PHASE SHIFTERS FOR THE FERMI@ELETTRA UNDULATORS*

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Abstract

The variable gap undulator system in operation at the FERMI@Elettra Free Electron Laser facility requires adjustable phase matching devices between consecutive radiator segments in order to maintain optimal lasing conditions while changing the radiation properties. A permanent magnet phase shifter has been designed to achieve the required electron beam delay in a compact structure that could be installed in close proximity to the undulators. In this paper we present the design of the phasing units and the results of the magnetic measurements performed on the five devices installed so far. We also describe the method used to properly set their field strength for any given electron energy, radiation wavelength and polarization.

MAGNETIC AND MECHANICAL DESIGN

The phase delay $\Delta\phi$ experienced by an electron passing through a magnetic chicane (or any path-lengthening device) with respect to a photon of wavelength λ propagating straight along the axis of the device (*s* axis) can be written as:

$$\frac{\Delta\phi}{2\pi} = \frac{L - L_0}{\lambda}$$

where L-L_0 is the difference in length between the actual and the unperturbed (free space) electron trajectory. This can be expressed in terms of the angular deflection X':

$$L - L_0 = \int_{S_1}^{S_2} \sqrt{1 + X'(s)^2}ds - L_0 \cong \int_{S_1}^{S_2} \frac{X'(s)^2}{2}ds$$

where $L_0=S_2-S_1$ and the angle X' can be derived, in the ultra-relativistic limit, from the distribution of the magnetic field along the longitudinal axis of the device:

$$X'(s) = -\frac{e}{\gamma m_0 c}\int_{S_1}^{s} B(s')ds'$$

Here e is the electron charge, m_0 its rest mass and c the speed of light. The magnetic structure of the phasing unit is composed of 14 NdFeB blocks (Vacuumschmelze VACODYM 655TP) arranged in an undulator-like configuration (figure 1). The total length of the arrays is 100 mm, and the minimum operational gap 10 mm. A non-standard end block arrangement was chosen to minimize the extent of the fringe field and limit the magnetic cross-talk with the adjacent undulators. To this purpose a series of measurements (not reported here) were performed on a prototype phase shifter placed at various distances from an APPLE-II undulator, leading to the conclusion that marginal interaction is observed for the nominal separation of 90 mm between the edges of the two magnetic structures.

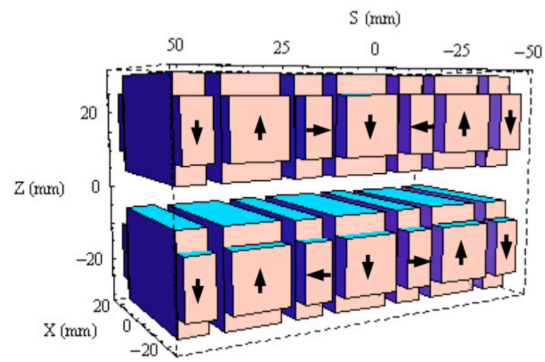

Figure 1: Schematic view of the magnetic structure.

Figures 2 and 3 below show the computed central magnetic field distribution and the corresponding angular deflection.

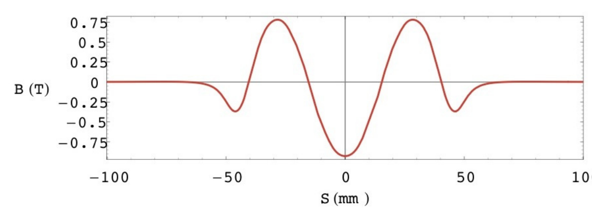

Figure 2: Theoretical magnetic field distribution for the minimum gap of 10 mm.

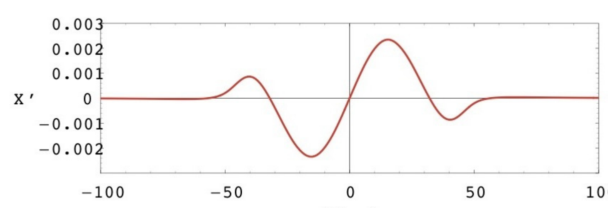

Figure 3: Angular deflection of a 1.2 GeV electron in the magnetic field of Figure 2.

The permanent magnets, inserted in individual holders (see figure 4), are supported by two beams whose vertical separation can be varied by means of three linear rails (HRW series from THK) and a single ball-screw equipped with two counter-rotating nuts (custom made by THK). A stepper motor (Phytron model ZSH57) is

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connected to the ball-screw through a 40:1 precision gearbox, allowing a gap change speed of between 0.1 and 2 mm/s.

