© 1993 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

Magnetic Performance of the NSLS Prototype Small-Gap Undulator*

George Rakowsky and Ralph Cover Rockwell International, Rocketdyne Division P.O.Box 7922, Canoga Park, CA 91309-7922 and Lorraine Solomon National Synchrotron Light Source Brookhaven National Laboratory, Upton, NY 11973

Abstract

The magnetic design of the pure-permanent magnet Prototype Small-Gap Undulator for the NSLS X-ray Ring is reviewed. Measurements of individual magnets, half-period modules and the complete undulator are described. Results of performance optimization, including minimization of optical phase error, trajectory wander and integrated multipoles by means of simulated annealing are presented.^{*}

I. INTRODUCTION

The NSLS Prototype Small-Gap Undulator [1] (PSGU) is a very compact insertion device, with magnetic length of only 320 mm, 16 mm period, and a variable gap as small as 4 mm. Its purpose is to study the effects of reduced vertical aperture in the NSLS X-ray Ring, as well as to generate undulator radiation at the first and third harmonics in the bands from 1.8 to 3.8 and 5.4 to 11 keV. The project is a collaboration between NSLS and Rocketdyne, with NSLS responsible for the vacuum chamber, mechanical structure and the dual gap (magnetic and vacuum chamber) drive system, and Rocketdyne building the PSGU magnetic assembly. The objectives of the magnetic design were to attain maximum brightness in the desired energy bands and to meet the limits on integrated multipoles dictated by X-ray Ring beam dynamics. The magnetic assembly has been completed and delivered to NSLS. In the following sections we review the magnetic design, the optimization procedures and the measured magnetic performance.

II. MAGNETIC DESIGN

The PSGU is to be installed in the X13 straight section at NSLS and its total length cannot exceed 320 mm. For a fundamental resonant optical wavelength $\lambda_0=5$ Å, with e-beam energy E=2.5 GeV (γ =4892), and a desired value of deflection parameter K≈1, we chose the undulator period to be $\lambda_u=16$ mm, nominal gap g=6 mm and a peak field B₀=0.67 Tesla. Depending on the type of termination, 18 or 19 full periods can be accommodated in the available length. The desired field can be attained with either pure permanent magnet (PPM) or hybrid technology, using available NdFeB magnets. We have

chosen the high-performance 6 block/period version of the Halbach PPM design [2], and employed multi-stage, multiparameter performance optimization using simulated annealing (SA) [3], as described in Section IV.

The design calls for magnets with remanent field $B_r \ge 1.2$ Tesla, a linear B-H characteristic extending well into the third quadrant, and tolerances of $\pm 2\%$ on variation of total magnetic moment and $\pm 2^\circ$ on magnetization angle. Suitable NdFeB materials are available. We chose ¹ a local magnet fabricator ² to supply Sumitomo NEOMAX 35H³ material, to cut, machine, magnetize and certify the magnets, and to assemble the half-period triplet modules. Prior to magnetization, the finished magnets were coated with aluminum chromate by Sumitomo. Helmholtz coil characterization of the magnets was done by the Magnetics Group at Lawrence Berkeley Laboratory (LBL).

In the 6 block/period design, magnets are grouped into halfperiod triplet modules, consisting of a vertically magnetized (Type A) magnet flanked by two 60° (Type B) magnets. "Up" and "down" modules alternate in the array. The three magnets forming each triplet were brought into alignment in a special fixture and bonded under pressure with an anaerobic, fastcuring, radiation resistant adhesive.⁴ The triplets are positioned on the trays by stainless steel dowel pins and are held down by nonmagnetic clips. The magnets are thus constrained even if the adhesive should fail.

Since the PSGU magnet gap drive system was unavailable during magnet assembly, a fixed-gap test stand was built to allow repeatable positioning for bench measurements of magnets, triplets, of the top or bottom half individually or the complete magnet assembly, at a fixed gap of 6 mm. The completed PSGU magnetic assembly has been shipped to NSLS, where it will be mounted to the gap drive system while still in its test fixture, so the initial magnet alignment will be preserved. Only then will the test fixture be removed.

III. MAGNETIC MEASUREMENTS

⁴ Loctite #325 with Activator #707. Loctite Corp., Newington, MA (213)390-4357

Work performed under Brookhaven Contract No. 535600 and U.S. Department of Energy Contract No. DE-AC02-76CH00016

¹ Product and source data provided for information only.

