Magnetic Field Measurements of A Superconducting Undulator for a Harmonic Generation FEL Experiment at the NSLS

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Abstract-

An 18mm period, 0.54 Tesla, 8mm gap superconducting undulator with both horizontal and vertical focusing has been built and tested. This magnet, which is fabricated in 25 cm length sections, is being tested for use in the radiator section (total magnet length of 1.5m) of the Harmonic Generation Free Electron Laser experiment at the National Synchrotron Light Source - Accelerator Test Facility at Brookhaven National Lab, in collaboration with Grumman Corp. The measurement system is outlined, sources and estimates of errors are described, and some magnetic field data are presented and discussed.

Introduction

A three stage superconducting undulator (modulator, dispersive section, and radiator) is under construction at the NSLS at Brookhaven for use in a high gain, harmonic generation experiment.[1] The three stage undulator triples the frequency of a 10.4 micron CO_2 seed laser using a 30MeV electron beam. The superconducting magnet yokes are iron core with a pole face shaped for transverse focusing. The magnets are machined in physical sections which are 25cm long and are wound independently of each other. The full length magnet is made up of several of these yoke sections, which are assembled end to end. There are no axial drift spaces other than those between each of the three stages of the undulator. Additional design details and considerations are provided in Ref.1. Prototype radiator undulator sections have been built and tested. The test setup allows measurement of up to two sections (for a total magnet length of 50 cm, with 27 periods) at a time. The testing results can be used for sorting of the magnet yoke sections so that errors from adjacent sections tend to cancel, analogous to the sorting and annealing techniques often used in permanent magnet and hybrid wigglers.

The magnet pole faces are shaped to establish transverse focusing, which is accomplished with a 1mm depth and +/-3mm width parabolic cut in the pole faces. The flat pole region of the magnet has a 6mm gap. The transverse focusing necessitates measurements with multiple probes in order to map the transverse field profile. For testing of the magnet sections before assembly of the full magnet, the sections are supported in a vertical cryostat with a magnet holder which permits measurement of 2 sections, or 50 cm of magnet, at a time (Figure 1-left).

Measurement System

For testing, the magnets are assembled into a aluminum box for clamping, with a precision ground spacer setting the gap. A slot machined into the spacer serves as a guide for a G10 slider which holds an array of five hall probes for measurements. This probe array is required for characterization of the field focusing due to the pole shaping. Taking z as the long axis of the magnet, y as the main direction of the undulator field , and x as the direction orthogonal to both of these, the hall probes are mounted so that one is nominally along the magnet centerline (x=y=0), and the others are displaced by 1.5 mm in the +y,-y,+x,or -x direction. The slider is attached to an actuator, and is driven with a stepping motor. The probe voltages are read through either a HP data acquisition switching system, or through independent voltmeters. The control and acquisition software is PC based.

Hall Probes

The hall probes used for testing are Siemens SBV604. The probes are powered in series with an excitation current of 50 mA, which gives a probe output voltage of about 27 microvolts/gauss. The power supply stability is $\approx$ 50 ppm, corresponding to $\approx$ 0.3G. A third order fit to the probe voltage as a function of field is adequate to the level of +/-0.75 Gauss, which is also the level of the repeatability of the probe, at room temperature, as referenced against an NMR probe. Upon thermal cycling of the probe, the subsequent dependence of voltage on field is unpredictable. Both cooldowns which made little difference in the probe calibration, and cooldowns which significantly changed the calibration were observed. For this reason a Helmholtz coil was incorporated into the test setup, permitting in-situ calibration and cross calibration of the probes. The Helmholtz coil has a 16mm radius, and although a larger coil gives a larger uniform field volume, the difference in the coil field at the central probe as compared to the offset probes of the array is about 10 Gauss in a field of 5500G, so cross calibration errors are minimal. Figure 1 (right) shows the output of the

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5 probes of the array with the data for each probe shifted by the physical distance between each of the probes along z. This data was taken at an excitation current of 75 amps in the Helmholtz coil, which corresponds to about 8600 Gauss. The different probe voltages are due to the different calibrations for each probe, and the fact that the probes are displaced in x or in y from the center of the Helmholtz coil.

