# Design, Construction and Testing of Insertion Devices for ELETTRA

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*Abstract*
The design, construction and testing of the first two undulators that will be installed in ELETTRA is described. Some details are given also of the future program of Insertion Device development.

## I. INTRODUCTION

The ELETTRA storage ring wil accommodate 11 insertion devices, each up to 4.8 m long. At present five devices have been approved for construction, serving a total of 8 beamlines, as detailed in Table 1. Undulators (U) will have a pure permanent magnet configuration, while the multipole wiggler (W) will be of the hybrid type. Each device consists of up to 3 separate sections based on a standard 1.5 m support structure. Previous work on the construction of prototypes was reported in ref. [1].

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

| Beamlines | ID | N | Gap (mm) | Bo (T) | K |
|---|---|---|---|---|---|
| ID3A,B | U12.5 | 36 | 25.0 | 0.486 | 5.67 |
| ID2A,B | U5.6 | 81 | 25.0 | 0.445 | 2.33 |
| | | | 20.0 | 0.590 | 3.09 |
| ID5A,B | W14.0 | 30 | 25.0 | 1.15 | 15.0 |
| | | | 20.0 | 1.55 | 20.3 |
| ID4 | U8.0 | 19 | 25.0 | 0.713 | 5.33 |
| | | | 20.0 | 0.866 | 6.47 |
| ID6 | U12.5 | 36 | 25.0 | 0.486 | 5.67 |

The first device (U12.5) has been constructed and tested, and the second (U5.6) is presently being assembled. Both devices will be installed in the ring this Summer, before beam commissioning. At this time the standard vacuum chamber will permit a minimum gap of 60 mm. Early next year one section of the wiggler and the undulator U8.0 will be installed, together with the 25 mm narrow gap vacuum vessels. The remaining two sections of the wiggler W14.0 and a second U12.5 will subsequently be installed. Beyond this first phase there are plans for other undulators, including a device for circularly polarized radiation. Initial operation will be at 1.5 GeV. Future developments will include operation at 2 GeV, and reduction of selected ID gaps to 20 mm.

## II. UNDULATOR U12.5

The first undulator is required to operate over a total range 10-800 eV, for ring energies of 1.5-2 GeV. To obtain the minimum energy various period lengths could have been chosen. The value selected, 12.5 cm, is a compromise between minimizing the power density (long period, small K) and maximizing the flux at high energy (small period, high K). The resulting field strength, 0.486 T, is sufficiently small that a space of 5.25 mm can be left between the blocks (4 blocks per period), and a block height of only 21.5 can be used. In addition a simple clamping scheme can be used, increasing the gap between magnets to 29 mm. A block width of 100 m was chosen in order to limit the systematic quadratic field variation, cos $(k_x x)$, to $k_x/k < 0.2$ $(k=2\pi/\lambda_o)$. The correct periodicity is maintained by means of an accurately machined 'comb', making use of the spaces between the blocks. The resulting structure, shown in fig. 1, is thus very simple and cost effective.

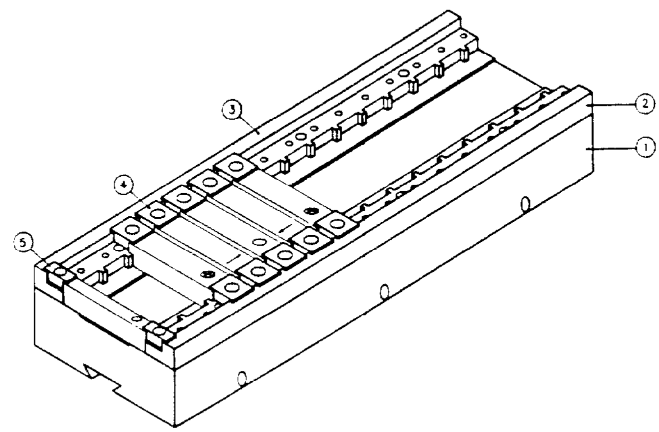


Figure 1. Structure of the magnetic arrays of undulator U12.5.

