CONSTRUCTION AND TESTING OF A PAIR OF FOCUSING UNDULATORS FOR ALPHA-X

B.J.A. Shepherd[#] & J.A. Clarke, ASTeC, CCLRC Daresbury Laboratory, UK

Abstract

ALPHA-X is a four-year project shared between several research groups in the UK to build a laser-plasma accelerator and produce coherent short-wavelength radiation in an FEL. A pair of undulators for the project have been designed and built by ASTeC at Daresbury Laboratory. The undulators are 1.5m long, 100 period permanent magnet devices with a minimum gap of 3.5mm, a peak field of 0.7T and a two-plane focusing design. The devices were modelled using RADIA, and data from the magnet block manufacturer was used to sort the blocks. To optimise the trajectory in the real devices, magnetic testing (using Hall probe and flipping coil techniques) and block swapping has been performed in Daresbury's dedicated insertion device test facility. The measurements agree well with the models, and the undulators will perform well within specification.

INTRODUCTION

The ALPHA-X project [1], based at Strathclyde University, is a collaboration between several UK universities and CCLRC. The aim of the four-year project is to develop laser-plasma accelerator technology and use this to produce coherent short-wavelength radiation in a free-electron laser. ASTeC at Daresbury Laboratory is responsible for designing and building the undulators for the free-electron laser.

The two undulators are constructed from permanent magnets with a period of 15mm and 100 periods [2]. The gap is to be adjustable to enable the deflection parameter (K) to be changed, in the range 0.5 to 1.0. This is an unusual device in that it is required to accept a very large range of electron energies (10-100 MeV).

Each magnet block is designed with a 5x1mm slot cut into the centre [2], to coincide with the beam axis (Figure 1). The field in this configuration increases with x^2 off-axis in both wiggle and non-wiggle planes. This provides the required focusing for the beam at all K values and energies, and ensures that it is confined in both planes.

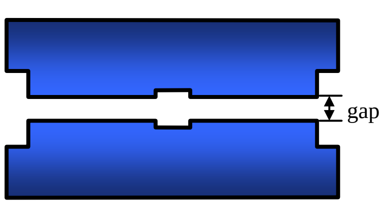

Figure 1: Slotted undulator profile.

[#]b.shepherd@dl.ac.uk

BLOCK SORTING

The magnet blocks for the pair of undulators were manufactured by Vacuumschmelze (VAC) from NdFeB. Testing of the individual magnet blocks was carried out at the manufacturer's site to determine the strength and direction of the magnetisation of each block. This data was incorporated into a RADIA [3] model of the undulator in order to optimise the sort order of the blocks within the undulator.

The sorting algorithm was designed to optimise the trajectory of an electron beam through the undulator. Phase errors were not taken into consideration. The algorithm worked by building a model of the undulator, two periods at a time (with matching structures at the ends). A 'mini-undulator' was modelled using several random sets of magnet blocks (using the data from VAC). The best of these was selected, and a new model constructed with two extra periods, again using several random sets of blocks. In this way, an undulator with 100 periods was built up. The process was monitored closely to ensure the trajectory wander did not become too great. Most of the time, any small trajectory errors tended to be cancelled out by the next two periods. This method seems to work well in producing an undulator with a straight trajectory function, at least in simulations.

UNDULATOR TESTING

Both undulators were built at Daresbury Laboratory's dedicated magnet assembly area. Since the devices have quite a short period, the magnet blocks were held in place in pairs rather than singly. These modules were designed so that they could be easily removed and swapped with other modules within the device if necessary. This made it easy for corrections to be made quickly. The modules could be replaced and re-aligned horizontally within the array with sufficient accuracy – simulations showed that errors in the transverse position of each module did not have a large effect on the field quality. The magnetic forces on a pair of blocks were low enough so that specialist tooling was not required for this operation.

A moving Hall probe was used to generate an on-axis field map of each undulator, and this was used to plot the trajectory of a single electron through the device.

Figure 2 shows the on-axis peak field plotted against the gap. The device produces an on-axis peak field of 0.54T at 5.5mm gap. K values of 0.5 and 1.0 (the design values) can be reached using gaps of 7.7mm and 4.2mm respectively.