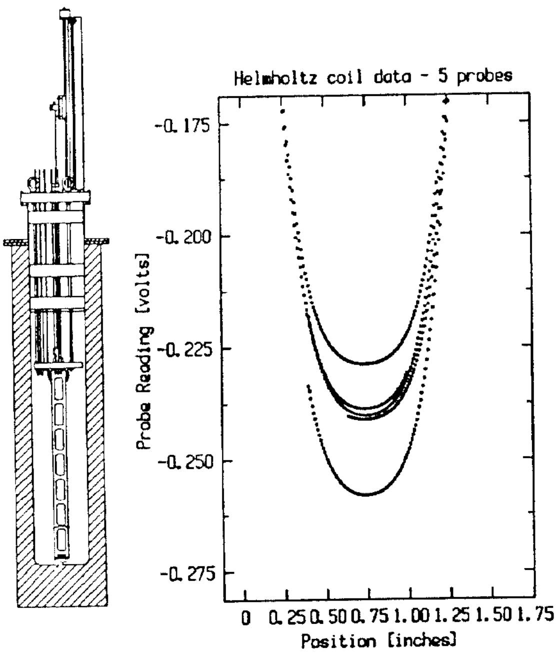

Figure 1:
Left:
A schematic of the magnet box supported within the vertical cryostat for measurement of the magnet sections.
Right:
Helmholtz Coil data of the five probe of the array at a field of 8600 Gauss.

Determination of the field profile requires both relative probe calibrations, and knowledge of the relative positions of the probes on the slider. A dual setup consisting of a needle magnet (an iron needle held and magnetized by a permanent magnet block) and a quadrupole magnet has been used for this. The needle magnet provides a high spatial gradient field, in which the position of maximum probe output voltage is searched for. The transverse (x) and axial (z) positions of the probes with respect to each other are determined. The magnetic center of the quadrupole provides a field point which can also be used to determine the relative probe positions, taking into account the probe offset voltage in zero field. If there is no angle "error" of the probe on the slider, i.e. if the probe is in the x-z plane, and therefore senses only the y field, then the null readings of the field are independent of y. The dependence of the null readings on y yields the probe angle with respect to the coordinate system of the quadrupole magnet. The data obtained indicate that the probes had angle errors below 4 degrees, with repeatabilities of +/-0.3 degrees. Application of pressure to maintain a desired orientation while the probes are being mounted is not possible due to the mechanical fragility of the hall element.

The position of the active areas on the probes is repeatable and consistent between these two methods to +/-.002". The axial position of the probes along the length of the slider is redetermined in the superconducting undulator magnet itself, both with the zero crossings of the magnetic fields which serve as extremely sensitive position markers, and with the data from the Helmholtz coil. The data obtained from the undulator magnet in this way agreed with the data taken in the lab on the slider to within 0.001".

Measurement Errors

The errors associated with the relative position determination of the hall probes directly affects the level to which the absolute transverse field profile of the magnets can be determined. As the spatial dependence of the field increases, the sensitivity to the position information about the probes also increases. Taking the probe location error as +/-.002", and a field reading error of +/- 10 Gauss (i.e. assume probe linearity is +/- 1% between calibration points spaced 1000G apart), then the absolute value of the curvature of the magnetic field can be determined to ≈ +/- 10%, and the centerline of the magnet can be determined to ≈ +/- 70 microns. This absolute focusing determination error is within specification in terms of FEL performance.

Optical survey measurements have been made of the slider in the magnet assembly, indicating horizontal and vertical motions of the slider below +/- 0.001" along the magnet length. Field reading changes due to these mechanical translations and possible rotations are negligible (e.g. the change in peak field readings are below 0.03%).

Results

Measurements were made on two magnet yokes assembled end to end, and on a single magnet yoke. Magnetic field measurements were made at several fields (see Table 1). The quench current for these magnets is 170 Amps. The peak field data highlights four magnet poles whose fields differ by more than 1% from the average. Mechanical inspection revealed large pole width machining errors for three of these poles (≈ 75 microns). All the other poles were within 10 microns of an average value, indicating that the stringent tolerances can be achieved. There is one remaining significant field error which has not yet been linked to a machining error. The yoke was rewound and all the four larger errors were present in the rewound yoke data, indicating that all four are due to the iron, and not the details of the winding. These four poles have been left out of the calculation of the RMS field errors, since we consider them errors which can be eliminated with improved machining procedures. When this is done, rms field error levels at 15amps, where saturation effects in the iron are at a minimum (see ref.1 for an excitation curve for this magnet), give a rms peak field error of 0.1%. This is consistent with the measured machining tolerances of 10 microns. As the current is increased, the field errors increase but level off, as seen in Table 1. This error increase with excitation is possibly due to inhomogeneities in the iron which is reflected in a difference in the slope of the permeability as a function of field for various parts of the yokes. As the iron saturates and it's mu value decreases, the contribution of coil placement errors to the peak field errors will increase.

