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DESIGN OF A SHORT PERIOD HELICAL SUPERCONDUCTING UNDULATOR*

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Abstract

Superconducting technology provides the possibility to develop short period, small bore undulators that can generate much larger magnetic fields than alternative technologies. This may allow an x-ray free electron laser (XFEL) with optimised superconducting undulators to cover a broader range of wavelengths than traditional undulators. At STFC, we have undertaken work to design and build a prototype superconducting helical undulator (HSCU) module with parameters suitable for use on a future XFEL facility. This work includes the design of a full 2 m long undulator module, including an undulator with 13 mm period and 5 mm inner winding diameter, the supporting cryogenic and vacuum systems required for operation, and quadrupoles, phase shifters and correction magnets for use between undulator sections. We present here the magnetic and mechanical design of the HSCU, including a turnaround scheme to allow continuous winding of the undulator without the need for superconducting joints.

INTRODUCTION

For undulators with short periods and small bore, superconducting technology can be utilised to achieve higher magnetic fields on axis than can be achieved with current cryogenic permanent magnet based technologies [1]. STFC has a history of developing helical [2] and planar [3] superconducting undulators for use in positron and light sources respectively. A prototype helical superconducting undulator has been designed at STFC to allow future XFEL facilities to access a broader range of photon wavelengths at a given beam energy by achieving high fields at short periods.

The parameters of the prototype undulator were chosen to coincide with the parameters being explored for the CompactLight project [4]. The parameters of the HSCU are summarised in Table 1. The use of high performance superconducting undulators and the corresponding parameters were defined to maximise the photon energy and peak FEL brilliance for an electron beam energy lower than those available at current FEL facilities [4]. The lower beam energy would allow a reduction of the facility building size and decrease in power consumption. For the parameters chosen, a peak brilliance at the highest photon energy of 16 keV of the order 10^{33} ph/s/mm^2/mrad^2/0.1% BW was expected, with a peak power approaching 10 GW [4].

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A helical undulator was chosen for the design because the coupling between the electron beam and the radiation field is more efficient for a helical than for a planar undulator [5]. This increased efficiency would result in a decrease in the FEL saturation length and an increase in the peak energy at a fixed electron beam energy.

Table 1: Summary of Undulator Parameters

Parameter	Value	Units
Period Length	13	mm
Inner Winding Diameter	5	mm
Beam Pipe Inner Diameter	4	mm
Photon Energy Range	8-16	keV
Deflection Parameter K (8 keV)	1.33	
Deflection Parameter K (16 keV)	0.62	
Peak Field on Axis	1.09	T
Electron Beam Energy	5.5	GeV
Undulator Length	1.8	m
Cryomodule Length	2.3	m
Total Number of Modules	16	

MAGNETIC DESIGN

The undulator fields are generated by a bifilar winding of superconducting wire. The winding consists of two helical coils separated by half an undulator period with current flowing in opposite directions in the two coils. A bifilar superconducting undulator is currently in operation at the Advanced Photon Source (APS) [6] with a period of 31.5 mm and peak field of 0.41 T.

Opera Finite Element Analysis (FEA) software [7] was used to investigate the fields that could be generated from different winding stack configurations in the coils in order to determine an appropriate arrangement for meeting the parameters described in Table 1. The design assumed the use of SuperCon [8] VSF-678 0.44 mm diameter niobium titanium (NbTi) wire. A small diameter NbTi wire was chosen to allow winding of the undulator on a small bore.

Simulation showed that the use of iron poles between the winding coils would boost the field on axis for a given winding arrangement and current compared to a coil dominated case with aluminium poles. This can be seen in Fig. 1, which shows the fields on axis produced by models with a stack containing 85 wires per coil. The increase in field from the iron poles at a given current is approximately

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0.1 T for wire currents larger than 200 A. For the aluminium former models, an increase in field on axis of 0.1 T could be achieved by an increase in current of 22 A. This limited increase in the field from the iron poles is due to the saturation of the poles at low currents.

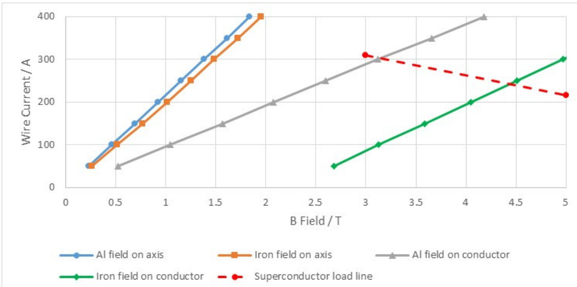

Figure 1: Fields on axis and load lines as a function of wire current for models with and without helical iron poles.

