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FIRST TEST RESULTS OF A SHORT PERIOD SUPERCONDUCTING HELICAL UNDULATOR *

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Abstract

Superconducting undulators provide a possible means of broadening the range of wavelengths that can be covered by an X-ray Free Electron Laser (XFEL) facility by generating larger magnetic fields at a given period than can be achieved using permanent magnet undulators. As part of ongoing prototyping work at STFC to develop a superconducting helical undulator with 13 mm period and 5 mm magnetic gap, techniques to measure the field profile and the integrated field components inside the small, closed magnet bore are under investigation. These measurements are crucial for understanding the magnetic performance of the prototype magnets and identifying and implementing suitable corrections to the field integrals. Measurements made at room temperature and low current give initial field profile measurements with reduced infrastructure compared to cryogenic testing. A test cryostat has been designed and built to investigate the performance of 325 mm long prototype magnets. The test cryostat will be used to cool prototypes to less than 4.2 K and to power them to a full operational current of 240 A. We present here the first magnetic field measurement results of a prototype undulator.

INTRODUCTION

Superconducting undulators (SCUs) are an attractive option for future light sources to broaden the range of photon wavelengths that can be produced at a given electron beam energy because SCUs can generate larger magnetic fields at short periods than traditional permanent magnet based undulators [1].

At STFC, we have designed a helical superconducting undulator (HSCU) with a 13 mm period and 5 mm winding bore diameter capable of generating photons in the energy range 8-16 keV from a 5.5 GeV electron beam [2]. The project is currently in the prototyping stage with 325 mm long magnet formers being developed to refine the manufacturing and winding processes and hence reduce mechanical tolerances.

Characterisation of the magnetic fields of prototype undulators is a key aspect of the development process and can be used to quantify the quality of the device as a radiation source in an XFEL facility [3].

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LOW CURRENT MEASUREMENTS

Accurate field mapping using Hall sensors in closed bore superconducting undulators operating at cryogenic temperatures is a challenging process because there is insufficient space to fit guiding rails to control the motion of a mounting sledge, as can be used to measure planar SCUs [4]. The concept of creating a warm bore in the magnet aperture that is isolated from the SCU vacuum and cryogenic systems [5] to house the Hall sensor sledge is not appropriate here because the 4 mm diameter magnet bore is too small. Mapping the undulator field at room temperature with the coil powered to low current to avoid excessive heating is an attractive option to avoid the added complexity and infrastructure required to perform measurements inside the undulator cryostat.

The undulator former has been designed to be made from aluminium as opposed to mild steel to allow a larger peak magnetic field to be achieved by reducing the self field on the conductor and to improve the conductive cooling of the coils by increasing the thermal conductivity of the former [2]. The former is non-ferromagnetic; therefore, field measurements performed at room temperature and low current can be scaled linearly to give the expected field profile at full operational current.

A prototype 325 mm undulator former has been tested at low current. The resistance of the undulator coil at room temperature was measured as 38 Ω. The coil was powered to a maximum current of 0.6 A at room temperature, and 4 A in a liquid nitrogen bath. A uniaxial Hall sensor was used to map the field profile at a series of undulator currents and sensor orientations inside the undulator.

Field Profile

The field profile through the tested undulator measured at 0.5 A is shown in Fig. 1. The Hall sensor was rotated by 90° to measure the fields in the vertical and horizontal planes.

The magnitudes of the field peaks are not constant along the length of the undulator, as shown more clearly by Fig. 2. There is a systematic decrease in the magnitude of the field peaks along the first 100 mm in the main body of the undulator before becoming more constant over the remaining 25 peaks. This field peak distribution represents a changing undulator deflection K parameter along the undulator length. The variation in K would result in the degradation of the FEL power produced by this undulator [3]. Therefore, the source of this error needs to be eliminated.

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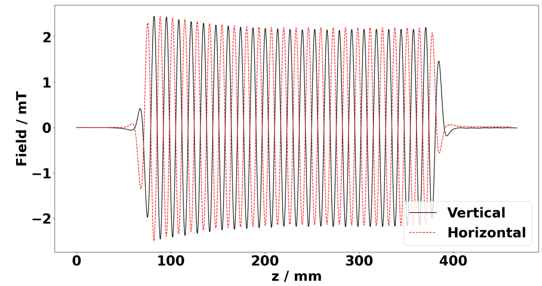

Figure 1: Field profile measured in orthogonal planes along the undulator axis powered to 0.5 A at room temperature.

