Construction of Undulator U5.6 for ELETTRA

B. Diviacco, R. Bracco, A. Codutti, D. Millo, R. P. Walker and D. Zangrando
Sincrotrone Trieste, Padriciano 99, 34012 Trieste, Italy

Abstract

The construction and performance of the U5.6 undulator for ELETTRA is described, including the methods used to optimize the field quality and the results of detailed magnetic field measurements.

1. INTRODUCTION

The recently commissioned ELETTRA storage ring [1] presently accommodates 3 insertion devices out of a total number available of 11. Table 1 summarizes the main parameters of these devices including the maximum field and K value at the operational minimum gap. The two undulators (U) have a pure permanent magnet configuration, while the multipole wiggler (W) is of the hybrid type. Each device consists of 3 separate sections based on a standard 1.5 m support structure. The construction of the U12.5 device was reported previously [2], while a companion paper deals with the construction of the multipole wiggler [3]. A forthcoming report will deal with the operating performance including effects on the electron beam and analysis of the first radiation spectra [4].

Table 1
Main parameters of the initial ELETTRA Insertion Devices; N = number of periods.

ID	N	Gap (mm)	Bo (T)	K
U12.5	36	28.0	0.506	5.91
U5.6	81	27.0	0.444	2.34
W14.0	30	26.0	1.30	17.0

Initial operation of the U5.6 device was with the standard vacuum chamber which permitted a minimum gap of only 70 mm, and hence a low K value of 0.2. The first light was observed on 7th November 1993. Since then narrow gap vessels, 4.8 m long, and with nominal external dimension of 25 mm, have been installed in all of the 3 ID straight sections. Figure 1 shows a view of the undulator in the storage ring. The actual minimum gaps that are currently allowed, as a result of alignment tolerances and the safety interlock system requirements, are reported in Table 1. Although slightly larger than the nominal value the field achieved in all cases either equals or exceeds the specified values.

Beyond this first phase an undulator with 8 cm period is under construction. There are also plans for further undulators, including a device for circularly polarized radiation.

2. DESIGN AND CONSTRUCTION

Undulator U5.6 is designed to cover the photon energy range 250 eV - 1 keV at 1.5 GeV. A period length of 5.6 cm was selected to give a sufficiently high K value (2.3) for a reasonable overlap between the first and third harmonics at minimum gap. A standard arrangement of 4 blocks per period with 28 mm block height was used. A block width of 85 mm was chosen to obtain a field roll-off defined by $k_x/k < 0.1$. Blocks are clamped into individual holders, which are then assembled onto a baseplate.

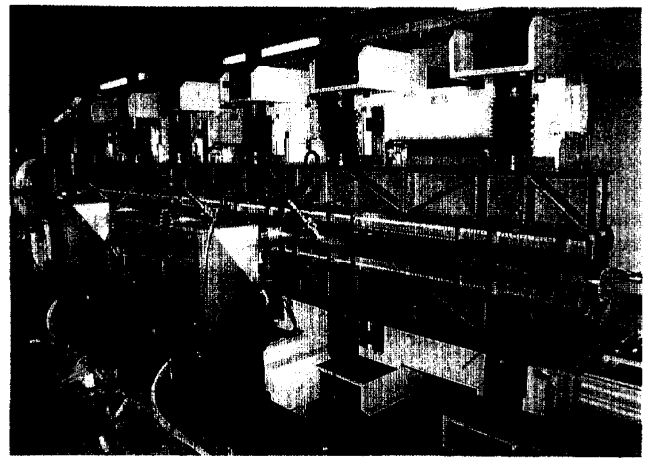

Figure 1. Photo showing the installed U5.6 device.

NdFeB permanent magnet blocks were obtained from Outokumpu magnets (NEOREM 440i), passivated and oiled to prevent corrosion. Each block has been measured in detail in the two possible orientations that were allowed for assembly using a small Hall plate bench dedicated to block measurements. Both transverse field components were measured at a grid of points, 81 points in z over ± 2 period lengths and 13 points in x over ± 60 mm; the vertical height (y) corresponded to the future minimum gap of 20 mm. About 15 minutes were required in total for each block. Two months were required to measure the 740 blocks. A reference block was measured each day in order to guarantee that there were no changes in conditions during the measurement period.

