MAGNET SORTING FOR THE XFEL HYBRID UNDULATOR—COMPARING STUDY

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Abstract

Current permanent magnet material quality is insufficient to obtain field qualities in undulators, which satisfy FEL requirements. Therefore position and orientation of magnets have to be carefully chosen in order to obtain mutual cancellation of field errors. In this paper we compare two different sorting schemes, simulated annealing and a straight forward paring method. They are applied to a 5m prototype structure built for the European XFEL facility. The algorithms of these two methods are described in detail and the sorting results and the expected field qualities are carefully compared.

Key words: undulator, sorting, annealing, pairing

INTRODUCTION

The European XFEL will be a user facility in the wavelength range from 0.1 to 1.6 nm [1]. It will use the so-called Self Amplified Spontaneous Emission (SASE) scheme to reach saturation in a single pass [2, 3]. The XFEL will use a technology similar to FLASH [4]. The electron beam is generated in an RF photo cathode gun, accelerated and compressed twice before it reaches its final nominal energy of 17.5 GeV. After acceleration and collimation, the beam will be distributed among several SASE undulators and wigglers for spontaneous emission. The radiation is distributed among 10 user stations. The wavelength can be changed by changing the electron beam energy or by changing the undulator gap.

Studies for FLASH have shown that the transverse overlap between radiation and electron beam has to be better than 20% of the beam size in order not to have a too large reduction in gain and therefore a too large increase in needed undulator length [5]. A similar criterion holds for keeping the resonance condition, i.e. keeping the phase shake within reasonable values. A typical rms deviation here is a few degrees. The undulator magnet quality needed to provide this overlap and phase shake without additional effort does not exist. Therefore, additional methods have to be used in order to guarantee a sufficiently good undulator quality.

Given the quality of the individual magnets, several methods can be used to obtain the appropriate undulator quality. One such method is magnet sorting, i.e. measuring the magnetic properties of the individual magnets and putting them into the structure such that errors in the magnet blocks cancel each other [6]. Another method which can be applied to correct the main field component of the structures that are discussed in this paper is pole-height adjustment [7]. This procedure, which has to take place in any case, is outside of the scope of this report and can only be applied to the main field. Therefore, our main aim is to correct the transverse field components that cannot be corrected by this method.

The structure for which the magnets are sorted is shown in Fig. 1. It consists of magnets separated by iron poles that focus the flux lines resulting in the main magnetic field. Of each magnet, several parameters have been measured: the magnetization in all three directions (M_x, M_y, M_z) and the main magnetic field at a given distance $(B_z^{(n)}, B_z^{(s)})$, thus giving the north-south inhomogeneous field. For a perfect magnet, $M_x = M_y = 0$ and $B_z^{(n)} = B_z^{(s)}$. In order to uniquely identify the orientation of the magnet, each of them is marked as in Fig. 1. Therefore, the direction of the field components is known independent of the orientation of the magnet.

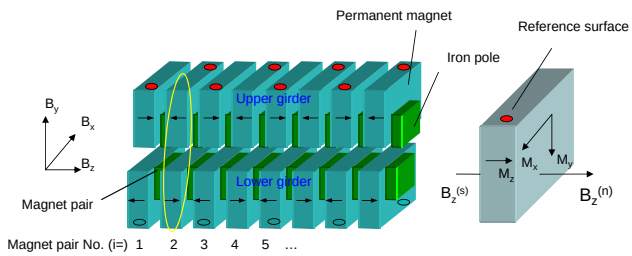

Figure 1: Coordinate system for the undulator and the magnet blocks. The red dot is used to determine the orientation of the magnet under any transformation that may be applied inside the magnetic structure. The arrangement shown here is referred to as the normal state.

