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DEVELOPMENT OF A SHORT PERIOD SUPERCONDUCTING HELICAL UNDULATOR*

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Abstract

Superconducting undulators (SCUs) with short period and small magnetic gap have the potential to generate larger magnetic fields than alternative technologies. Implementing SCUs on future x-ray free electron laser (XFEL) facilities will allow a broader range of photon wavelengths to be generated. At STFC, we have undertaken work to design and build a prototype helical superconducting undulator (HSCU) module with parameters suitable for use within a future XFEL facility. This work includes the design of an undulator with 13 mm period and 5 mm magnetic bore diameter, as well as the supporting cryogenic and vacuum systems required for operation. Mechanical tolerances on the HSCU have been simulated to investigate the effect on the performance of the undulator. The fields produced by prototype undulators will soon be measured using a Hall sensor system to verify that the wound formers are within acceptable tolerances.

INTRODUCTION

At STFC, we are developing the design of a superconducting helical undulator with 13 mm period and 5 mm magnetic bore gap aimed at producing photons in the energy range 8-16 keV from a 5.5 GeV electron beam from a peak on-axis field of 1.09 T [1]. The use of high performance HSCUs 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 [2].

The performance of an XFEL facility using this HSCU design is partly limited by the field quality produced by the undulators [3]. Errors in the field will reduce the radiated output power of the facility. The field quality will be limited by the mechanical tolerances on the manufacture and winding of the HSCU. An Opera 3D [4] model of the HSCU has been used to simulate how these mechanical tolerances affect the field quality.

Methods for manufacturing the magnet formers and winding the superconducting wire have been advanced to reduce the tolerances in order to improve the undulator field quality and FEL performance.

TOLERANCE MODELLING

There are two main mechanisms by which the undulator performance can be degraded that have been considered: the trajectory errors of the electron beam through the undulator and the root mean square (rms) peak-to-peak field deviation. Numerical simulations using Genesis 1.3 [5] have been used to define how the trajectory wander and field deviation will affect the degradation of the FEL output power for a 5.5 GeV electron beam generating 16 keV photons from a self-amplified spontaneous emission (SASE) line [3] comprised of HSCUs.

Trajectory Errors

In an ideal undulator, the electron beam will travel parallel to, and centred on, the axis of the undulator. This will ensure the radiation produced in the undulator overlaps the electron beam so that the two can interact via the SASE process and produce bright synchrotron radiation. If the radiation and electron beams overlap poorly then the process is weaker and the radiated power from the undulator will be reduced. Genesis simulations indicate that the power loss caused by trajectory errors can be kept below 10% if the trajectory error is less than 5 μm.

Local field errors in the undulator can result in the field integrals being non-zero. This will manifest as trajectory errors through the undulator. These errors can come as a result of manufacturing or winding tolerances. However, the trajectory of an electron through a non-ideal undulator can be influenced by dipole correction coils at either end of the undulator. It has been shown that correction coils will be required at either end of the undulator to correct for the kick to the electron beam caused by the wire turnaround periods [1]. These coils can also be used to correct for trajectory errors through the undulator caused by local field errors.

The first and second field integrals through an undulator are directly proportional to the exit angle and displacement, respectively, of an electron that has travelled through the device [6]. If the measured first and second field integrals through an undulator are non-zero, the corrector coils currents can be set to minimise the field integrals. This results in the exit angle and displacement of the electron beam being minimised, but also reduces the trajectory error significantly by minimising any net kick to the electron beam. Figure 1 shows an example of this. The plot shows the modelled trajectory of a single electron in the vertical plane through a 1.1 m long HSCU with a ±50 μm tolerance on the pitch and groove depth of the former (black). The trajectory error is larger than the specified 5 μm. However, with the corrector coils activated, the trajectory error is maintained within a 2 μm window of the axis (red). This has been shown for multiple models with former manufacturing tolerances up to ±50 μm. As this is a considerably larger tolerance than can be achieved, it has

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been determined that trajectory error of the electron beam will not be a significant issue for the HSCU because correction coils can be used to keep the trajectory within an acceptable window.

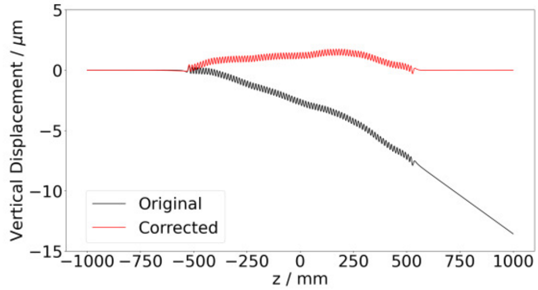

Figure 1: Example corrected (red) and uncorrected (black) electron trajectory in the vertical plane for an undulator with 50 µm tolerance on the former pitch and groove depth.

