MAGNETIC DESIGN OF A FOCUSING UNDULATOR FOR ALPHA-X

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Abstract

ALPHA-X [1] 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. The FEL undulator will be a 1.5m long, 100 period permanent magnet device with a minimum gap of 5.5mm and a peak field of 0.7T. Horizontal and vertical focusing of the beam within the undulator is realised by the undulator's block shape, which is designed to approximate a parabolic pole face. The magnetic design of the undulator is complete; design of the support structure is well under way. Test pieces have been built to ensure that the clamping arrangement is strong enough to cope with the magnetic forces involved (7.9kN between the two arrays). The complete undulator will be built in late 2004 at Daresbury Laboratory, and tested on-site in the new magnet test facility.

INTRODUCTION

The ALPHA-X project, 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 undulator for the free-electron laser.

The undulator is a permanent magnet type with a period of 15mm and 100 periods. The gap should be adjustable to enable the deflection (K) parameter to be changed, in the range 0.5 to 1.0. This will be an unusual device in that it is required to accept a very large range of electron energies (10-100 MeV). The electron trajectory should be modelled at each energy to make sure the beam is focused in both planes, and does not diverge along the whole length of the undulator.

MAGNETIC DESIGN

The magnetic design for the undulator was carried out using the *Radia* package [2]. Using this, it was possible to create a model of the undulator, calculate the magnetic field, and find the trajectory of a single electron passing through it.

Block Layout

The layout of the permanent magnet blocks within the undulator is sketched in Fig. 1. The layout is a standard Halbach type with four blocks per period. Matching schemes are used at each end with one full-length block and two half-length blocks. This ensures that the exit position and angle of the electron beam are minimised, and that the beam oscillates on the undulator axis.

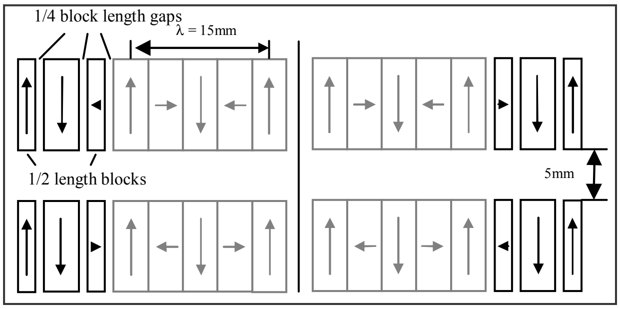

Figure 1: Block layout within the undulator.

Creating the Focusing

Originally the focusing was to be implemented using canted blocks (see Fig. 2). The vertically-magnetised blocks are 'tilted' in alternate directions, and this introduces a transverse field gradient without reducing the on-axis field. This is known as **quadrupole focusing** since the field shape is similar to that seen in a quadrupole magnet. In this arrangement, electrons injected slightly off-axis see a force tending to push them towards the axis. This scheme was originally chosen since it would be very simple to implement.

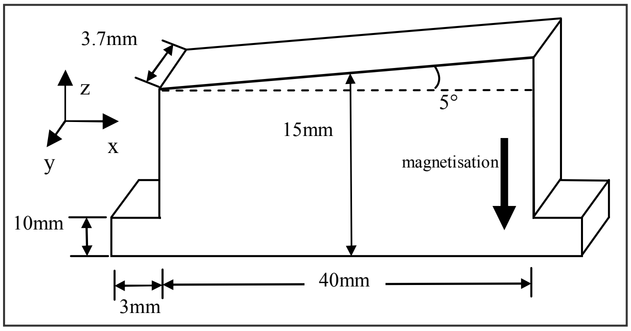

Figure 2: The dimensions of a canted magnet block.

The trajectory of an electron beam through this canted undulator was calculated, and is shown in both wiggle and non-wiggle planes in Fig. 3.

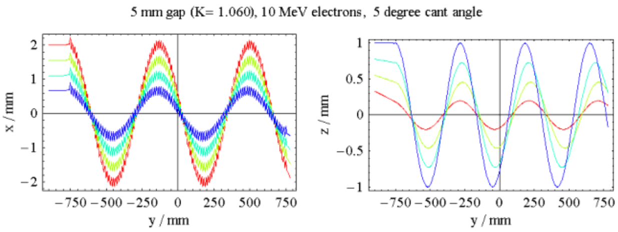

Figure 3: Electron trajectory through the undulator.

The trajectory can also be plotted in terms of phase space (x versus x'), which allows us to see the focusing effect – the electron is confined to an ellipse in phase space (see Fig. 4).

