Magnetic Measurement and Alignment of the ELETTRA Storage Ring Quadrupole, Sextupole and Steerer Magnets

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Abstract

The results of magnetic measurement of the quadrupoles, sextupoles and steerer magnets for the ELETTRA storage ring are presented. The performance of the rotating coil measurement bench and the system used for positioning the reference targets is also described.

I. INTRODUCTION

The ELETTRA storage ring contains 108 quadrupoles in three families of different lengths, 72 sextupoles of two different lengths and 82 steerers [1,2]. All of the magnets have now been constructed : the quadrupoles and sextupoles by Ansaldo Componenti, Italy, the steerers by Tesla Engineering, England. A previous report dealt with the measurement of the prototype magnets [3]. This report presents the definitive results of the magnetic measurements of all the quadrupole and sextupole series production using the test system developed at CERN [4] and later transferred to Trieste. Also presented are some preliminary results of the steerer magnets.

II. MEASUREMENT AND ALIGNMENT SYSTEM

A. General

Magnetic measurements have been carried out with a rotating coil system. The voltage induced in the coil during one constant speed rotation (T=25.6 sec.) is read out by a 3852A HP voltmeter. A FFT analysis is then executed to calculate the harmonic components of the signal. In order to maximize sensitivity different coils have been used for quadrupoles and sextupoles having as large an outer radius as possible - 36.17 mm for the quadrupoles (inscribed radius = 37.5 mm), and 43.69 mm for the sextupoles (radius 45.0 mm). The accuracy of the system is about 0.5 μV, which corresponds to between $2\ 10^{-5}$ and 10^{-4} of the main component at the coil radius at maximum current level, depending on the magnet type. At the reference radius of 25 mm the sensitivity to the higher multipole components is even greater.

Calibrations have been calculated directly from the geometric parameter of the coil. Each coil assembly includes a total of 4 separate coils: divided between left and right, and between outer (radius R) and inner (radius R/2). Each coil has 8 turns and can be selected separately or together with another coil in order to obtain the sum or the difference of the induced voltage. The alignment of the quadrupole or sextupole magnetic axis to the coil axis is performed using the left and right coils separately, in order to eliminate any compensation of the alignment errors (i.e. pitch and yaw errors). The inner coils were used to check that the multipole terms scaled correctly with radius, and hence that rotation errors were not introducing false harmonics.

The system also allows a Hall plate to be installed (radius = 29.7 mm) in order to determine the central field strength and hence magnetic length, and also to make a harmonic analysis of the field at any desired longitudinal position.

During routine operation about 4 hours were needed for installation, measurement and alignment of each magnet. Thus, 3 magnets were regularly measured per day, however only 13 magnets per week could be achieved due to need to check the system alignment using a reference magnet (see below). The reproducibility of the system as determined by measurement of the reference magnet, was within 0.01% for both the main and the multipole components.

Since the poles of the magnets have to be opened to install the vacuum chamber, the measurements have been performed after opening of the poles. The reproducibility measured after two successive opening and closing operations was within 10^{-4}.

B. Alignment System

The location of the magnetic axes of the quadrupole and sextupole magnets must be determined with good accuracy [5] to install and align correctly the magnets in the storage ring. This operation was executed by means of a Micro-Alignment telescope manufactured by Rank Taylor-Hobson. During the magnetic measurements supports for Taylor-Hobson survey targets and an adjustable reference plane were positioned on each magnet. The sensitivity was about 20 μm for the targets and 20 μrad for the reference plane.

To align the telescope axis to the coil axis so as to define a vertical plane we used the following procedure: align the magnetic axis of a long-quadrupole with the coil axis; centre the Taylor-Hobson spheres with the telescope axis and level the reference plane; rotate the magnet around the vertical axis by 180^{o} and re-align it using the Taylor-Hobson spheres and the reference surface. Then, if the telescope axis is aligned to the coil axis the measured displacement between the magnetic axis and the coil axis is zero. Otherwise a correction is made to the telescope axis and the operation repeated. In practise about 4 magnet rotations were necessary to perform a bench alignment to within 25 μm.