Peak-to-Peak Field Error

The other factor that can affect the FEL power output from the undulator is the rms peak-to-peak field deviation. Differences in the magnitudes of the local field peaks affect the local undulator *K* parameter. For an undulator with negligible field integrals, changes of the local *K* parameter along the length affect the phase shift per gain length. This will lead to a degradation of the FEL power output [3]. Genesis simulations have shown that the power can be kept within 5% of the nominal if the tolerance on the rms peak field deviation (ΔB/B) is less than 10^{-3} (assuming trajectory errors have been negated by setting the field integrals to zero).

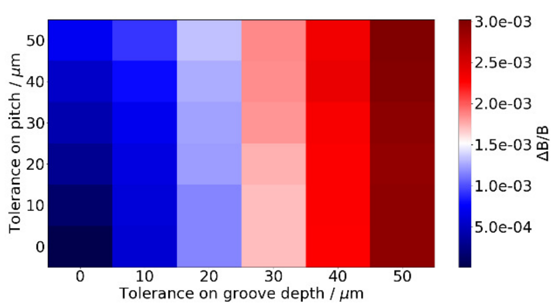

Figure 2: rms peak-to-peak field errors as function of tolerance on groove pitch and depth.

The main manufacturing tolerances of concern are on the pitches and the groove depths of the former because these tolerances will affect the positions of the superconducting wire stacks and therefore the field produced on axis. Both tolerances will affect the peak field deviation, but not independently. Figure 2 shows a plot of the rms peak to peak field error for models with random distributions of tolerances on the pitch and groove depth over the undulator length. For each combination of tolerances, the rms peak field error was averaged over 10 models with different tolerance distributions. As both tolerances increase, the peak-to-peak field error increases. For tolerances on the groove depth greater than ±20 µm, the field error will exceed the target value of 10^{-3}. The tighter the tolerance that can be met on the pitches, the looser the allowable tolerance on the groove depth can be.

The techniques for machining the undulator former have been refined to allow for accurate manufacture of full length, 1.1 m long formers. A machining jig was designed to ensure that the axes of the machine work piece and of the bored HSCU former were coincident in order to maintain tight tolerances on the machined former pitches. The formers were made from aluminium in order to achieve a higher undulator peak field and ease the mechanical design compared to a ferrous former [1]. Metrology reports from the 1.1 m formers show that the measured groove pitches are predominantly within a tolerance of ±10 µm (Fig. 3). This allows the groove depths to be within a tolerance of ±15 µm, whilst keeping the rms peak-to-peak field error within its set target.

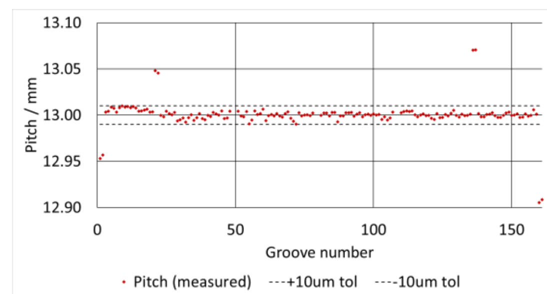

Figure 3: Metrology report of measured pitches from 1.1 m HSCU former.

The outliers in Fig. 3 are most likely caused by aberrations on the former surface. The report shows that there is no systematic build-up of tolerances on the groove pitch which would degrade the FEL power output.

The positioning of individual wire turns within the grooves is also important to maintain the field quality. The wire stack contains 10 layers of alternating 9 and 8 turns. There are two identical wire stacks, which are offset by half an undulator period to form the bifilar winding structure. The total magnetic field generated on the axis of the undulator is the superposition of the fields generated from each wire turn, where the fields from an individual turn can be calculated from the Biot-Savart law.

Therefore, in order to model the effect of tolerances on each wire turn in the HSCU, the field errors produced by each turn in the stack can be summed in quadrature to estimate the total field error on axis if the positioning errors on each turn are assumed to be independent. For the nominal peak undulator field of 1.09 T, the allowable rms field error is 1.09×10^{-3} T. If the allowable rms field error produced per turn is 8.4×10^{-5} T, then the quadrature sum of the errors over all 170 wire turns will be equal to the allowable rms field error of 1.09×10^{-3} T.

The field error produced on axis by each turn depends on the nominal radial distance of the turn from the axis. Figure 4 shows the rms field error produced by a turn in the innermost layer (layer 1) and outermost layer (10) as a function of the tolerance on the positioning accuracy of the turn. For a turn closer to the axis, a given tolerance on the position will cause a larger rms field error. The turns in the

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innermost layer must be positioned with a tolerance better than ±20 μm, whilst those in the outermost layer can be positioned with a tolerance of ±90 μm to have the same contribution to the field error.