NdFeB permanent magnet blocks of NEOREM 30 H were obtained from Outokumpu magnets, with Nickel coating. Each block was measured in detail using a Hall plate system [2] in the two possible orientations that were allowed for assembly. 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 minimum gap of 29 mm. About 15 minutes were required in total for each block.

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 for the complete device and separately for the top and bottom arrays. Further details may be found in a separate report [3]. 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.

Each of the 3 sections has been assembled using the

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Table 2.
Magnetic measurement results for the 3 sections of U12.5 before and after shimming. Units: gap (mm), $\sigma_B$ (%), $\sigma_\phi$ (deg.), $\Delta I_{1,x,y}$ (Gm), $\Delta I_{2,x,y}$ ($Gm^2$)

| | Section 1 | | | Section 2 | | | Section 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| gap | 29 | 50 | 100 | 29 | 50 | 100 | 29 | 50 | 100 |
| *before shimming* : | | | | | | | | | |
| $\sigma_B$ | 1.1 | 0.8 | 0.8 | 1.3 | 0.8 | 0.6 | 1.4 | 1.0 | 1.0 |
| $\sigma_\phi$ | 4.5 | 4.7 | 4.1 | 2.9 | 3.2 | 3.6 | 5.4 | 4.9 | 3.7 |
| $\Delta I_{1,x,y}$ | 1.4 | 0.7 | 0.5 | 0.9 | 0.6 | 0.3 | 1.5 | 0.7 | 0.3 |
| $\Delta I_{2,x,y}$ | 1.5 | 0.8 | 0.3 | 1.0 | 0.5 | 0.2 | 1.0 | 0.5 | 0.2 |
| $R_1$ | 1.0 | 1.0 | 0.99 | 1.0 | 1.0 | 0.99 | 0.97 | 0.97 | 1.0 |
| $R_3$ | 0.96 | 0.94 | 0.95 | 0.99 | 0.98 | 0.98 | 0.89 | 0.96 | 0.96 |
| $R_5$ | 0.85 | 0.86 | 0.84 | 0.93 | 0.92 | 0.91 | 0.85 | 0.81 | 0.88 |
| *after shimming*: | | | | | | | | | |
| $\sigma_B$ | 0.8 | 0.6 | 0.7 | 1.1 | 0.8 | 0.6 | 0.9 | 0.6 | 0.7 |
| $\sigma_\phi$ | 3.2 | 3.5 | 3.8 | 3.0 | 3.2 | 3.6 | 2.8 | 3.0 | 3.4 |
| $\Delta I_{1,x,y}$ | 0.5 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.4 | 0.3 | 0.2 |
| $\Delta I_{2,x,y}$ | 1.3 | 0.8 | 0.3 | 1.0 | 0.5 | 0.2 | 1.3 | 0.7 | 0.3 |
| $R_1$ | 1.0 | 1.0 | 0.99 | 1.0 | 1.0 | 0.99 | 0.98 | 0.98 | 1.0 |
| $R_3$ | 0.97 | 0.96 | 0.95 | 0.98 | 0.98 | 0.95 | 0.94 | 1.0 | 0.97 |
| $R_5$ | 0.92 | 0.90 | 0.88 | 0.96 | 0.91 | 0.90 | 0.95 | 0.90 | 0.92 |

defined configuration and measured using the same system as for the block measurements. The results for all sections are summarized in Table 2, which includes the r.m.s. field amplitude and r.m.s. phase, the maximum range of variation of the first and second field integrals over the "good field region" of ± 25 mm, and intensities of the first, third and fifth harmonics relative to an ideal undulator ($R_1$, $R_3$, $R_5$). The results are generally in very good agreement with the predictions based on the superposition of the field from individual blocks [3]. However, although the field integrals are similar in magnitude to the predictions the actual distribution is different, being very sensitive to the errors in the block measurements. The field integrals are close to or within the specificied limits of ± 1 Gm and ± 2.5 $Gm^2$ at all gaps. The r.m.s. phase error is less than 5.4° for all sections, with the result that the 5th harmonic has at least 80% 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.