Some problems were experienced with maintaining a good alignment of the measurement system even though the measurement area was temperature stabilized within 5 °C. It is presumed that this was caused by ground movements due to either settlement and/or external temperature changes. As a result it was necessary to check the alignment at the beginning and end of each week using a reference quadrupole.

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If errors greater than 30 μm were seen a re-alignment of the telescope was carried out. After each re-alignment the magnet was rotated and re-measured to confirm that the survey target positions on the reference magnet had not altered.

The roll angle of each magnet was aligned with respect to the coil within 0.01^o. However, the accuracy of setting the coil angle i.e. the effective starting point of the measurement was within $\pm 0.02^o$, determined by the spirit level that was used.

The maximum alignment error permitted between the quadrupole or sextupole magnetic axis and the coil axis (left and right coil separately) was 10 μm.

III. QUADRUPOLES

Table 1 presents the main magnetic measurement results for the three types of quadrupole.

Table 1. Main component in the three quadrupole types at maximum current (300 A).

	Short	Medium	Long
Peak gradient (T/m)	19.6	20.4	20.6
Peak integrated gradient (T)	5.07	8.27	10.16
Magnetic length (m)	0.26	0.41	0.49

The specified integrated strengths are obtained with a current of about 295 A, at which level the saturation is 15% for the short quadrupole, 12% for the medium quadrupole and 11% for the long quadrupole.

Tables 2-4 summarize the variations in the main component and the multipole components at 1/3, 2/3 and maximum current level. The numbers of each type of magnet are indicated. Both systematic (average) and random (r.m.s.) parts are given, separately for normal and skew components. The values refer to the percentage field error at a reference radius of 25 mm. Only components with systematic or random components above 10^{-5} are shown.

With respect to the prototype results [3] it can be seen that an improved technique for pole positioning has led to a reduction in components n=3,4,5, while selection of a suitable end-cut has significantly reduced the dodecapole (n=6) component. Some changes in the systematic octupole (n=4) and dodecapole with current can be seen; the former due to a small closure of the C-shaped support structure, the latter due to saturation effects.

The performance is within specification [6] apart from the random variation in quadrupole strength and systematic normal octupole component, which are at most two times larger than the specified values. However, calculations have shown that the magnets are acceptable [7].

The magnets were aligned magnetically at 300 A. The centre of the magnetic axis moves slightly with current in both planes, but on average by less than 10 μm between 100 and 300 A, and with a maximum displacement of 50 μm. No appreciable change in angle was seen ($\leq 0.01^o$).

IV. SEXTUPOLES

Table 5 summarizes the main results for the two sextupole types.

Table 2. Multipole content of the short quadrupoles (60)

Normal Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
2	-	0.125	-	0.134	-	0.174
3	0.036	0.023	0.027	0.024	0.025	0.026
4	0.019	0.019	0.024	0.021	0.029	0.023
5	0.001	0.003	0.001	0.003	0.001	0.003
6	-0.001	0.002	-0.005	0.002	-0.018	0.003
10	-0.011	0.0	-0.011	0.0	-0.012	0.0

Skew Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
3	0.0	0.027	-0.001	0.026	-0.004	0.029
4	-0.002	0.003	-0.002	0.004	-0.002	0.004
5	-0.001	0.003	-0.001	0.003	0.0	0.003

Table 3. Multipole content of the medium quadrupoles (24)

Normal Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
2	-	0.065	-	0.064	-	0.083
3	0.028	0.029	0.019	0.029	0.014	0.034
4	0.016	0.015	0.025	0.016	0.033	0.017
5	0.003	0.004	0.003	0.004	0.003	0.004
6	-0.009	0.002	-0.013	0.002	-0.028	0.002
10	-0.007	0.0	-0.007	0.0	-0.009	0.0

Skew Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
3	-0.009	0.024	-0.010	0.023	-0.015	0.020
4	-0.001	0.004	-0.001	0.003	-0.001	0.004
5	0.0	0.002	0.0	0.002	0.001	0.002

Table 4. Multipole content of the long quadrupoles (24)