With the magnet transverse flux M_x, M_y, the transverse undulator field can be evaluated by:

$$B_{x,i} \propto (F_{l,i} M_{x,l,i} + F_{u,i} M_{x,u,i})(-1)^i$$
$$B_{y,i} \propto F_{l,i} M_{y,l,i} - F_{u,i} M_{x,u,i} \quad (1)$$

The subscript l refers to magnets on the lower girder, u to magnets on the upper girder, i means pole position, F stands for a possible flip of magnet at a certain position, with $F = 1$ the magnet in its normal state and $F = -1$ in its flipped state. $B_{x,i}$ and $B_{y,i}$ are undulator transverse fields on each magnet pair, one in the upper girder, another in the lower girder (see Fig. 1).

In this paper, we will sort the magnets using two different methods, namely simulated annealing and pairing of magnets based on the magnetic measurements.

ALGORITHMS DESCRIPTION OF SIMULATED ANNEALING AND PAIRING

The method of simulated annealing [8, 9, 10] is a technique that has been used for optimization problems. Its main purpose is to avoid getting trapped in a local optimum. Because of the the analogy with the slow cooling down of liquids this process is called (simulated) annealing. In the case of sorting magnets, the magnet position and orientations are changed and the magnetic field for this magnet distribution is calculated. It is quite possible that any single change makes the field quality worse, whereas a combination of changes improves the quality. Simulated annealing offers the possibility to move through a state which is worse to a state which has a better undulator quality needing several magnet permutations in a row. The simulated annealing algorithm can be divided into several steps:

1. Find all possible magnet permutations
2. Find a generator of random changes in this configuration
3. Define a cost function E (analog of energy) whose minimization is the goal of the procedure.
4. Change the system configuration randomly; depending on the values of the cost function before and after changing (E_1, E_2), calculate the value p :

   $$p = exp[-(E_2 - E_1)/T = exp[-\Delta E/T]$$

   If $E_2 < E_1$, the change is accepted; if $E_2 > E_1$, randomly generate a number m in the range of $[0, 1]$. If $m < p$, then this change will still be accepted, if $m > p$, this change will be refused.
5. Control the parameter T (analog of temperature) decreasing during the process. This annealing schedule tells how the T value is lowered, e.g., when and by what amount T is decreased.

A simulated annealing program controls the main annealing progress: first the undulator's configuration is randomly rearranged for 20000 times to determine the range of values of ΔE that will be encountered from move to move, by this the average value $\langle \Delta E \rangle$ can be obtained. Depending on $\langle \Delta E \rangle$ a starting value for the parameter T is chosen which is considerably larger than the largest ΔE which is normally encountered. Then after I_1 times accepted changes or I_2 times refused changes (I_2 is normally larger than I_1), the parameter T decreases by a certain amount. If three times in a row T decreases because of refused changes, the program will be terminated by a last 'quenched' sorting, in which only the change of $\Delta E < 0$ is accepted.

If the undulator is ideal, the field $B_{x,i}$ and $B_{y,i}$ should be zero, so the cost function includes these two elements. Two neighbouring magnet pairs construct one undulator period, so $B_{x,2i-1} + B_{x,2i},\ B_{y,2i-1} + B_{y,2i},\ i = 1, 2, 3...$ represents the transverse field in $i-$th period and these two elements are also included in the cost function. The first and second magnetic field integral of the transverse fields $B_{x,i}$ and $B_{y,i}$ determine the electron beam angle and distance from axis, so the first integral of the transverse field is included too. Consequently six elements are included in the cost function, three in each plane:

- Rms value of transverse field of each magnet pair
- Rms value of transverse field of each undulator period
- Rms value of first integral transverse field on each magnet pair along undulator

So the value of the cost function E is

$$E = w_1 A + w_2 B + w_3 C + w_4 D + w_5 E + w_6 F\,, \quad (2)$$

with $w_1, w_2, w_3, \ldots$ the weights for these six elements, which need to be given each time the annealing program is executed.