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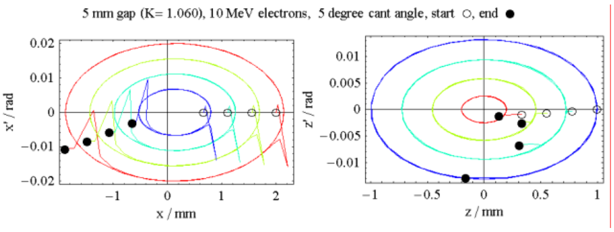

Figure 4: Electron trajectory in phase space. Note that the wiggle motion is not plotted for clarity.

At 10 MeV and a gap of 5mm the trajectories are acceptable – the electron is kept inside an ellipse in phase space close to the origin in both planes. However, at larger gaps (at which the undulator is required to operate) and higher energies problems begin to occur. The electrons become defocused in the non-wiggle (vertical) plane, orbiting a new fixed point in phase space on an egg-shaped trajectory. This is obviously undesirable as the size of the beam envelope increases through the undulator. Significant beam loss will occur as some of the beam will be steered into the vacuum chamber walls. Fig. 5 illustrates this defocusing effect for a 10 MeV beam and a gap of 8.4mm (K=0.5).

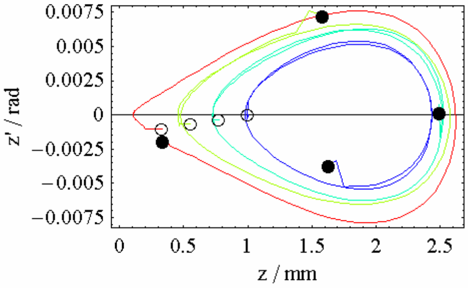

Figure 5: Non-wiggle plane phase space trajectory showing defocusing.

Alternative Designs

Several alternative designs were considered and modelled in *Radia* to implement the focusing without causing this defocusing effect.

A hybrid design was considered using canted poles. This uses steel poles, which are narrower than the iron blocks in order to concentrate the magnetic flux. A schematic of this type is shown in Fig. 6.

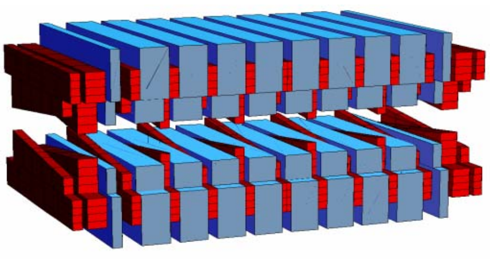

Figure 6: The hybrid canted undulator.

The hybrid undulator design had exactly the same problems as the original design, with very little improvement in the focusing.

The next step was to alter the block shape to try a different approach to the focusing. In the **sextupole focusing** scheme [3], the blocks are shaped such that the field profile in the centre of the undulator has a quadratic, or sextupole-like shape.

This geometry focuses the beam since the oscillating electron will always see a field gradient which tends to push off-axis electrons back to the nominal beam trajectory. This has been used before by Fortgang [4] in a high average power FEL. This type of focusing is useful in an FEL as the phase between the wiggle motion and the optical electric field remains constant. Note that this is not the case for quadrupole focusing.

The ideal pole face geometry for sextupole focusing is hyperbolic. However, a very rough approximation to this shape is acceptable – the field profile in the centre will still be the correct shape. A ‘dual canted’ design was tested – this has a V-shaped profile as shown in Fig. 7.

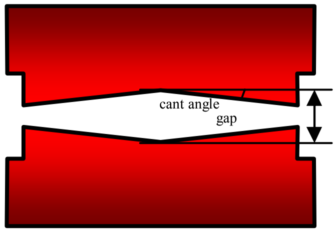

Figure 7: Dual canted undulator profile.

The required narrow undulator gap and the width of the poles (40mm) place limits on the cant angle, and therefore on the focusing strength. For a gap of 5mm and a cant angle of 5°, the horizontal focusing strength is about three times weaker than the natural focusing strength in the vertical plane.

A design with a slot cut into the centre of each block, would improve the focusing strength since the magnetic field gradient would increase more dramatically off-axis. Fig. 8 shows the profile of a slotted undulator.

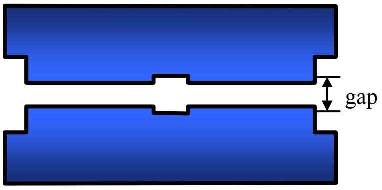

Figure 8: Slotted undulator profile.

