MAGNETIC CHARACTERIZATION OF AN APPLE-II UNDULATOR PROTOTYPE FOR FERMI@Elettra

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INTRODUCTION

The FERMI@Elettra free-electron laser will use APPLE-II undulators in the radiating sections to produce variably polarized coherent photon beams. In preparation of the manufacturing of the final devices, a prototype has been developed in order to test different field optimization methods. For this purpose, an existing variable-gap support structure was retrofitted with a new mechanical interface (see figure 1) providing the required capability to longitudinally shift two of the four magnetic arrays.

Figure 1: The undulator prototype.

Except for a shorter length, the undulator parameters (see table 1 below) are within the range under consideration for the short wavelength (10 ÷ 40 nm) free-electron laser to be built for the facility [1].

Table 1: Main Undulator Parameters

Period length	50.36 mm
Undulator length	1.5 m
Magnetic material	NdFeB
Blocks dimensions	25 x 25 x 12.5 mm
Minimum gap	12 mm

The aim of this work is the development of an accurate and efficient method of field optimization, offering good control during the assembly and minimizing the effort required for post-assembly corrective measures.

SORTING METHOD AND RESULTS

Usually the permanent magnet blocks are characterized by measuring their magnetic moment with a Helmholtz coil or similar instrument. The measured data, describing the errors in magnetization strength and direction, can be used to optimally arrange the blocks within the undulator in order to minimize the unwanted field, trajectory, phase and multipole errors. This approach works well in many cases, but shows its limits when applied to small gap devices. This happens because the magnetic moment, measured in the far field, doesn't describe the errors originating from inhomogeneous magnetization inside the magnet volume, and this can be the dominant source of magnetic field errors at short distances from the blocks.

Alternative methods have been proposed to overcome this difficulty. One of these consists in grouping the blocks in small compensated "modules" that can be accurately characterized by measuring their field integral distribution using a stretched wire or flipping coil system. These measured data contain the effect of inhomogeneous magnetization, and can therefore be used for a more accurate optimization. This method was first developed at ESRF [2] and then successfully used by other laboratories [3, 4] and industries [5, 6], in particular for in-vacuum undulators.

In our case, the block holders are grouped in units containing either three or five magnets (see figure 2) by means of small aluminium bars. A symmetrical design allows placement of the modules in any of the four quadrants of the APPLE structure. The bars connecting the holders are removed once the modules have been assembled, thus enabling individual blocks to be later adjusted in position (e.g. for shimming) or replaced if necessary.

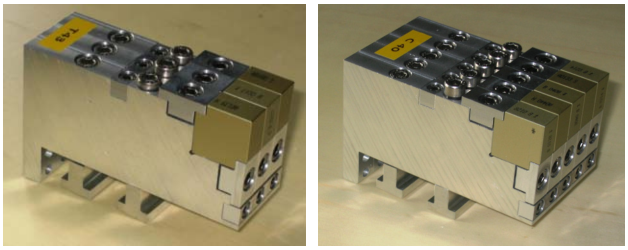

Figure 2: Three-block (M3) and five-block (M5) modules.

Each module contains an even number of vertically magnetized blocks, so that the field is anti-symmetric and the measured field integral signatures only reveal the error term. Figure 3 shows the error distributions for the 56 measured M3 modules. The stretched wire was scanned at a distance of 6 mm from the blocks, corresponding to half the minimum gap. Similar results have been measured for the 56 M5 modules.

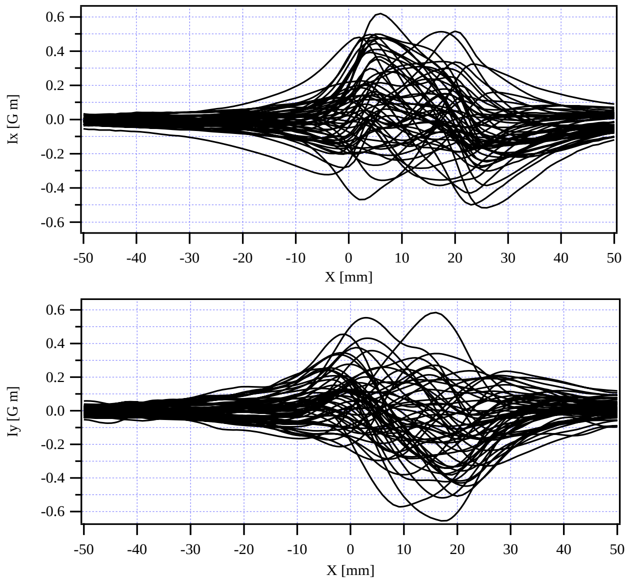

Figure 3: Measured signatures of the M3 modules.