Data from the measurements were used in a "simulated annealing" program to optimize the block configuration, based on linear superposition of the fields of different blocks. The optimization was performed for all 3 sections at the same time, but including some parameters based on the individual sections. The cost function to be minimized included the following terms : first and second field integrals of both field components at all x positions within ± 60 mm, for each section separately and for all 3 sections; r.m.s. phase error and trajectory straightness for the complete device and separately for the top and bottom arrays [5].

The first section was assembled using the defined configuration and measured using Hall plate and flipping coil benches [6]. Good agreement was obtained between the predicted and measured field distributions apart from the appearance of a large (~ 7 Gm) integrated horizontal field component, that would have been hard to remove by shimming alone. Measurements revealed that this was distributed over the entire device, consistent with an error in the individual block measurements of about 32 Gmm. Such an error is an order of magnitude greater than considered possible due to the planar Hall effect. Measurements of the Hall plate that was used however revealed a strange dependence of the output with the angle of the in-plane field component that is consistent with the observed error in the field integral [7]. An empirical correction was therefore applied to the block data to remove the discrepancy in the horizontal field integral, and then the simulated annealing was re-run. The first section was then dismantled and re-constructed according to the new configuration. As expected, much better agreement was then obtained between predictions and measurements.

After construction all three sections were close to the required performance, apart from the integrated multipole errors. A shimming was therefore carried out, using algorithms previously used on the U12.5 undulator, which take into account simultaneously field integral errors and phase error [2,5]. In the previous case the shimming had resulted in improvements in all parameters, but in this case since the correction required for the multipole errors was greater, it only proved possible to maintain the same phase error, without employing an excessive number of shims.

3. PERFORMANCE

Table 2 summarizes the final results obtained after shimming for all 3 sections [8], including the r.m.s. field amplitude (σ_B), r.m.s. phase (σ_Φ), the maximum range of variation of the first (ΔI_1) and second (ΔI_2) field integrals over the "good field region" of ± 25 mm, and intensities (i.e. peak angular flux density) of the first, third and fifth harmonics relative to an ideal undulator (R_1, R_3, R_5). It can be seen that the field integrals are well within the specified limits of ± 1 Gm and ± 2.5 Gm^2 at all gaps. Fig. 2 shows a typical distribution of field integrals for one section. The second field integral is defined in such a way that it corresponds to the displacement of the electron beam referred to the centre of the device. The r.m.s. phase error is less than 5^o for all sections at any gap, with the result that the 5th harmonic has at least 60% of its ideal intensity for each section. The r.m.s. field error is shown only for interest since it bears little relationship to the resulting performance.

Table 2
Performance of the 3 sections of the U5.6 undulator.
Units : gap (mm), σ_B (%), σ_Φ (degree), ΔI_1 (G m), ΔI_2(G m^2)

	section 1			section 2			section 3		
gap	20	30	50	20	30	50	20	30	50
σ_B	0.7	0.7	1.2	0.7	0.8	1.1	0.7	0.8	1.4
σ_Φ	4.9	4.8	2.6	4.5	4.3	2.2	4.8	4.7	3.0
ΔI_1	.38	.33	.57	.58	.44	.29	.54	.56	.37
ΔI_2	1.0	.49	.14	.64	.36	.23	1.3	.84	.41
R_1	.97	.99	.95	.96	1.0	.96	.96	1.0	.95
R_3	.90	.81	.76	.92	.85	.81	.93	.88	.79
R_5	.70	.61	.59	.78	.70	.68	.82	.70	.58

The superposition of the measured field for the three sections produces the trajectory shown in fig. 3. The phase values at the position of the poles is also shown. Table 3 summarizes the performance of the combined undulator at

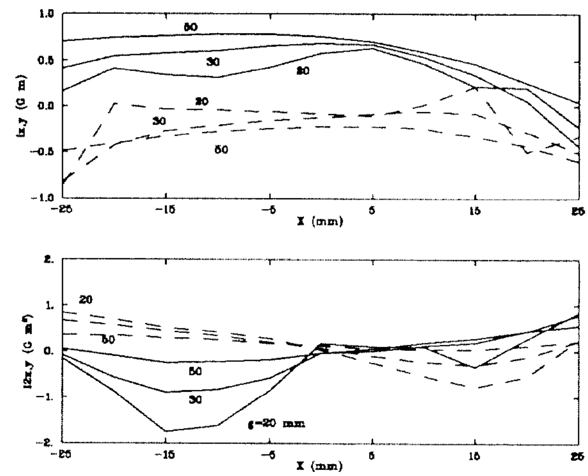

Figure 2. First and second field integrals for a typical section of U5.6.