Field	1550 G	4030 G	5800 G	6675 G	7220 G
I(amps)	15	50	100	130	150
RMS Error	0.1%	0.29%	0.35%	0.34%	0.33%

Table 1 : Field (in Gauss), and RMS Variation in the Peak Field Values of a Magnet Section as a Function of Excitation Current. A different undulator section showed 0.22% RMS errors at 50Amps.

The 150 amp, 50 amp, and the 15 amp data is shown in Figure 2, integrated twice to give the electron trajectory for a 30 MeV electron beam. These integrals contain the four bad poles of the magnet which result from machining errors, discussed above. Though the rms field error changes by more than a factor of 3 as the current is increased from 15 to 150 amps, the wander in the electron trajectory is within +/- 20 microns for all currents (1/10th of the electron beam radius, as required). This may be due to the fact that as the iron saturates and mu decreases, the effects of the errors is increasingly localized, leading to compensating effects in the trajectory.[2] New magnet pieces without the large machining errors are being tested, and should show improved performance.

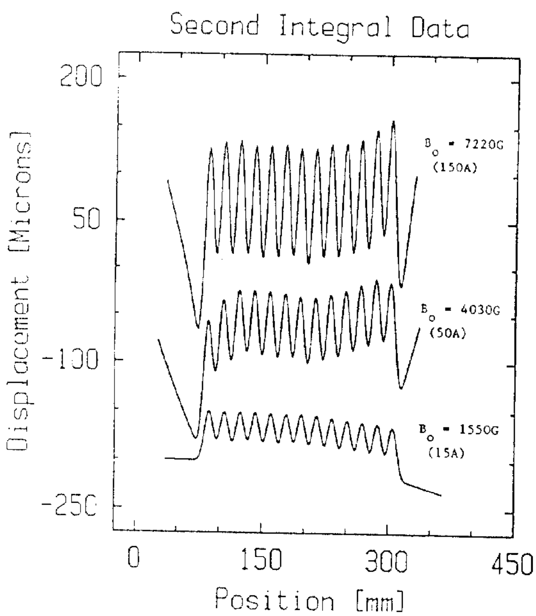

Figure 2 : The electron trajectories at 150,50,and 15 amp excitation (top to bottom plots) corresponding to a 7220, 4030, and 1550 Gauss central field in the magnet. The plots are displaced vertically for clarity.

Figure 3 shows the results of the transverse field measurements for the magnet at 0.5amps, 15, 50, and 100 amps. The 0.5A measurements are made with at room temperature with single probe on a precision translation stage. The cryogenic measurements (15,50,and 100 Amps) are made with the multiple hall probe setup, i.e. there are three probes along the y=0 plane, which are cross calibrated in the helmholtz coil. As the field increases from 1550 Gauss to 5800 Gauss, a decrease in curvature of about 15% is measured, due to saturation effects in the iron. This change is consistent with Tosca predictions.[3] The agreement between the 15A (multiple probe data) and the 0.5A (single probe data) results is consistent with the error estimates due to relative position and cross calibration errors.

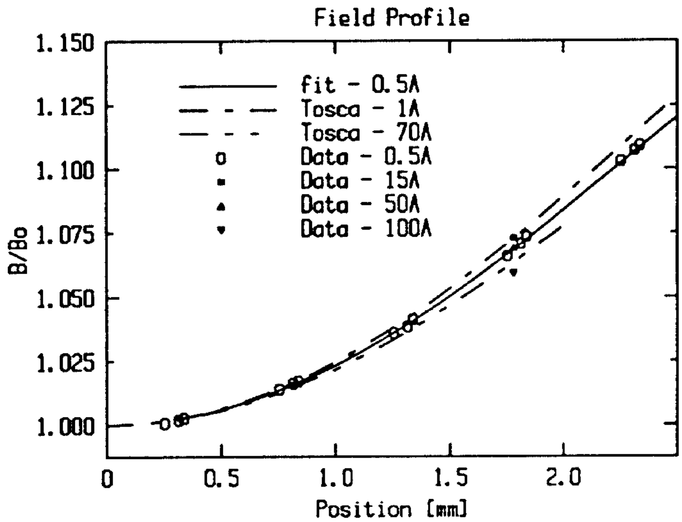

Figure 3 Transverse Field Profile Measurements at 0.5A, 15A, 50A, and 100A compared to Tosca calculations at 1A and 70A.

References

1. G.Ingold et.al, *IEEE PAC Conference Proceedings*, 1993.
2. K.Halbach, *Private communication*, 1993.
3. Tosca results provided by D.Weisenburger, Grumman Corp,Princeton, N.J., 1992.