Based on these measured distributions, optimization is performed iteratively using the following steps:

- the undulator terminations are mounted and their field integral measured;
- a limited number of modules (eight in our case, corresponding to two periods) are selected and oriented so that their contribution cancels that of the previous measurement;
- after assembly of the selected modules, the partial undulator structure is measured again and the process it repeated choosing the modules amongst the remaining ones until the undulator is completed.

Since phase dependent errors are usually small (provided the mechanical construction if rigid enough) and in any case they cannot be corrected by sorting, the undulator was arbitrarily set to zero shift mode (purely vertical field) during all the measurements.

A simulated annealing algorithm is used in the selection and orientation process. This enables optimization of a multi-objective merit function taking into account simultaneously the peak and central values of the field integral distributions and their first and second derivatives, correlated with quadrupole and sextupole terms. A prediction of the integrals for the complete undulator is also included and minimized in order to avoid accumulation of errors during the last assembly steps [7]. This is particularly important when, as in the present case, no spare modules are available.

Figure 4 shows the field integrals measured at four assembly steps (1 = first, 7 = intermediate, 13 = second to last, 14 = last one).

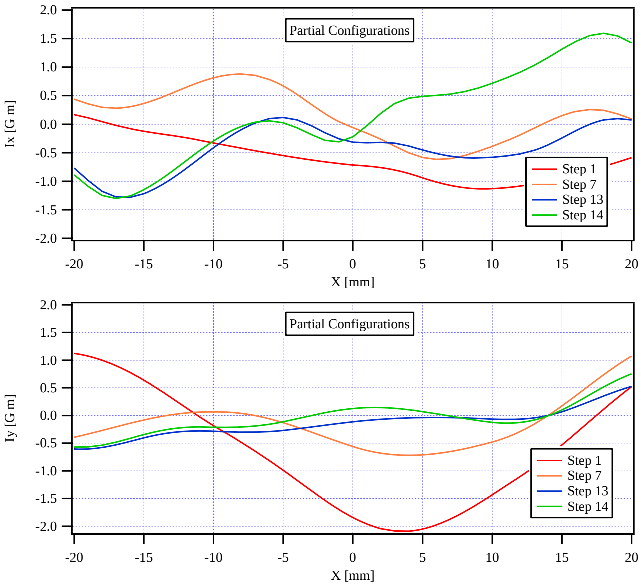

Figure 4: Field Integrals at steps 1, 7, 13 and 14.

The initial improvement and subsequent control of the field integral distributions is clearly seen until step 13. At the last step, although the central field integrals remained small, large skew quadrupole and sextupole terms were introduced. This is believed to be due to either a measurement error or a mechanical problem in one of the modules. It must be pointed out that misalignments of the modules either during their characterization or their assembly create a systematic error component that shows up in the horizontal integral while cancels out in the vertical plane.

A Hall probe scan was also performed at each intermediate assembly step in order to verify that the procedure, which does not utilize any information of the local field, was adequate to also keep the trajectory and phase error below the required values. This is indeed the case, as illustrated in figure 5, showing the trajectories computed from the field measured at three intermediate steps. This is a consequence of progressively controlling the central field integrals every two periods, i.e. it is a consequence of this method.

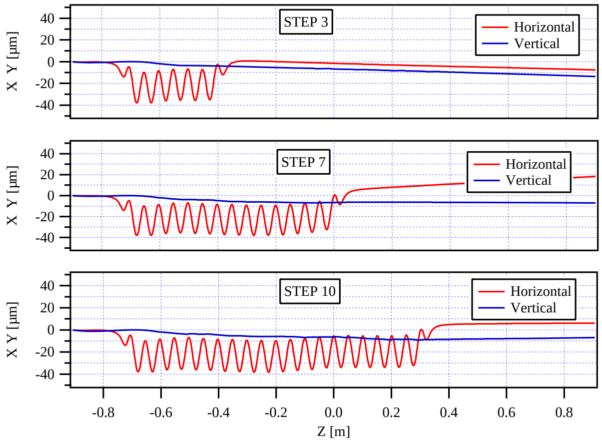

Figure 5: Trajectories at steps 3, 7 and 10.

