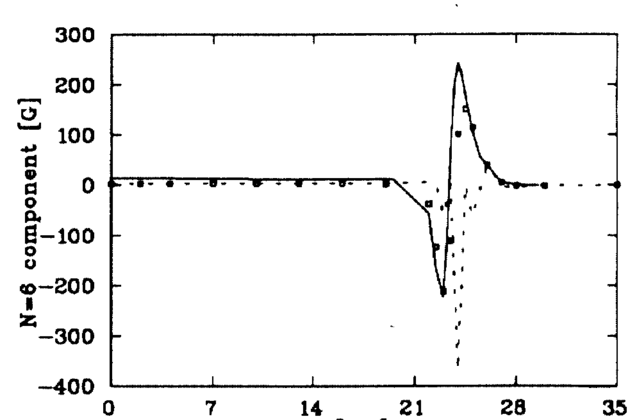

Fig. 3. Variation of dodecapole component with longitudinal position , referred to a radius of 25 mm; z=0 is the magnet centre. Solid line - measured, dashed line - calculated with no end-cut, points - calculated with end-cut.

An interesting feature of the measuring system is the ability to measure the harmonic content at a variable longitudinal position in the magnet by means of a rotating Hall plate instead of an integrating coil. In particular this has allowed us to verify the effect of the end profile, which had been chosen empirically in order to minimize the integrated dodecapole (n=6) component. Figure 3 shows the measured variation of this component and for comparison the results of 3D field calculations using TOSCA [5], both with no end cut and for a very similar end cut to the one used in practise. With no end cut there is a strong negative dodecapole component. The measurements and calculations indicate that an end cut introduces a compensating positive dodecapole, so that by correct choice of dimensions the integrated value can be reduced to zero.

4. STEERER MAGNET

The steerer magnet is of a simple design with a U-shaped yoke which can be installed in such a way as to provide horizontal or vertical steering correction [2]. The single coil contains 170 turns of enamelled copper wire is used, with cooling provided by an external water-jacket formed by standard water-cooled copper conductor. Magnetic measurements were performed using the point-by-point (Hall plate) and integrated field (flipping coil) measurement systems set up for the ELETTRA insertion devices [6]. Table 5 summarizes the the main parameters of the magnet and the measured field strength at the nominal maximum current (25A). The required deflection of 3 mrad at 2 GeV, i.e. field integral of 20.0 T mm, is clearly met.

Table 5. Main parameters of the steering correction magnets

Central field	0.0925 T
Integrated field	24.005 T·mm
Pole gap	50 mm
Number of turns (total)	170
Maximum current	25 A
Steel length	200 mm
Magnetic length	260 mm

Figure 4 shows the homogeneity of the integrated magnetic field, in the horizontal (x) and vertical (y) directions when the magnet is orientated so as to produce a vertical field component. As expected the field is very uniform in the field direction, about 0.5 %. There is a greater variation along the length of the poles with a uniformity of about 4 % inside the beam aperture of ± 2.5 cm, which is acceptable.

The integrated remanent field in the magnet after repeated uni-directional cycling up to 25 A is about 0.15 T mm, or 0.6 % of the maximum strength, which is within the required specification.

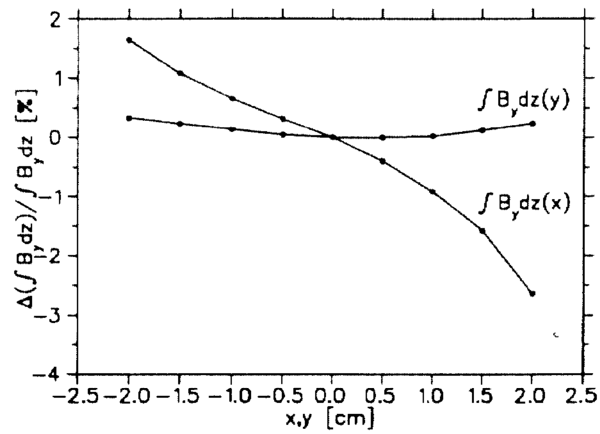

Figure 4. Variation of integrated field in the steerer magnet with transverse position.

5. ACKNOWLEDGEMENTS

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