Further improvements have been made to the field quality by means of shimming [3]. A simulated annealing algorithm has been developed to position the shims in order to correct both field integrals and phase error simultaneously, at 3 different gaps. The program uses "shim signatures" calculated using a model for the shim effect. In all 3 sections it has proved possible to both improve spectral performance and reduce field integral variation, using between 21 and 35 shims. Table 2 includes the final results obtained after shimming and fig. 2 shows a typical distribution of field integrals for one section.

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 three different gaps. The field amplitude and K values are also

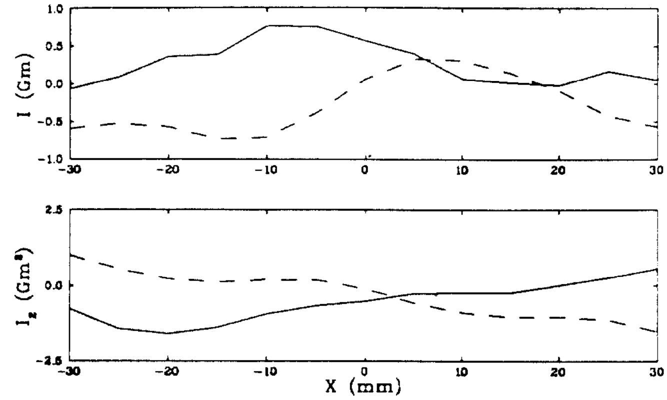


Figure 2. First and second field integrals for a typical section of U12.5.

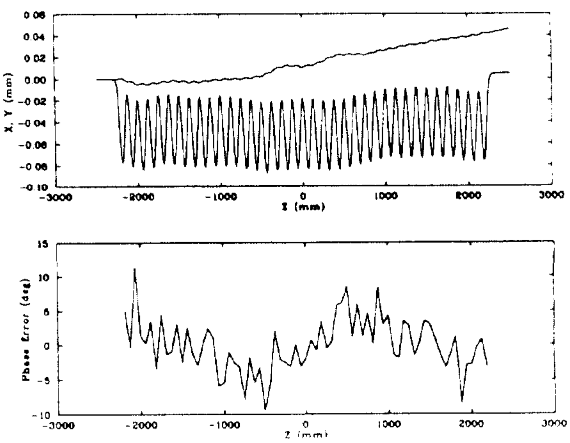

Figure 3. Calculated trajectory and radiation phase in the complete U12.5 undulator at minimum gap.

Table 3.
Results of the superposition of the measured field of the three U12.5 sections.

| Gap (mm) | 29.0 | 50.0 | 100.0 |
|---|---|---|---|
| $B_o$ (T) | 0.545 | 0.315 | 0.083 |
| K | 6.4 | 3.7 | 1.0 |
| $\sigma_B$ (%) | 1.0 | 0.6 | 0.6 |
| $\sigma_\phi$ (deg.) | 4.1 | 3.8 | 3.7 |
| $R_1$ | 0.99 | 0.99 | 0.99 |
| $R_3$ | 0.94 | 0.96 | 0.92 |
| $R_5$ | 0.88 | 0.87 | 0.81 |

shown, and it can be seen that they meet the required performance given in Table 1. The phase error is sufficiently small to produce good output up to at least the 9'th harmonic, as shown in fig. 4.

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. In the present case this will be minimized by positioning the devices with less than 1 mm separation. Secondly, the non-unit permeability of the NdFeB material introduces a small vertical field component that will be compensated using small

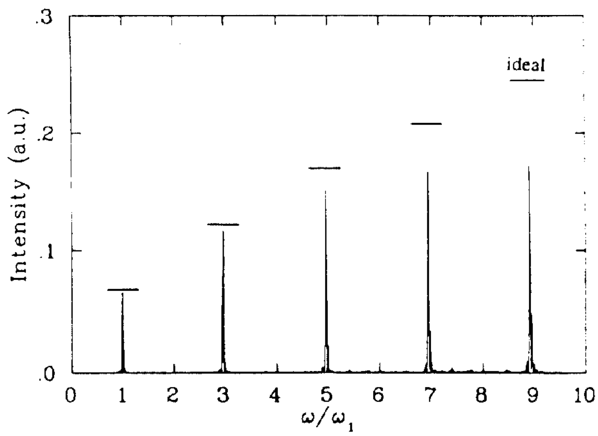


Figure 4. Calculated on-axis spectrum for the complete U12.5 device at minimum gap. The intensities of an ideal undulator are as indicated.