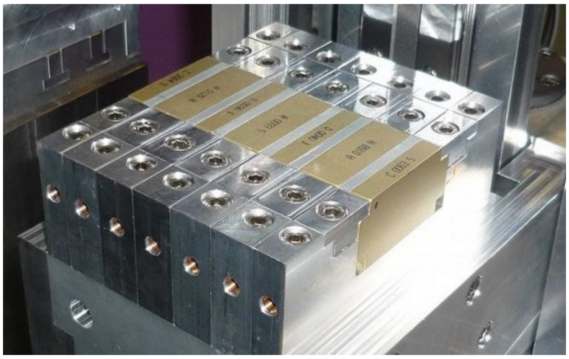

Figure 4: Photo of the lower magnet array, showing the permanent magnet blocks and the block keepers.

A 3D model of the whole structure is shown in figure 5. Except for the ball-screw, the rails, the gearbox and the motor all other parts of the frame are made in Aluminium alloy (ALCOA). The gap is read and adjusted by means of a semi-absolute linear encoder (ANILAM ACU-RITE SENC50-05), providing sub-micron resolution.

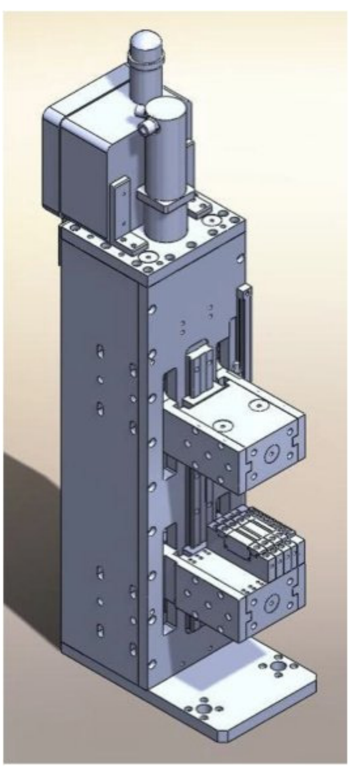

Figure 5: CAD model of the phasing unit.

A series of five phasing devices was realized for the long wavelength FEL (100÷20 nm), which comprises six identical 2.4 m long, variable polarization undulators separated by 1.3 m breaks (see figure 6).

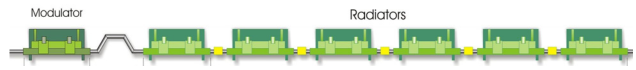

Figure 6: Layout of FEL-1, composed of a modulator, a dispersive section and six radiators.

The parameters of the magnetic structure described above were chosen to provide the required path lengthening with a 50% safety margin, resulting in a design value for $L\text{-}L_0$ of 90 nm @ 1.2 GeV electron energy.

MAGNETIC MEASUREMENT RESULTS

The average central field measured at the minimum gap on the five units is 0.92 T, with a maximum variation between the units of 0.5%, due to magnet-to-magnet strength variations and small differences in the mechanical gap adjustment. This variation is however taken into account by individual calibration curves.

Figure 7 shows the measured field distribution of one device, showing good agreement with model calculations.

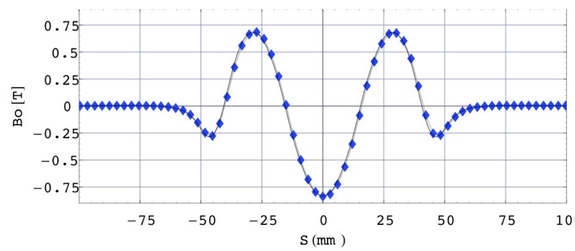

Figure 7: Measured (dots) and computed (solid line) longitudinal field profile for a gap of 12 mm.

The corresponding phase jump (λ=52 nm, E=1.2 GeV) is plotted in figure 8. This analysis, repeated for different gap values, provides a calibration table to be used for the proper setting of the gap of each phase shifter according to the operational parameters (see next section for a more detailed explanation).

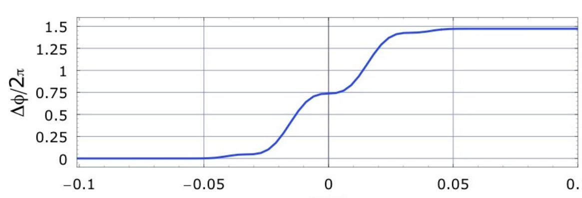

Figure 8: Phase delay between 1.2 GeV electrons passing through the magnetic field of figure 7 and 50 nm photons.

Multipole errors are not a major concern in a single pass FEL. However, in the few cases where the integrated dipole, quadrupole or sextupole field components were initially exceeding the specifications (10 G·cm, 100 G and 100 G/cm respectively) small cylindrical trim magnets ("magic fingers") were used to compensate.