The slot size was optimised to find the best focusing, and was eventually set at 5mm wide by 1mm deep. The vacuum chamber can be fitted into the slot, and the gap can be slightly increased from 5mm to 5.5mm, keeping the K parameter at 1.0. Fig. 9 shows the undulator’s field profile. Using this geometry, the horizontal focusing is greatly improved.

The undulator was tested across a range of energies and gaps, as before, and no non-wiggle plane defocusing was found. The electron beam was confined to an ellipse (or partial ellipse) in phase space from 10-100 MeV and from K=0.5-1.0. The gap sizes corresponding to these K values using this slot size are 9.2mm and 5.5mm.

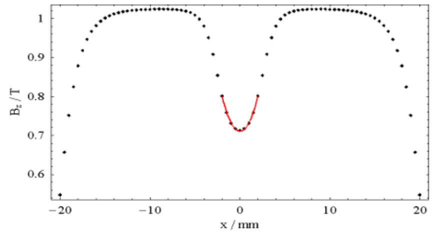

Figure 9: The field profile of the slotted undulator, with a quadratic fit.

MECHANICAL DESIGN

Some further modelling of the undulator arrays was carried out using *Radia*, in order to assess the magnetic forces involved. Estimates of the forces both in the completed arrays and in the construction stages were required. The magnitude of the force between the two arrays is estimated to be 7.9kN. Clearly the mechanism controlling the undulator gap will need to be able to handle this amount of force. The gap will be controlled by a handwheel since it is not required to change very often. The system will be upgradeable to motorised control in case this is needed in the future.

Detailed modelling of the entire undulator was carried out using the *Pro Engineer* CAD package, to decide how the blocks should be held in place and how the undulator should be assembled. The design should be as simple and inexpensive as possible while still allowing the blocks to be aligned precisely, and having the flexibility to add shims after testing if necessary. Fig. 10 shows a 3D model of the undulator generated by this software. Note that the arrays are mounted horizontally rather than vertically as shown earlier – this simplifies the engineering support arrangement.

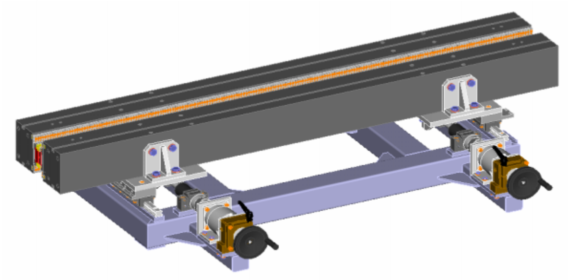

Figure 10: Engineering drawing of the undulator.

Since the individual magnet blocks are very thin (3.7mm), the blocks will be clamped together in pairs to make up the array. After the arrays are built, it will then be possible to adjust the transverse positions of a pair of blocks if necessary.

A test piece was built at Daresbury (see Fig. 11) consisting of a clamp holding a pair of blocks. This was done to make sure the clamp could withstand the estimated forces between the arrays, as well as holding together a pair of blocks against the longitudinal forces. The arrangement was found to be more than adequate – the forces required to separate the blocks are much greater than any that will be present in the completed arrays.

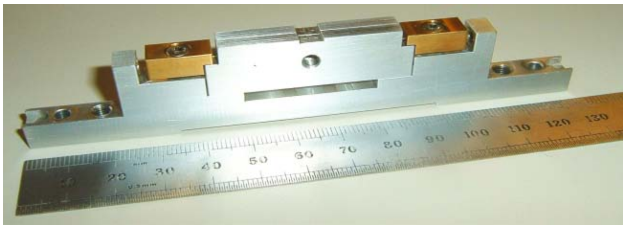

Figure 11: Test piece manufactured at Daresbury.

CONCLUSIONS AND FURTHER WORK

The magnetic design of the undulator is complete. The shape of the magnetic blocks and their positioning within the device have been finalised. The required focusing is implemented using a slot cut into each block: this has the useful side-effect of allowing the gap to be slightly increased. The slot is also useful mechanically, as it provides a convenient method for aligning each magnet block with the others in the array. Table 1 summarises the final details of the magnetic design.

The project is now in the mechanical design stage. Detailed drawings of the support structure are being prepared. The procurement of the magnet blocks will take place in the next three months. It is expected that the undulator will be ready for testing at the ID test facility at Daresbury by the end of 2004.

number of periods	100	
period length	15mm	
block length	3.7mm	
block width	40mm	
block height	15mm	
slot size	5x1mm	
operating gaps	5.5mm	9.2mm
peak field	0.71T	0.36T
K parameters	1.0	0.5
energy range	10…100 MeV	

Table 1: Final undulator design parameters

ACKNOWLEDGEMENTS

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