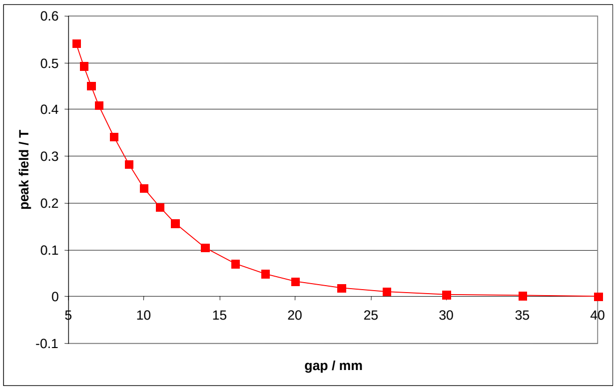

Figure 2: Field versus gap.

The trajectory calculated from the initial field plot was not ideal, so some correction was necessary. This was usually carried out by swapping pairs of blocks, though in some instances individual blocks were taken out of the array and replaced with spare ones.

The field map and trajectory plot were used as the basis for optimisation of the undulator layout. A slightly stronger or weaker field at a point along the undulator would clearly lead to a kick in the trajectory at that point. These regions of non-ideal field were found by plotting a moving average of the field, with the period set to the undulator period. In the ideal case, this plot would equal zero everywhere except at the ends of the device. However, in a real undulator, variations in the field show up on this plot. The blocks responsible can be easily identified by taking additional field maps with the undulator gap fully open and the Hall probe next to each array in turn. Figure 3 illustrates this: the moving average of the on-axis field is shown next to the moving average of the field from each separate array. Peaks and troughs in the on-axis field can be matched with those in the individual array plots. The distance between the Hall probe and the array for these separate scans is not critical, since the moving average is not sensitive to the peak field.

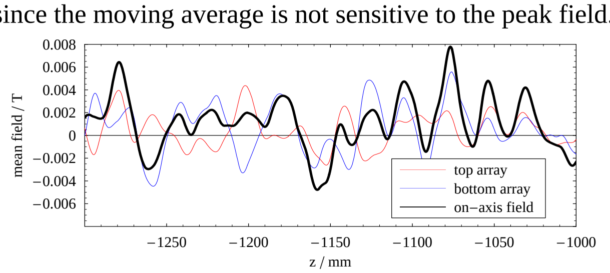

Figure 3: Moving average Hall probe plot, showing the on-axis field as well as the field near each array.

In this way, pairs of blocks that produce a slightly high (or low) field can be identified, and matched up with other pairs. Swapping a 'high' pair with a 'low' pair from the same array, or swapping two 'high' pairs from opposite arrays, has the effect of reducing the field towards the nominal level at both points. Figure 4 illustrates the process.

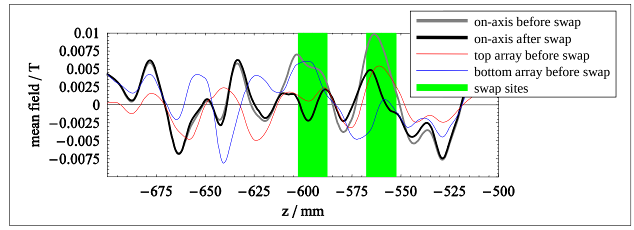

Figure 4: Moving average field plot illustrating the block swapping technique. A pair of blocks on the top array generating a slightly high field is swapped with a pair generating a high field on the bottom array. The result is that both regions of high field are reduced.

This process was repeated several times for each undulator. It worked extremely well and would be a useful tool for correction of future undulators that were built in a similar (modular) fashion. This time, it was used fairly cautiously, swapping only two pairs of blocks at a time. However, the effects turned out to be very predictable and repeatable, so greater numbers of swaps could be done in one operation in future, thus speeding up the process greatly.

Using this technique, the overall field integral of each undulator was reduced to an acceptably low level in a reasonably short space of time (Figure 5).

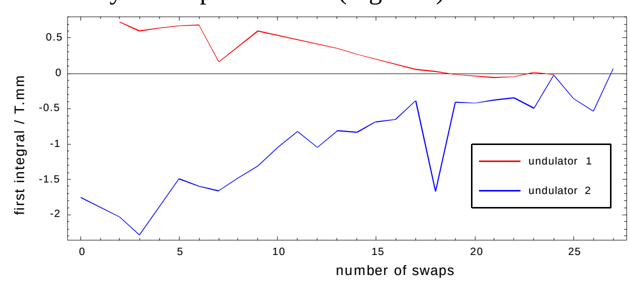

Figure 5: Reduction of first field integral (at 7mm gap) over the course of block swapping.

The slot cut into each block produces a 'focusing' effect; electrons injected off-axis experience a force pushing them back on-axis. To confirm this focusing effect, a 2D field map was taken in the wiggle plane, with 0.5mm spacing between points. Interpolating this data, it was possible to track the motion of an electron through the map and confirm the focusing effect. Figure 6 shows the electron tracking plots at 50MeV.