Figure 6 shows the trajectory and phase error for the complete undulator, showing that excellent trajectory straightness and field quality (phase error $\sigma_\Phi = 2.4^\circ$ rms) can achieved with this method alone.

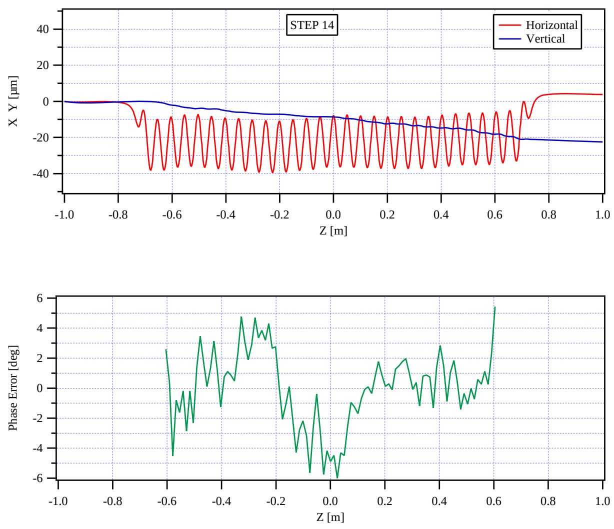

Figure 6: Trajectory and phase error distribution of the complete undulator at 12 mm gap.

Figure 7 shows the trajectory and phase error for larger gaps and non zero phase, showing that the performance is maintained when tuning the undulator to vary the output wavelength and polarization.

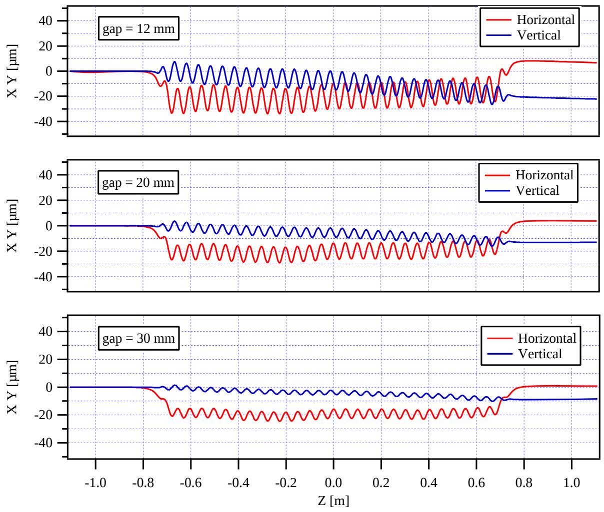

Figure 7: Trajectory and phase error distribution at 12, 20 and 30 mm gap, phase = $\lambda_0/4$.

Table 2 lists the phase error, quadrupole and sextupole terms at three different gaps. It can be seen that the largest errors (skew quadrupole and skew sextupole) rapidly reduce with increasing gap, suggesting that inhomogeneous magnetization plays an important role.

Table 2: Normal and Skew quadrupole (Q), sextupole (S) and rms phase error (σ_Φ) at three different gaps.

Gap (mm)	phase (mm)	Q_X (G)	Q_Y (G)	S_X (G/cm)	S_Y (G/cm)	rms σ_Φ (deg)
12	0	118	24	431	-73	2.5
20	0	47	15	50	-10	2.3
30	0	34	12	4	-8	1.9

SHIMMING STRATEGY

To bring the multipole errors within the specified tolerances we foresee using adjustable trim magnets [8] attached at the extremities of the undulator, shimming of selected magnetic blocks and correction coils placed at the undulator ends. Correction of the residual phase dependent multipole errors, if necessary, will require additional effort and development of dedicated methods [3].

CONCLUSION

The method described offers good control over the errors originating from magnetization defects. Further improvements are however planned including:

- using a dedicated short stretched wire measuring system. This should provide higher measurement speed, and better alignment capabilities.
- pre-sorting of the blocks in the modules based on Helmholtz coil data, thus reducing the field integrals of each module.
- spare modules for increased sorting flexibility.

This work was supported in part by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3.

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