Algorithm of pairing magnets

Sorting work can also be done by pairing of magnets. It is divided into two steps: first list all magnets in increasing order of their flux, secondly pairing the magnet with smallest flux to the one with largest flux one by one. The algorithm is:

1. Calculate the absolute transverse field value $|M_x|$ and $|M_y|$ for each magnet, then store them as ascending order in two arrays;
2. Choose another magnet to match the magnet whose absolute value is largest. First step we choose the magnet whose $|M_x|$ and $|M_y|$ is closest to the one that has to be matched. This includes the possibility that by flipping the magnet the sign of M_x and M_y changes at the same time. If matching both cannot be satisfied, then flipping the magnet to make the sign of M_x different has priority.
3. After pairing the magnets, we pair the pairs. Because the x-direction of the field had higher priority during the previous step, the y-direction is considered first during this step. After this treatment, as shown in Fig. 3, the spikes appear by couples and the sign is different, so the integral field can be decreased.
4. After pairing the pairs, we pair double pairs. This time it considers x-direction field more (the result of this step is shown in Fig. 3). Then we pair four pairs by y-direction field, and then eight pairs by x-direction field, and so on.

From the algorithm described above, one can see that the pairing method, unlike to the annealing method, does not

randomly rearrange of the undulator magnet configuration and is therefore less computer intensive. The result of the pairing method and the annealing method will be compared in next section.

SORTING RESULTS OF SIMULATED ANNEALING AND PAIRING

Magnet sorting by simulated annealing

It is known that suitable weight of the elements included in the cost function must be set before running the program. One reasonable method to determine the weight is that first randomly setting the undulator configuration for many times and then observing how much the deviation of each element's contribution to the cost function is. Then each of element weight is set depending on this deviation [11]. The random setting time is 20000. We set as weight of each element the inverse of the deviation of its contribution to the cost function. Table 1 illustrates the different weights. As can be seen, the weight of the field integral is much smaller than the others and in fact can be nearly neglected in the cost function. If the field integral is not neglected, the value of cost function is mainly determined by it.

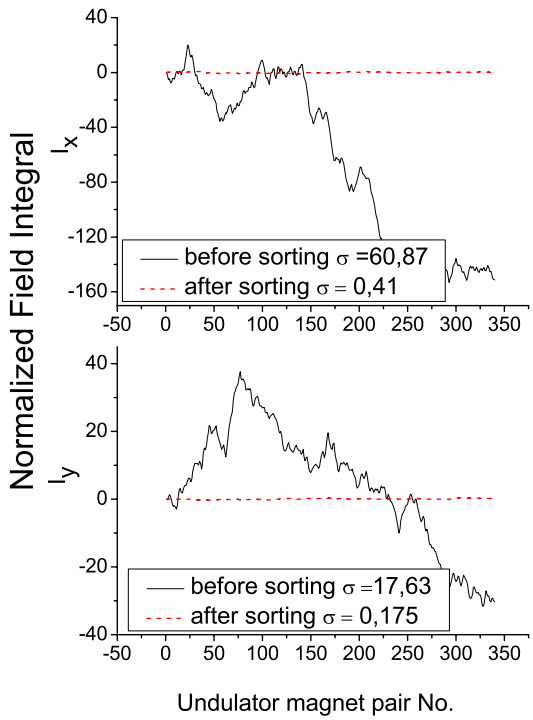

Figure 2: Sorting result by annealing with different element weight listed in Table 1. Both of the field integrals are decreased by two orders of magnitude.

Fig. 2 illustrates the result. One can see that the field integrals decrease by an order of magnitude.

Table 1: Weight for the rms value of each element for cost function

Elements for the cost function	**weight**
B_x on each magnet pair	35971
B_y on each magnet pair	89365
First integral of B_x on each magnet pair	1.513
First integral of B_y on each magnet pair	4.0816
$B_x(i) + B_x(i+1)$ on each undulator period	13210
$B_y(i) + B_y(i+1)$ on each undulator period	33333

Sorting for the 5 m long undulator by pairing

As described earlier, the pairing method is divided into many steps: pairing magnets, pairing magnet pairs, paring double magnet pairs and so on. The result of the different steps on the field at different length scales is shown in Fig. 3.