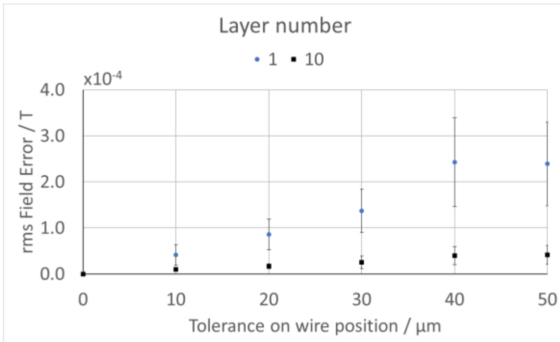

Figure 4: rms field error produced by a single turn as a function of the tolerance on the position of the turn for turns in layer 1 and 10 of the stack.

Machining and winding techniques have been developed to ensure the accuracy of the winding of the inner layers of turns. If the inner layers are wound with good accuracy, this will create a bed to wind the subsequent layers on. The width of the winding grooves has been defined to a precision of 100 μm to ensure that the bottom layer of turns fits optimally into the groove. This will minimise the tolerance on the axial position of turns within the groove. The wire is wound under a tension of 1 kg in order to minimise the radial tolerance in the positioning of the wound turns.

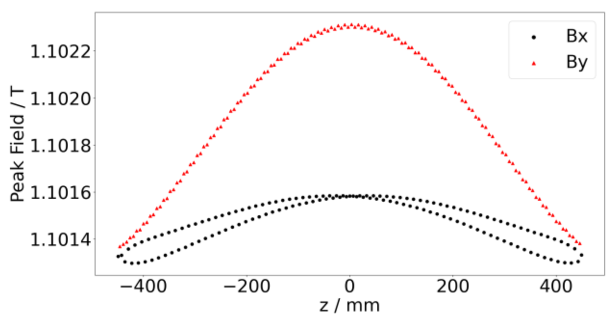

Figure 5: Peak field magnitudes for a 1.1 m undulator with 100 μm sag.

The peak-to-peak field error calculated on the reference axis of the electron will also depend on the alignment and straightness of the undulator axis relative to the electron beam axis. If the undulator sags under gravity, it will affect the local peak fields seen by an electron beam, as shown in Fig. 5. This will cause an increase in the rms peak to peak field deviation and hence decrease the radiated power out-put of the undulator. A sag of 100 μm from the electron reference axis to the magnetic axis in the centre of the undulator former bore will lead to a spread in field peak values of the order 10^{-3}. A combined strong back and potting jig (Fig. 6) has been designed. This jig will mechanically support the undulator to reduce sag and allow it to be potted in epoxy resin to provide a means of heat transfer from the wires to the cryostat cold head. No liquid cryogens are envisaged for this undulator.

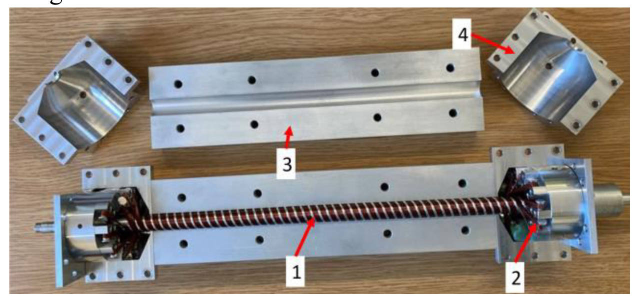

Figure 6: Wound 325 mm HSCU in strong back; 1-Wound HSCU former, 2-Turnaround pins, 3-Potting jig strong back, 4-Potting jig turnaround section.

The estimated mechanical and winding tolerances from the magnetic modelling are summarised in Table 1. Future work will aim to model tolerances on the machining and winding in combination to give a more realistic view of the impact on the field.

Table 1: Estimated Mechanical and Winding Tolerances

Value	Tolerance	Unit
Groove depth	±15	μm
Groove pitch	±10	μm
Winding accuracy (layer 1)	±20	μm
Winding accuracy (layer 10)	±90	μm
Angular alignment	±0.025	deg
Linear alignment	±30	μm
Sag	100	μm

CONCLUSION

A 13 mm period, 5 mm magnetic bore gap helical superconducting undulator has been designed and 1.1 m long prototype formers have been manufactured and will soon be wound. Metrology of the prototypes indicates that the machining tolerances on the former pitches are within acceptable limits defined by magnetic modelling.

Next steps will be to verify the performance of the manufactured prototype undulators by measuring the generated fields using Hall sensors. The first measurement tests will be performed on 325 mm long prototype formers in a 4 K test cryostat. The peak-to-peak field quality and trajectory errors must both be assessed in order to determine whether the undulator fields conform to the defined tolerances. Accurate measurement of the first and second field integrals of manufactured undulators will be necessary to set the correction coils and keep the trajectory errors within an acceptable 5 μm window.

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