

# PERFORMANCE OPTIMIZATION OF A PROTOTYPE UNDULATOR U38 USING MULTI-OBJECTIVE GENETIC ALGORITHM\*

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## Abstract

Genetic Algorithm (GA) is one of the most excellent method to search the optimal solution of a problem, which has been applied to solve various problems. It is hard to estimate shim applied on raw undulator precisely. There are many methods have been developed to solve the problem. In this proceeding, we measured the magnetic field distribution of prototype undulator U38 and concluded the shim using multi-objective GA. The code was written with the language of Python and based on the package pyevolve. A multi-objective fitness function was setup to implement the multi-objective optimization. Experimentally, performance satisfied the requirements by shimming U38 three times. The trajectory center deviation, peak-to-peak error and phase error are reduced to 0.15 mm, 0.49% and 1°.

## INTRODUCTION

Light sources based on accelerator, including Synchrotron Radiation (SR), Free Electron Laser (FEL) and Energy Recovery Linac (ERL), use extensively undulators creating a periodic magnetic field for the production of intense of radiation for users [1–3]. The common-used permanent magnet undulator was invented by K. Halbach in 1980's and contains two magnet and pole arrays [4]. Imperfections and errors are inevitable during design and manufacture of undulators, such as positioning errors of the magnets and poles, small differences of magnetization value and direction from one magnet block to the next, the inhomogeneities of the magnetization inside a volume of a single block. These will introduce magnetic field errors [5, 6]. Uncontrolled magnetic field errors of undulators, including electron trajectory center deviation, peak-to-peak error and phase error, will degrade light sources [7]. There are various shimming methods for correcting them in order to optimize undulator performance. The shimming methods are based on the fact that either moving a magnet or a pole (mechanical shim) or by placing some thin piece of iron at the surface of the magnet (magnetic shim) can make a small local correction of the magnetic field [8]. To shim undulator, it must be concluded that how much to move or how thin piece to place first. Many methods have been developed to solve the problem. In this proceeding, the shim of a prototype undulator U38 was concluded using multi-objective GA, based which we optimized undulator performance.

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## PRINCIPLE OF GA

GA was first put forward by professor J. Holland in 1975 and had a prosperous development era in the 90's. Now, GA has been applied in various areas and especially shows many advantages in combination optimization problem.

In an optimization problem based on GA, there is a population consisting of candidate solutions of the problem (individuals). Every candidate solution in population has a set of properties (chromosomes) which can mutate and crossover. An initial population usually contains individuals generated randomly or as required, which is evolved toward better populations. The evolution is an iterative process, and the population in every iteration is a generation. In every generation, the fitness of every individual is evaluated. Portion of individuals is selected from the current population, where fitter individuals decided by fitness are more likely to be selected. Then, chromosome of every individual being selected is modified (crossover and mutation) to form a new generation. The new generation of candidate solutions is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population.

## PROTOTYPE UNDULATOR U38

U38 is a hybrid planar undulator with two antisymmetric Halbach-type magnetic arrays. Table 1 lists the specifications of U38. Each array includes 11 periods made of NdFeB blocks and DT4 blocks. The gap of U38 is fixed at 18 mm. The magnetic structure is shown in Fig. 1, where one DT4 block and two half-NdFeB blocks form a sandwich-like magnetic module. So, one period contains two modules.

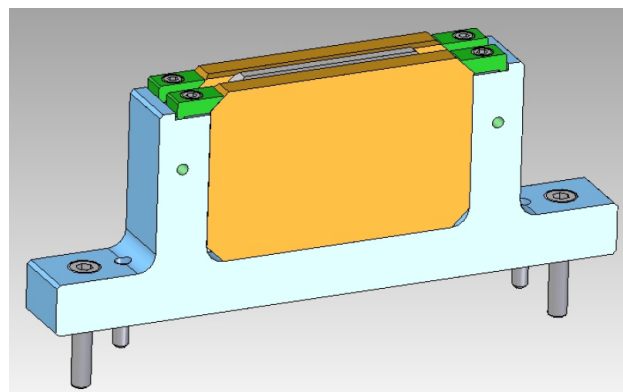


Figure 1: One sandwich-like magnetic module.

Table 1: U38 Specifications

Parameter	Value
Magnetic Structure	Planar, Hybrid
Period Length (mm)	38
Gap Range (mm)	18
Number of Periods	11
Max. Peak Field (T)	0.5
Max. K	1.77
Trajectory Center Deviation (mm)	0.2
Peak-to-Peak Error	0.5%
Phase Error	5°
Total Length (mm)	570
Magnetic Block Material	NdFeB
Pole Block Material	DT4

## MEASUREMENT AND SHIMMING METHOD

The magnetic field measurement was performed by magnetic measurement bench (MMB). MMB worked on go-stop mode with step length of 0.5 mm and pause time of 0.5 s. Magnetic field was acquired by three-dimension Gaussmeter Bell 8030 with accuracy of 0.05% and resolution of 0.1 Gs. Besides, the lab temperature was controlled within  $23 \pm 0.5^\circ\text{C}$  to minimize the field variation of U38 and ensure an acceptable stability of the MMB. The vertical component of earth field in our lab is about 0.3 Gs, which also must be considered.

Mechanical shim was implemented by inserting copper pieces with various thicknesses between magnetic modules and beam to modify local field. Besides, to simplify work only magnetic modules of upper magnetic array were adjusted.

## OPTIMIZATION PROBLEM SETUP

A typical genetic algorithm requires genetic representation of the solutions and fitness function to evaluate the solutions.