The presence of the iron poles and former in close vicinity to the coil stack also resulted in an increase of the conductor field at a given current, as shown in Fig. 1. To achieve a given field on axis, an undulator with iron poles and former would operate at a higher fraction of the conductor critical current than for a conductor dominated undulator with an aluminium former, as shown in Fig. 2.

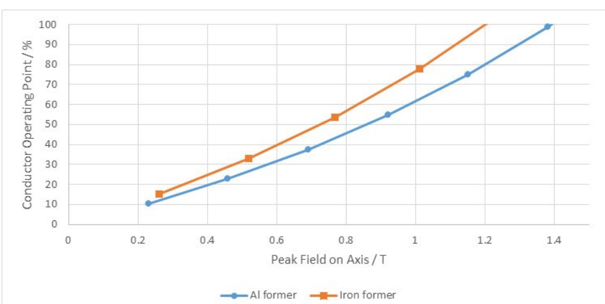

Figure 2: Fields on axis as a function of wire current for models with and without helical iron poles.

The final design therefore used an aluminium former to decrease the superconductor operating point. The high thermal and electrical conductivity of aluminium would also allow indirect cooling of the undulator by thermally connecting the former to a cold head and mitigation of wakefield effects [9] that may broaden the radiation bandwidth or reduce the peak power [4]. The winding stack consisted of 85 wires per coil, arranged in 10 layers and reached the target peak field of 1.09 T at 79% of the wire critical current.

TURNAROUND DESIGN

A turnaround design has been developed to allow the undulator to be wound from a single length of superconducting wire without the need for superconducting joints between wire sections. These joints would provide an unwanted source of heat in the undulator cryostat. At the ends of the undulator, the wires come away from the helix at a tangent to the winding direction. The wires are turned 180 degrees around a non-ferromagnetic pin and then returned into the adjacent winding groove with opposite direction. There are 10 turnaround pins at each end of the undulator former, spaced evenly over a single undulator period. Figure 3 shows an image of this turnaround design with five of the turnaround pins wound.

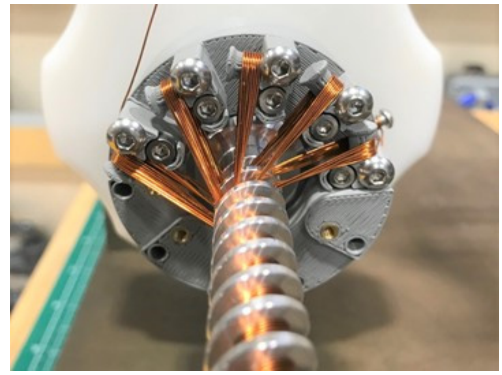

Figure 3: Image of the undulator turnaround design, showing five of the total 10 pins wound at one end.

The turnaround design was modelled in Opera so that the field integrals through the undulator could be simulated. Figure 4 shows an image of the Opera conductor model with the turnarounds included. The field profile through a 10 period long model, where the peak field is 1.09 T, and the trajectory of a 5.5 GeV electron beam through the field profile are shown in Fig. 5. This trajectory shows that the fields from the turnarounds provide a kick to the electron beam at both ends. Correction coils in the horizontal and vertical directions will be required at both ends of the undulators to correct the field integrals. Simulation has indicated that the maximum required integral correction will be 0.3 T mm.

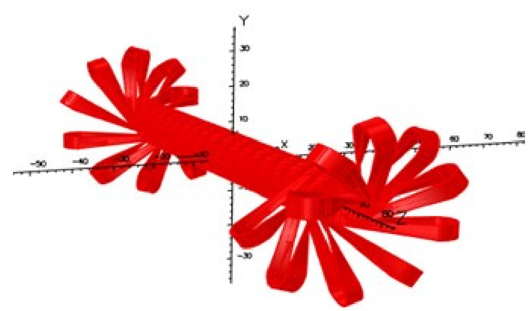

Figure 4: Image of Opera conductor model including turnarounds.

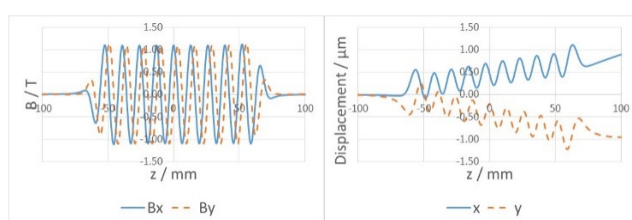

Figure 5: Example field profile and corresponding electron trajectory through a 10 period model.

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WINDING TRIALS

Prototype aluminium formers have been machined on a 4-axis milling machine. First a 4 mm diameter bore is drilled into an aluminium pipe. Then the pipe is machined down to form a double helix structure with a remaining thickness of 0.5 mm to wind the coils on. Nine period long formers have been manufactured with tolerances on the pitch of ±10 µm.