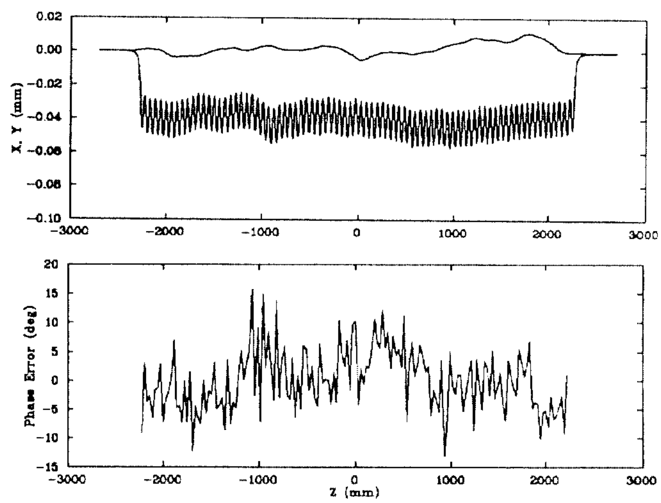

Figure 3. Calculated trajectory and radiation phase in the complete U5.6 undulator at minimum gap.

three different gaps. The average measured values of field amplitude, K value and transverse roll-off parameter, $B_y = B_o(1-k_x x^2/2)$, are also shown. The latter meets the required specification of $k_x < 11.2$ at minimum gap.

Table 3
Results of the superposition of the measured field of the three U5.6 sections.

Gap (mm)	20.0	30.0	50.0
B_o (T)	0.654	0.374	0.121
K	3.7	2.0	0.6
k_x (m^{-1})	8.9	11.2	15.3
σ_B (%)	0.8	0.8	1.3
σ_ϕ (deg.)	5.5	5.4	3.3
R_1	0.98	0.99	0.98
R_3	0.91	0.88	0.88
R_5	0.77	0.72	0.72

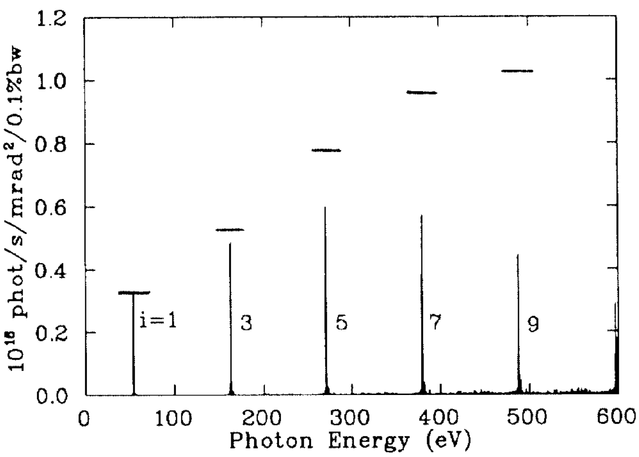

Figure 4. Calculated on-axis spectrum for the complete U5.6 device at minimum gap. The intensities of an ideal undulator are as indicated.

The phase error is sufficiently small to produce good output up to at least the 9'th harmonic, as shown in fig. 4.

It is worth mentioning that the relative intensities in Table 2 and 3 are with respect to an ideal undulator with equal field strength for each pole, as assumed in the usual analytical calculation. An undulator constructed of perfect permanent magnet blocks however does not give such a field distribution. The field of the outermost poles are not equal to the central ones, an effect which increases with the gap. Thus even in the perfect undulator case, there is a non-zero phase error and hence significant intensity reduction which depends on the gap. Table 4 shows this effect in the present case for a single section and for the three undulator sections. In calculating the r.m.s. phase in Tables 2,3 and 4 the first 8 full poles have been neglected in order to eliminate the edge effect.