Normal Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
2	-	0.118	-	0.120	-	0.109
3	-0.012	0.038	-0.019	0.041	-0.020	0.042
4	0.013	0.027	0.025	0.029	0.038	0.031
5	-0.003	0.005	-0.003	0.005	-0.003	0.005
6	-0.004	0.003	-0.008	0.003	-0.022	0.003
10	-0.006	0.0	-0.006	0.0	-0.008	0.0

Skew Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
3	-0.006	0.029	-0.007	0.027	-0.010	0.026
4	-0.001	0.003	-0.001	0.003	-0.002	0.003
5	-0.001	0.002	-0.001	0.003	0.0	0.003

Table 5. Main component (B/r^2) in the two sextupole types at maximum current (300 A)

	Short	Long
Peak strength (T/m^2)	262	282
Peak integrated strength (T/m)	40	74
Magnetic length (m)	0.152	0.264

The specified strength is reached at 247 A for the short sextupole, and 278 A for the long sextupole, at which level the saturation is 6 % and 4 % respectively.

Tables 6 and 7 summarize the measurement results for the sextupoles, referred to a radius of 25 mm. As for the quadrupoles, an improved technique for pole positioning has led to significant reductions in the n=4,5,6 errors with respect to the prototype [3]. The magnets are within specification apart from the random variation in sextupole strength, and the random normal and skew octupole components, which in both cases are up to two times larger than the originally specified values. Later calculations however showed that the magnets are acceptable.

The sextupoles also contain small systematic and random dipole errors, with maximum values (300 A) of 1.3 10^{-4} Tm for the short sextupoles and 3.2 10^{-4} Tm for the long sextupoles.

Alignment was carried out in this case at 150 A. The maximum displacement of the magnetic centre in the range 100-300A was 20 µm in the horizontal plane and 40 µm in the vertical. The maximum angle error was less than 0.02°.

Table 6. Multipole content of the short sextupoles (24)

Normal Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
3	-	0.234	-	0.232	-	0.182
4	-0.021	0.031	-0.025	0.030	-0.019	0.032
5	0.001	0.012	-0.001	0.012	0.012	-0.002
6	0.015	0.013	0.016	0.012	0.018	0.012
9	-0.023	0.001	-0.023	0.001	-0.024	0.001

Skew Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
4	0.034	0.046	0.031	0.042	0.022	0.037
5	-0.014	0.017	-0.015	0.017	-0.014	0.016
6	0.001	0.003	0.001	0.002	0.001	0.003

Table 7. Multipole content of the long sextupoles (48)

Normal Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
3	-	0.147	-	0.165	-	0.182
4	0.001	0.039	0.002	0.038	0.014	0.037
5	0.008	0.012	0.006	0.012	0.006	0.012
6	0.018	0.012	0.024	0.012	0.031	0.012
9	-0.007	0.001	-0.007	0.0	-0.008	0.001

Skew Components (%)

	100 A		200 A		300 A	
n	syst.	rand.	syst.	rand.	syst.	rand.
4	0.020	0.045	0.017	0.046	0.007	0.045
5	-0.007	0.014	-0.006	0.013	-0.007	0.013
6	0.0	0.002	0.0	0.002	0.0	0.002

V. STEERERS

The steerer storage ring magnets (82 units) [2] have been designed to provide both horizontal and vertical correction. Measurements of the first magnet have been performed with the same rotating coil bench used for the quadrupole and sextupole magnets. The series magnet measurements will be carried out in June. In Table 8 are shown the magnetic measurement results of the prototype.

Table 8. Main field components in the prototype storage ring steerer magnet

	Horizontal Field	Vertical Field
I (A)	12	16
B_0 (G)	493.9	450.9
$\int B\,dl$ (G m)	139.0	126.9
L_{mag} (m)	0.281	0.281

Table 9 shows the integrated field homogeneity of the magnet measured at maximum current, referred to a radius of 25 mm. The harmonic content does not change appreciably with excitation level.

Table 9. Harmonic content of the steerer magnet (%)
(N) = Normal component, (S) = Skew component

n	Horizontal Field	Vertical Field
2	2.1 (N)	0.1 (S)
3	1.2 (S)	0.8 (N)
4	0.15 (N)	0.02
5	0.02	0.1
6	≤0.01	0.1
≥ 7	≤0.01	≤0.01

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