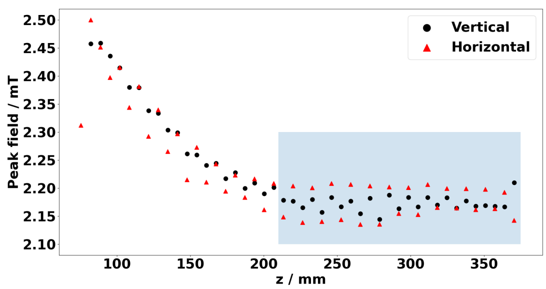

Figure 2: Measured field peaks in one plane of the undulator powered to 0.5 A at room temperature. The shaded region represents the peaks used for calculating the average field strength and rms peak field error.

The field peak distribution was attributed to out of tolerance manufacturing of the undulator former. Machining tolerances of ±10 µm have been defined in order to keep the FEL power produced in the undulator within 5% of the nominal [6]. Metrology data of the former before it was wound showed that the pitches were all within this tolerance. It was suspected that the field peak distribution was caused by variations in the undulator groove depths. The groove depths of previously machined formers were measured and found to vary by up to 100 µm. The same variation can be expected for the measured undulator. As the groove depth varies, the proximity of the wire stack to the undulator axis will also vary. If there is a systematic decrease in the groove depth along the undulator axis, the wire stack will sit further from the axis, resulting in a decreased contribution to the on axis field and hence a reduction in the measured peak field strength.

The formers are machined from gun drilled aluminium blanks. The outside diameter of the blank is the datum for the winding groove depth. Metrology data showed that the outside diameter of blanks varied by 100 µm and corresponded to the variation in the machined groove depths. The blanks for making future formers will be machined using centreless grinding to reduce the variation on the outside diameter to less than 10 µm. This will provide a much better datum that is held and sits uniformly in the work piece fixture and will subsequently reduce machining tolerances on the finished formers. Measurements of the next production run of formers will be used to test whether the variation in field peaks has been resolved.

Figure 3 shows the measured peak field as a function of current for the tested undulator, calculated from the 25 peaks in the region after the systematic decrease in field magnitude. The peaks used for the averages are shown by the shaded region in Fig. 2. Error bars on the points represent the standard error on the mean calculated from multiple field maps at the same current but are too small to be clearly visible. The field magnitudes up to 4 A show a linear trend and the magnitudes are in good agreement with the prediction from the Opera 3D [7] model of the undulator. This gives a good indication that the model can be used as an accurate predictor of the peak field as the undulator current is scaled up to the full operating value of 240 A at cryogenic temperatures. However, forces on the coil at higher currents may cause deformation of the former and field measurements at full current will be required to verify these results.

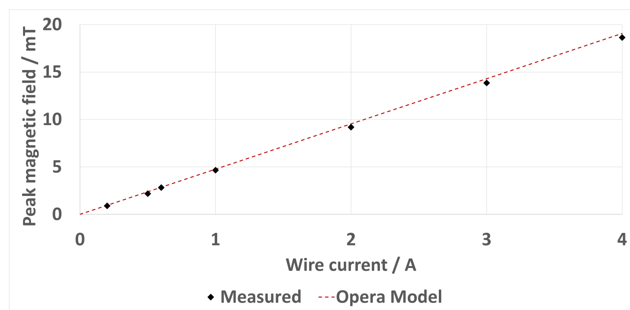

Figure 3: Measured peak field as a function of undulator current.

Peak Field Error

A target normalised root mean square (rms) peak field error $\Delta B/B$ of 10^{-3} has been defined in order to keep the FEL power produced in the undulator within 5% of the nominal [6]. The normalised field error is independent of the undulator current due to the linear scaling of the field and can be determined from low current measurements. Measurements would need to be repeated in the cryostat to confirm that coil forces do not cause distortion of the field errors at higher currents.

The 25 peaks used to calculate the field magnitude were used to calculate the rms peak field deviation. Figure 4 shows the field error as a function of the measurement current. Error bars represent the standard error on the mean calculated from multiple field maps at the same current. The plot shows no systematic relationship between the field error and the current, as would be expected.