Table 4
Relative intensity and r.m.s. phase error for a perfect pure permanent magnet undulator of N periods.

	N=27			N=81		
gap	20	30	50	20	30	50
σ_Φ	0.2	0.4	0.4	0.1	0.2	0.2
R_1	.97	1.0	.97	.99	1.0	.99
R_3	.97	.94	.86	.99	.98	.95
R_5	.94	.85	.75	.98	.95	.91

Placing the sections together introduces additional effects that need to be considered in order to achieve the performance indicated above. The finite separation introduces a phase difference of the radiation emitted in each section and the non-unit permeability of the NdFeB material introduces a small vertical field component [9]. The former has been overcome by positioning the undulator sections with a small separation of between 0.5 and 1.0 mm. The latter are overcome using a set of steering coils.

Sets of simple air cooled correction coils [10] have been installed at each end on each section of U12.5 and U5.6. Each coil has 100 turns of enamelled conductor. The four coil set at each end can produce horizontal or vertical dipole fields, depending on the coil connections, of up to 1.2 (1.6) Gm in the horiz. (vert.) plane at maximum excitation (1A). The power dissipation is sufficiently small that there is no significant temperature rise. Four channel ±1A power supplies have been implemented for each of the two IDs. At present the coils are configured to produce horizontal field correction at either end of the ID, and vertical field correction at the two interfaces between the 3 sections. This allows correction of first and second field integrals of both components including interaction effects between sections.

A factor that has to be taken into consideration in the construction of a segmented undulator is the relative strength of the sections. To have a negligible effect on the radiation linewidth it is required to set each section to the same output wavelength within ± 0.1 %, and hence (at large K) the field strengths within $\pm 5\ 10^{-4}$ and the gap within ± 10 µm. Such a variation can also be induced by a temperature difference of only ± 0.5 °C. The final measurements for each section, to determine the average field value for a range of gap settings, were therefore carried out under stable and carefully monitored temperature conditions. The data were then fitted to obtain a suitable calibration curve. The required gap for a given K value is expressed in the following form :

$$g = a_0 + a_1 \ln(K) + a_2 \ln(K)^2 + a_3 \ln(K)^3 + a_4 \ln(K)^4$$

The fit error was less than 10 µm over the useful range of gap from 20 to 70 mm. To take into account a difference in operating temperature (T) with respect to the value at which the measurements were performed (T_{ref}) the K value in the expression above is replaced by : $K/[1-\alpha(T-T_{ref})]$, where α was empirically determined to be $9.5\ 10^{-4}\ {}^\circ C^{-1}$. The inverse calibration is obtained from the following expression :

$$K = b_0 \exp(-b_1 g - b_2 g^2 - b_3 g^3 - b_4 g^4)[1-a(T-T_{ref})]$$

4. REFERENCES

[1] A. Wrulich, "Status of ELETTRA", these Proceedings.

[2] R.P. Walker et al., "Design, Construction and Testing of Insertion Devices for ELETTRA", Proc. 1993 US Particle Accelerator Conference, p. 1587.

[3] A. Codutti et al., these Proceedings.

[4] B. Diviacco and R.P. Walker, to be published.

[5] B. Diviacco, "Performance Optimization of Pure Permanent Magnet Undulators", Ref. [2] p. 1590.

[6] D. Zangrando and R.P.Walker, "Magnetic Measurement Facility for the ELETTRA Insertion Devices", Proc. 3rd European Particle Accelerator Conference, Berlin, March 1992, p.1355.

[7] D. Zangrando, "Magnet Measurement Techniques at Sincrotrone Trieste", Proc. Int. Workshop on Magnetic Measurements of Insertion Devices, Argonne Nat. Lab.., Sep. 1993, ANL/APS/TM-13, p. 44.

[8] B. Diviacco and R.P. Walker, ST/M-TN-93/14.

[9] B. Diviacco and R.P. Walker, "Magnetic Interaction Effects in ELETTRA Segmented Pure Permanent Magnet Undulators", Ref. [2] p. 1593.

[10] B. Diviacco et al., "Status of the Development of Insertion Devices for ELETTRA", Rev. Sci. Instr. 62 (1992) 388.