Figure 6 shows an image of a fully wound, 9 period former and a cut through of a solid former showing the arrangement of 10 layers of wire inside the winding groove. The cross section of the wires near the bed of the winding groove appear oval in shape compared to the wires further from the bore. This is because layers with a smaller inner winding radius must be wound at a more pronounced angle relative to the axis of the helix.

Next steps will be to increase the length of prototype formers whilst maintaining tolerances on the former pitch, building up to a nominal length of 1.8 m.

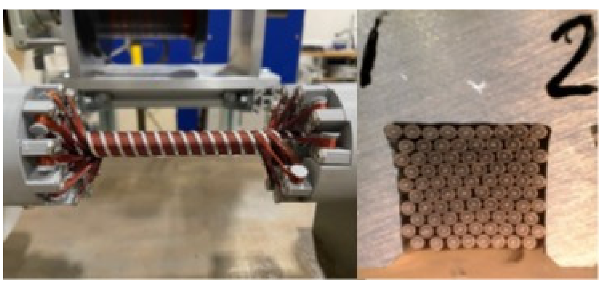

Figure 6: Image of fully wound prototype former and cut through of former showing winding stack.

TOLERANCE STUDIES

Previous tolerance studies on superconducting undulators have focussed on machining tolerances on the ferromagnetic formers in planar devices [10-12].

Due to the choice of a non-ferromagnetic former and poles, the accurate positioning of the superconducting wires in the former grooves is imperative to achieve a good field quality. A detailed tolerance study is underway to determine how the accuracy of the wire positioning affects the root mean square (rms) peak to peak field deviation. A target peak to peak deviation of 10^{-4} has been set in order to avoid significant degradation of the FEL light [5].

Initial results have focussed on how tolerances on the positions of individual wires within the stack affect the fields produced on axis. A model was created that allowed the inner winding radius of a single wire within the stack to vary randomly up to a maximum tolerance along the length of a 60 period long undulator whilst the positions of the other wires were kept constant. Figure 7 shows the error signature caused by the deviations in one model with a tolerance on the winding radius of a wire in the inner layer of the stack of 10 µm. The error fields are randomly distributed along the length of the undulator.

The rms field error was calculated as a function of the tolerance on the winding radius for wires in the inner-most and outer-most winding layers. For each set of conditions, results were taken for 10 simulations with different starting points. Figure 8 shows that tolerances on wires in the layer closest to the bore have a greater impact on the field calculated on axis and hence must be wound with a greater precision than wires further from the magnet bore. Control of the inner radius of the windings will be achieved by tensioning the wire as it is wound.

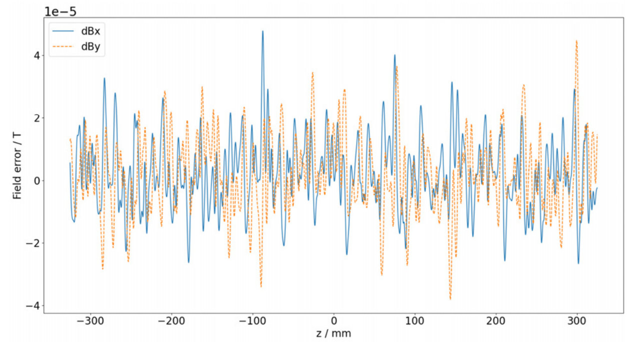

Figure 7: Field error signature caused by a 10 µm tolerance on the winding radius of a single wire in the innermost winding layer.

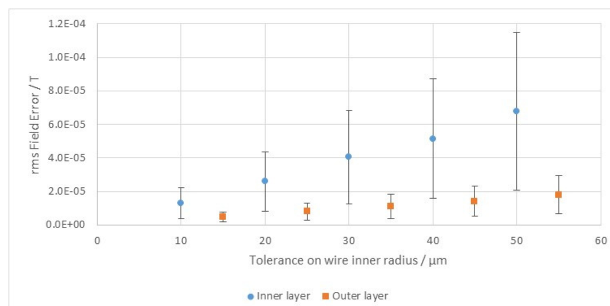

Figure 8: Plot of rms field deviation in the undulator due to tolerances on the inner winding radius of a single wire in the innermost and outermost layers of the winding stack.

The next steps in the tolerance study will be to build a database of the rms field errors and standard deviations generated by tolerances on individual wires in different layers in the winding stack. The tolerances can then be combined statistically to determine the combined impact on the peak to peak field quality of tolerances on multiple wires in the stack.

CONCLUSION

A short period, small bore superconducting helical undulator has been designed at STFC. This design aims to cover a broader range of photon wavelengths at future XFEL facilities than are accessible with current technologies. Good progress has been made in winding trials and the next steps will be to measure the fields of a short prototype to verify agreement with the simulations.

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