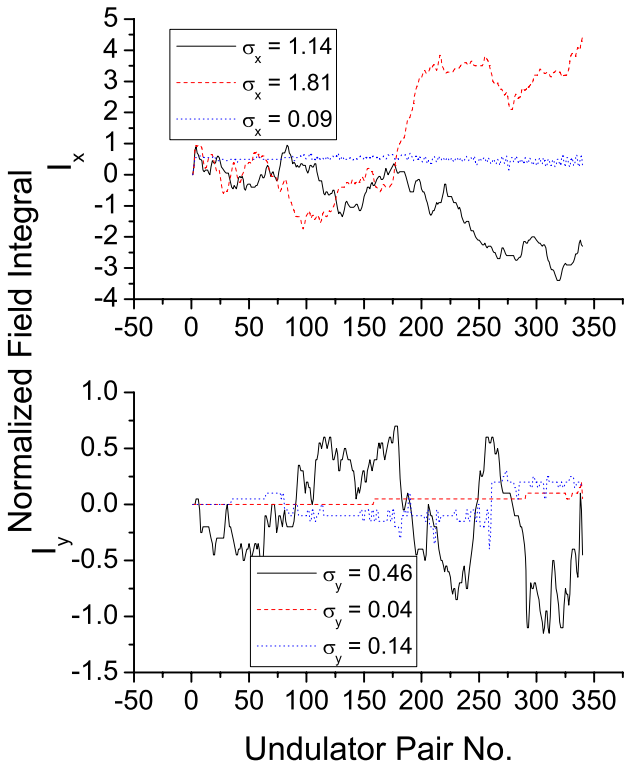

Figure 3: Improvement of the field integral after each step of optimization, pairing of magnets (black curve), pairing of pairs (red curve) and pairing of double pairs (blue curve). The field integral before pairing is the same as in Fig. 2 and therefore not shown.

It illustrates how the field integral depends on the subsequent sorting steps. Because in the first step the magnets are paired, attempting to improve both B_x and B_y, both of the corresponding field integrals improve by about an order of magnitude (black curves in Fig. 3 compared to the original integrals in Fig. 2). Pairing of magnet pairs results in a correlation for B_y such that on the scale of an undulator

period, the errors in B_y compensate each other, resulting in a reduced field integral in this plane after the second step (red curve). Because in this step B_x is not considered, this field integral is changed but not improved. The last step in Fig. 3 shows how sorting magnets on a scale of two undulator periods results in further correlations, now also on B_x which was taken into account in this (final) sorting step (blue curve showing an improvement in teh x-direction).