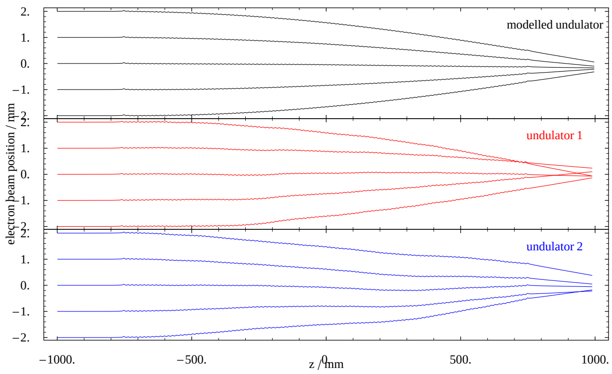

Figure 6: Electron tracking through each real undulator, together with the model results for comparison.

On-axis RMS phase errors were calculated from the Hall probe measurements. They were 4.9° for undulator 1 and 9.0° for undulator 2. The larger value for undulator 2 is probably due to the slightly larger trajectory wander for this undulator, calculated directly from the (linear) on-axis field measurements. In actual fact, the focusing effect of the undulator reduces the trajectory wander somewhat – off-axis particles see a restoring force – so these numbers are probably slightly pessimistic.

A flipping coil was used as a cross-check to ensure the integrals from the Hall probe data were accurate. The on-axis results are shown in Table 1.

Table 1: Undulator integrals measured with the flipping coil, at 7mm gap. (The field direction is horizontal.)

Integral	Undulator 1	Undulator 2
First horizontal	-16 μT.m	266 μT.m
Second horizontal	45 μT.m^2	318 μT.m^2
First vertical	67 μT.m	357 μT.m
Second vertical	76 μT.m^2	1 μT.m^2

Several measurements were made for each reading, and the typical variation in the results was about 35μT.m and 75μT.m^2 for first and second integrals respectively. The reason for these large uncertainties is probably the small width of coil that was needed (2mm) since the undulator gap is fairly narrow. The typical uncertainty is usually about half this size.

Where data was available, the flipping coil results agreed reasonably with the Hall probe results (Figure 7). Figure 7 also demonstrates the typical variation of the field integrals off-axis.

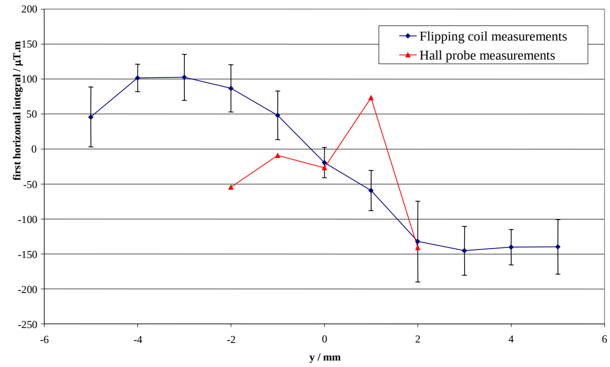

Figure 7: Comparison of Hall probe and flipping coil first horizontal integrals for undulator 1.

CONCLUSION

Two 1.5m long undulators have been designed, built and tested at Daresbury Laboratory for the ALPHA-X project. The devices have undergone thorough magnetic testing at our dedicated insertion device test facility.

The magnetic field from the undulators was optimised by swapping pairs of blocks from different points along the array. A successful algorithm was developed for this process, and this can be applied to future undulators.

Data from the magnet block manufacturer was used to create an initial sort order, and to optimise the electron trajectory through the device. However, neither undulator matched the expected trajectory from this modelling very well. It is possible that small errors in the magnetisation data for the magnet blocks contributed to large cumulative errors in the simulated undulator trajectories. It would be interesting to try constructing an undulator with a random sort order, to see whether the block sorting had any benefit. Alternatively, construction of future undulators could take place in parallel with testing, so that errors could be corrected for during the build phase.

After correction, the field quality of the undulators is excellent. The field integrals have been reduced as far as possible, and the devices will perform well within specification.

REFERENCES

[1] http://phys.strath.ac.uk/alpha-x/
[2] B.J.A. Shepherd & J.A. Clarke, "Magnetic Design Of A Focusing Undulator For ALPHA-X", EPAC 2004, p464.
[3] http://www.esrf.fr/machine/groups/insertion_devices/Codes/Radia/Radia.html