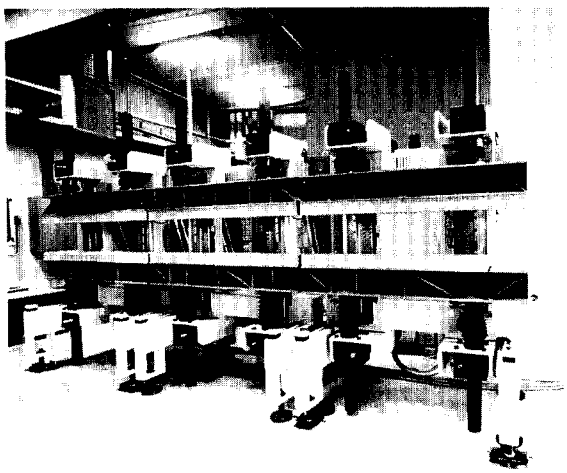

Figure 5. Photo showing the completed U12.5 device.

correction coils. Further details may be found in ref [4].

The undulator U12.5 is now ready for installation in ELETTRA. Figure 5 shows how the three sections will appear when assembled together to form a complete 4.5 m device.

## III. UNDULATOR U5.6

The second undulator is designed to cover the range 250 eV - 1 keV at 1.5 GeV, with higher photon energies at 2 GeV. A period length of 5.6 cm was selected in order to give a sufficiently high K value (2.3) to provide a reasonable overlap between the first and third harmonics with a minimum gap of 25 mm. A standard arrangement of 4 blocks per period will be used, with 28 mm block height. A block width of 85 mm was chosen to obtain $k_x/k < 0.1$. A similar construction scheme to that used for the prototype has been used : blocks are clamped into individual holders, which are then assembled onto a baseplate.

NdFeB permanent magnet blocks were obtained from Outokumpu magnets (NEOREM 440i). To prevent corrosion the blocks have been passivated and oiled, a cheaper option than metal coating and sufficiently effective for the ambient conditions in ELETTRA. Each block has been measured in an identical way to those of U12.5, but using a new bench dedicated to block measurements. This allowed measurements of completed sections to be continued during the 2 months that were necessary 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.

The simulated annealing algorithm used for these blocks was similar to that used for U12.5, with the exception that additional terms were included to guarantee a linear electron trajectory. Some difficulties were experienced in optimizing the structure, possibly due to the increased number of periods, or possibly because of the actual set of measurement data. The optimization was also hindered by the significant increase in the required computer time compared to U12.5 [3]. For the configuration chosen the predicted performance was very similar to that of U12.5, including also the phase errors, but with the exception of the first intgeral field errors, which showed maximum values up to 4 Gm in all sections. This was accepted however on the basis that shimming is more effective in correcting field integral errors than phase errors.

The first section of U5.6 has been completed recently and measurements will start soon.

## IV. WIGGLER W14.0

Construction of a 0.5 m prototype device which successfully reached the required 1.6 T field level was described in ref. [1]. Since then the mechanical design of each cell has been modified. Previously each permanent magnet block was a single piece 14 .0 x 11.5 x 2.38 cm, composed of 6 smaller blocks glued together. Problems arose however due to failure of the bonding, and so the new scheme uses only two blocks which are clamped into position. All components for the wiggler are presently on order, with the exception of the end-terminations, pending completion of tests using a rotating block for field integral correction.

## V. UNDULATOR U8.0

This device is required to operate over a very wide range of photon energy, from 250 eV to 1.5-2.0 keV in an undulator mode, and from 2-8 keV as a wiggler. The period chosen was a compromise between increasing the flux at low photon energy (short period and therefore small K value) or high energy (long period, high field and therefore high critical energy). Permanent magnet blocks have been ordered with a height of 40 mm, selected to give close to the maximum possible field, and with a width of 100 mm, to satisfy the requirement $k_x/k \sim 0.1$. A similar block holding structure to that of U5.6 will be used.

## VI. REFERENCES

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