For genetic representation, the relation between correction of local magnetic field distribution and movement distance of one module must be built firstly. We calculated the correction of local magnetic field distribution after moving one module 0.001 mm using Radia, which can be seen in Fig. 2 and defined as  $S(z)$ . Then, The correction of local magnetic field distribution for other movement distance can be concluded by multiplying a coefficient  $C_n$  ( $n$  is module's number) with  $S(z)$ . Now, the problem was changed to find optimal  $C_n$  for every module. At last, integer  $C_n$  was converted to 7-bit binary for genetic representation.

Multi-objective fitness function was defined as follows. The new magnetic field distribution was generated by adding  $C_n * S(z)$  of every module to old magnetic field distribution. Providing the electron energy of 8 MeV, trajectory was cal-

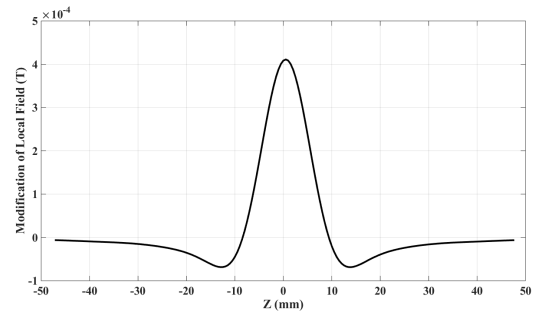


Figure 2: The correction of local magnetic field distribution after moving one module 0.001 mm.

culated by numerically integrating the new magnetic field distribution twice. The peak-to-peak error was obtained by root mean square value of peak field dividing mean value of peak field. The distribution of phase was calculated using Equation 1, where  $\phi(z)$ ,  $\lambda_u$ ,  $\bar{K}$ ,  $c$ ,  $m_0$  and  $e$  represented phase, period length, mean value of undulator parameter, light velocity, electron mass in rest frame and electron charge, respectively [9]. Then, phase error equaled phase at poles minus  $2n\pi$ , where  $n$  was pole number. The linear combination of trajectory center deviation, peak-to-peak error and phase error was defined as the multi-objective fitness function.

Commonly, the initial population is generated randomly, allowing the entire range of possible solutions. But, we filled initial population with zero to limit the number of modules must be moved. During evolution, too small individuals were removed, because it was hard to implement small shim practically. It is commonly accepted that a certain amount of elitism speeds up optimization. So, it was decided to keep the best chromosome to next generation. The evolution will terminate when fitness function satisfies the requirements. GA is a wide diverse group of algorithms, which qualitative working principles vary and our parameters of GA can be seen in Table 2.

Table 2: Parameters of GA

Parameter	Value
Population size	200
Mutation rate	0.02
Crossover rate	0.8
Elitism	1

Pyevolve is a complete GA framework, based on which the optimization code was written using Python language.

$$\Phi(z) = \frac{2\pi}{\lambda_u(1 + 0.5\bar{K}^2)} \left\{ z + \left( \frac{e}{m_0c} \right)^2 \left[ \int_{z_{start}}^z \left( \int_{z_{start}}^{z'} B(z'') dz'' \right)^2 dz' \right] \right\} \quad (1)$$

## RESULTS

The shimming of U38 was implemented as follows:

- Measuring the magnetic field distribution
- Calculating the optimal  $C_n$  for every module using GA
- Shimming U38
- Repeating process of a, b and c until the requirements are satisfied.

We finished three times shimming. The evolutions of trajectory, peak-to-peak error and phase error with the shim number are shown in Figs. 3, 4 and 5, respectively. It can be seen the performance was improved during evolution. After three times shimming, the requirements were satisfied. The trajectory center deviation, peak-to-peak error and phase error are reduced to 0.15 mm, 0.49% and  $1^\circ$ .

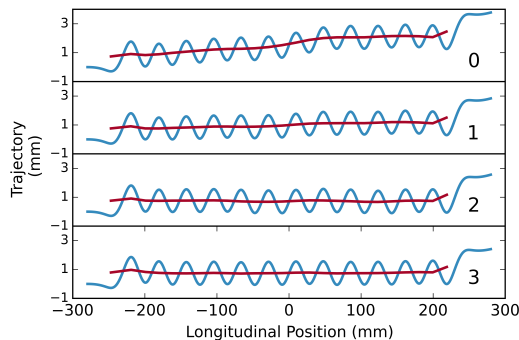


Figure 3: The evolution of trajectory

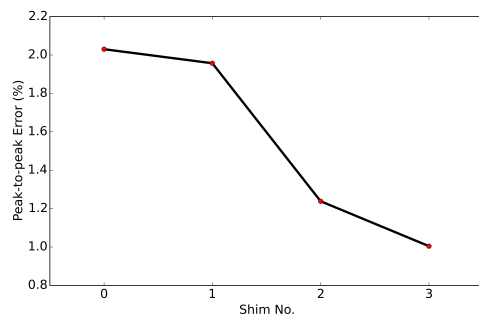


Figure 4: The evolution of peak-to-peak error.

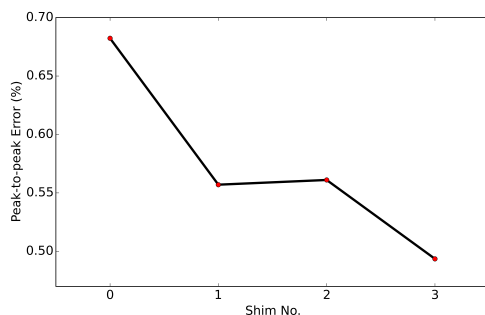


Figure 5: The evolution of phase error.

## CONCLUSION

In this proceeding, We measured the magnetic field distribution of prototype undulator U38, concluded the shim using multi-objective GA, and shimmed the U38. After three times shimming, the performance of U38 satisfied the requirements. The trajectory center deviation, peak-to-peak error and phase error are reduced to 0.15 mm, 0.49% and  $1^\circ$ .

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