The measured field error $\Delta B/B$, averaged over runs at all currents is $(8 \pm 4) \times 10^{-3}$, which exceeds the target value of 10^{-3}. The uncertainty on these measurements also exceeds the target peak error value. The root mean square fluctuation in the probe signal was measured as 0.02 mT. This error is significant for the measurement of the peak field error

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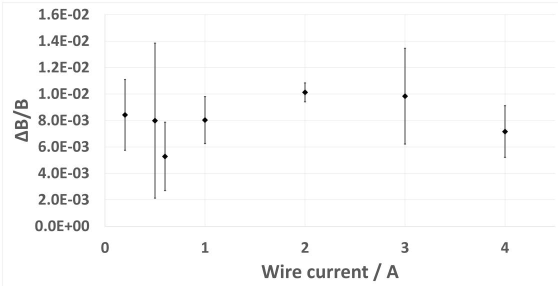

Figure 4: Measured rms peak field error as a function of undulator current.

at low current. At a current of 4 A, the error on the peak field measurement due to fluctuations in the probe signal is 0.1%. Therefore, the probe noise is of the same order as the field deviation that is expected due to mechanical tolerances and hence determination of the peak field to within the set tolerance is not possible with this measurement method. At the nominal operational field of 1.1 T, the same level of probe noise would represent a 0.002% error in the peak signal, which is below the required measurement tolerance. Reducing noise by taking more readings and averaging at each point in the low current scans is impractical due to the resistive heating of the undulator. Therefore, the field must be measured at full operational current with the undulator cooled to cryogenic temperatures in order to reduce measurement uncertainties in determining the field errors.

Electron Trajectories

The trajectory straightness of an electron beam through the undulator is another figure of merit that defines the performance of the undulator as a radiation source. The angle and displacement of the trajectory of an electron exiting the undulator are directly proportional to the first and second integrals of the magnetic field along the axis respectively [8]. In order to maintain trajectory straightness between undulator modules in a XFEL, limits on the first and second field integrals have been defined as 0.018 T.mm and 9 T.mm^2 respectively. The field profiles measured at room temperature can be integrated and scaled linearly to the operating current of 240 A to calculate the field integrals and predicted electron trajectories through the undulator. The trajectories for a 5.5 GeV electron in one plane calculated from 6 repeat field maps at 0.5 A are shown in Fig. 5.

The calculated trajectories all exceed the trajectory wander tolerance of 5 μm [6]. The trajectory wander will be corrected in an operational device using dipole corrector coils at either end of the undulator to reduce the field integrals below the stated limits. The necessary corrector coil currents will be determined by the measured field integrals of the device. The average first and second field integrals from the plots shown in Fig. 5 are (0.5 ± 0.4) T.mm and (490 ± 90) T.mm^2 respectively. The large integral values are explained by the varying field strength along the undulator resulting in a net kick to the electron beam. The uncertainties on these quantities are an order of magnitude greater than the required measurement precision. Field mapping at operational current in the test cryostat will be required to improve the signal to noise ratio of the measurements and reduce the uncertainty in the calculated field integrals.

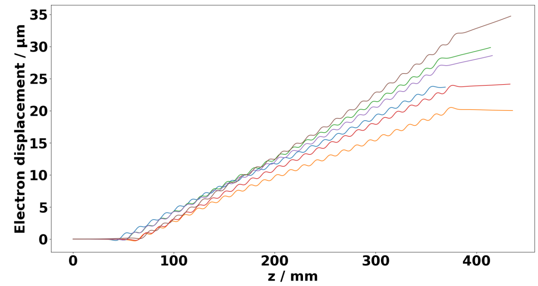

Figure 5: Calculated electron trajectories for a 5.5 GeV beam scaled to 240 A from 6 field measurements at 0.5 A.

HIGH CURRENT MEASUREMENTS

A test cryostat has been designed for high current testing of the 325 mm long prototype undulators. The cryostat implements a cryocooler to conductively cool the undulator without the use of liquid cryogens. Temperature sensors on the undulator strong back have measured a temperature of 3.5 K after cooldown. This is a sufficiently low temperature for the wires to be in the superconducting state. Initial testing has shown that the coil can be powered to 10% of the nominal current without significant temperature rises on the strongback or current leads. Further testing will involve ramping to the full nominal current to test the thermal stability of the system.

Field mapping within the test cryostat at full current will be required to precisely determine the field quality and necessary field integral corrections. Techniques to precisely actuate a cryogenic Hall sensor within the 4 mm diameter closed bore of the undulator for field mapping are currently under investigation.

CONCLUSION

Progress continues to be made on the production of 325 mm long prototype HSCU formers. Room temperature field mapping has proven to be a quick and effective method for determining the field profile and identifying manufacturing issues. However, the precision of these measurements is insufficient to fully characterise the field errors or necessary field integral corrections. Next steps in the project will be to develop a method of field mapping in the closed undulator bore inside the test cryostat to reduce the measurement uncertainties owing to poor signal to noise ratio. Experience manufacturing and testing 325 mm prototype formers will lead to the development of full length 1 m long undulator formers, designed for use as radiation sources in a future XFEL facility.

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