Comparison of Annealing and Pairing

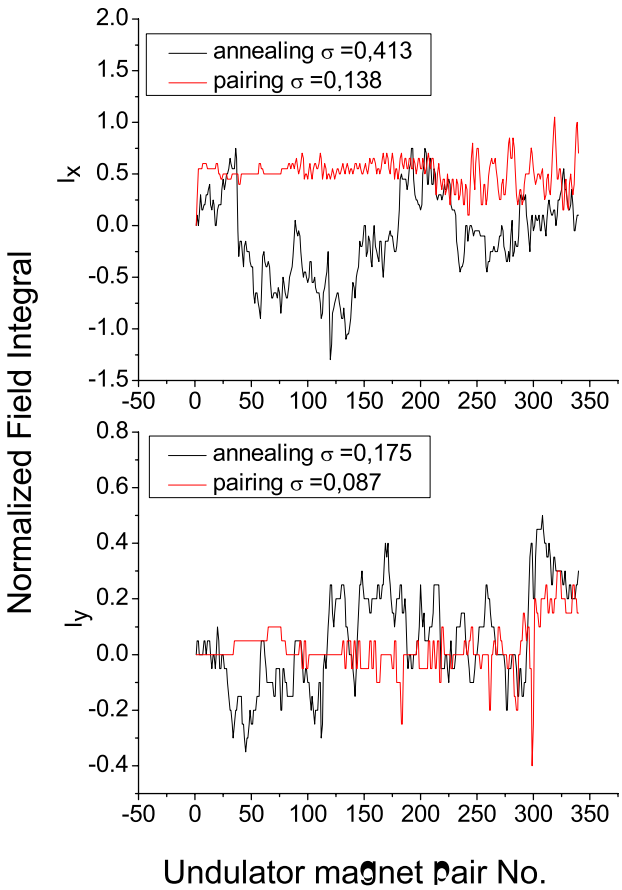

Figure 4: Comparing the transverse field integrals after sorting by annealing and pairing. One can see that for both of transverse field integrals the pairing method gives a factor of 2 smaller errors because the errors are compensated immediately and errors cannot build up to large deviations

The comparison of pairing and annealing is illustrated in Fig. 4. One can see that field integrals are clearly smaller in case of the pairing method. The reason for this is that errors are corrected locally. The results so far show that magnet pairing is much less computer intensive and gives slightly better results. As a consequence, one might say that there is no reason to use simulated annealing. However, in case some magnets have to be exchanged after part of the undulator magnets have already been assembled, the annealing method has the clear advantage that one can resort the remaining part of the undulator with magnets still available, whereas this is more difficult with the pairing method. This is illustrated in Ref. [12].

SUMMARY

In order to reach saturation in an FEL the overlap between electron and photon beam has to be guaranteed. To this aim individual magnets are measured and put into the undulator structure in a special order. The two methods discussed in this paper are simulated annealing and pairing of magnets. Only the transverse field components have been corrected.

As has been shown, both methods can greatly improve the transverse undulator field. The pairing method is more straightforward and gives a better field than the annealing method. The field integral is about a factor of 2 better for pairing, which would result in a better overlap. However, both methods meet and even exceed the required field accuracy.

REFERENCES

[1] Massimo Altarelli et.al., The European X-Ray Free-Electron Laser Technical Design Report, ISBN 3-935702-17-5

[2] A. M. Kondratenko and E. L. Saldin, Part. Accel. 10, 207 (1980)

[3] R. Bonifacio, C. Pellegrini, and L. M. Narducci, Opt. Commum. 50, 373 (1984)

[4] S. Schreiber, Proceedings of the 27th International Free Electron Laser Conference pp, 12-18, 2005, Stanford, California, USA

[5] B. Faatz, J. Pflueger, Y. M. Nikitina, Nucl.Instr. and Meth. A 393 (1997) 380

[6] B. Faatz and J. Pflueger, Magnet Sorting for the TTF-FEL Undulator using Simulated Annealing, TESLA FEL Report 1999-01

[7] J. Pflueger, H. Lu and T. Teichmann, Field fine tuning by pole height adjusting for the undulator of the TTF-FEL, Presented at the 20th International FEL conference, August 17-21, 1998, Williamsburg, USA

[8] Kirkpatrick, S., Gelatt, C.D and Vecchi, M.P. 1983, Science, Vol. 220, pp.671-680

[9] Kirkpatrick, S. 1984, Journal of Statistical Physics, Vol. 34, pp. 975-986

[10] Numerical Recipes, William H. Press, Saul A. Teukolsky, William T. Vetterling and Brian P. Flannery, Cambridge University Press, pp. 436

[11] Duncan Scott, An Introduction to Monte-Carlo Methods for Magnet Block Sorting An APPLE-II Type Helical Undulator, ASTEC-ID-024, 2004

[12] Y. Li, B. Faatz and J. Pflueger, Magnet Sorting for the XFEL Hybrid Undulator — Comparing Study, TESLA-FEL report 2007-06, DESY, Hamburg, Germany