PHASING THE UNDULATORS

The path lengthening (or equivalently the phase delay) required to properly phase any two consecutive undulators is determined by their physical separation, by their gap and array shift (undulators are of the APPLE-II type) and therefore changes with the radiation wavelength, polarization and with the electron energy. A numerical calculation is therefore necessary in order to predict the required phase shifter field. This is done first computing the phase difference ϕ_0 between the centres of two adjacent undulator segments. The measured undulator field maps and proper scaling and interpolation provide this information for any wavelength and polarization mode within the tuning range. The phase shifter field has now to be set so that this difference reaches an integer multiple of 2π, corresponding to a constructive interference between the two sources. To better illustrate this point figure 9 (upper plot) shows the magnetic field of two undulators (42 periods each) emitting horizontally polarized radiation at 52 nm, 1.2 GeV. The difference in phase between the centers of the two undulators turns out to be in this case $44.75 \cdot 2\pi$. An additional delay of $0.25 \cdot 2\pi$ is therefore needed to reach the next integer and put the undulators in phase. This occurs for a phase shifter gap of 27.5 mm, obtained from the calibration curve of the device. The field for this case is illustratively shown in figure 9 (lower plot).

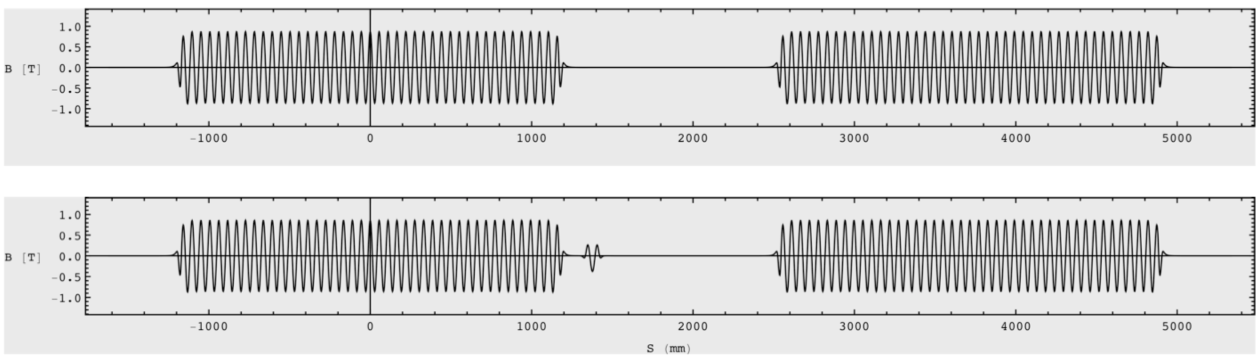

Figure 9: Field distribution of two adjacent radiators with the phase shifter gap fully open (upper plot) and with the phase shifter gap closed to 27.5 mm (lower plot).

To check this method, an experiment was recently performed measuring the FEL intensity emitted by only the first two radiators, fully opening the gap of the others. Figure 10 shows the signal of a gas ionization chamber (also known as "I_0 monitor") as a function of the phase shifter gap. The beam energy during this experiment was 1.2 GeV and the radiation wavelength 52 nm, the 5th harmonic of the seed laser. It can be seen that optimum phasing (i.e. maximum intensity) is obtained when the gap is closed to the predicted 27.5 mm.

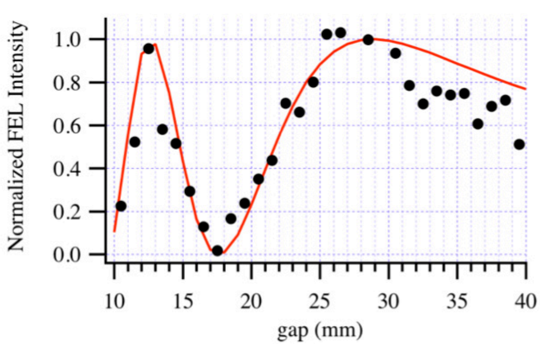

Figure 10: Measured FEL intensity (dots) as a function of the phase shifter gap compared with a simple model (solid line) based on the measured magnetic field.

Further decreasing the gap the intensity oscillates between maximum and zero, corresponding to successive integer or half-integer multiples of 2π. In a simple model of the interference between the two sources, the normalized intensity can be written as as:

$$I_{norm} = \frac{1 + Cos(\Delta\phi + \phi_0)}{2}$$

This is also shown in figure 10 (solid line) for $\phi_0 = 44.75 \cdot 2\pi$ (or equivalently $0.25 \cdot 2\pi$). The agreement with the experimental data confirms the correctness of the model and the applicability of the phasing procedure described above.

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