² Magnet Sales & Manufacturing Co. Inc., 11248 Playa Ct., Culver City, CA 90230

³ Sumitomo Special Metals, 23326 Hawthorne Blvd., Suite 360, Skypark 10, Torrence, CA 90505

A. Homogeneity of Stock Blocks

To help reduce field errors due to magnetic inhomogeneity, a 50x40x25 mm stock NEOMAX 35H block was cut into 15 PSGU-sized test magnets, which were then magnetized and characterized by Helmholtz coil measurement at LBL. The magnetic moment data indicated that only the samples from the interior 2/3 of the volume had angle errors of <2°. The fabricator agreed to supply the PSGU magnets solely from this core region of the large stock blocks.

B. Helmholtz Coil Measurements

The cut, coated and magnetized magnets were sent to LBL for measurement of magnetic moments. The Helmholtz coil data showed that for all 340 magnets the total magnetic moment variation was well under 1%, (σ =0.35%). Transverse angle errors were <1° for Type A and <2° for Type B magnets. Inclination angle in the vast majority of A-magnets was within 0°±2°, as specified. However, in the B-magnets the average inclination angle turned out to be 59° (rather than 60°), with variations as large as ±5°. We accepted the 1° systematic error, since its effect on the field would be minimal. However, nearly 19% of the B-magnets were excluded due to excessive angle error.

C. Integrating Coil Design

To predict the e-beam trajectory in a PPM undulator it is necessary to measure the vertical (y) and transverse (x) field components of each magnet or module along the undulator axis. In the past we have done this with Hall probes. The scans were integrated numerically to give total dipole kicks, which were then entered into a point-kick trajectory model. However, Hall probe measurements of 3D fields are subject to "planar-Hall effect" distortion [4] which contributes an apparent DC offset and results in systematic trajectory errors.

Planar-Hall errors can be avoided by integrating the on-axis field of single magnets or modules directly with a long integrating coil, as was done by Goodman et al. [5] and Poloni et al. [6]. For precise control of coil geometry, a 2-axis, 160turn, 480 mm long coil was designed and fabricated using multilayer printed circuit technology. The effective width of the y and x-field coils is 7.0 and 3.7 mm respectively. The coil was long enough to measure the entire PSGU, as shown in the photograph in Figure 1. It was mounted on a high-speed translation stage, its midplane at a height of 3 mm (half the nominal gap) above the test magnet, parallel to the nominal undulator axis. The stage moved the coil from a field-free region to the axis and back. The induced voltages were measured with an integrating voltmeter (fluxmeter).⁵ Integrated quadrupole and sextupole components were obtained by stepping the coil $\pm \Delta x$ about the axis (3-point characterization). In addition, detailed dipole profiles could be measured by stepping the coil in small steps along the midplane. To reduce noise due to integrator drift to <0.1% we typically averaged 10 scans per measurement. Each scan took about 15 seconds.



Figure 1. PSGU magnetic assembly set up on its test stand for measurements using the printed circuit integrating coil.

D. Multipole Measurements

From the Helmholtz coil measurements it was evident that the dominant contributor to y-field error would be the variation of the inclination angle in the B-magnets. For this reason the y-field dipole kicks of the B-magnets were measured in each of four possible orientations, using the integrating coil method. As expected, "up" and "down" kicks differed in magnitude by up to $\pm 1.5\%$ (0.8% RMS). This data was input to the SA code. However, the A-magnets, as well as the x-field components of the B-magnets showed much less inhomogeneity, and therefore for these components the Helmholtz coil data was input to the SA code.

The half-period triplet modules were characterized in more detail, with measurement of both normal and skew dipoles, quadrupoles and sextupoles, in each of two possible orientations, for use in trajectory optimization and multipole minimization by SA. Some 40 spare single magnets were characterized in the same way, in each of 4 orientations, to provide a selection of magnets for the terminations. The coil was also used to measure the integrated multipoles at all stages of assembly, as well as of the complete undulator.

E. Integrated Dipole Profiles

Initially, dipole profiles of representative single magnets and triplets were mapped, from which $\Delta x=4$ mm was found to give a good 3-point fit to the actual field profile in the vicinity of the magnetic axis. Dipole profiles were also mapped for each unterminated and terminated tray, as well as for the complete PSGU. These measurements revealed a skew octupole component, which suggests the need for 5-point, rather than 3-point characterization of magnets and the assembled structure. This could achieve flatter field profiles.

⁵ Model MF-5D Fluxmeter, Walker Scientific, Inc. Rockdale St., Worcester, MA 01606

IV. MULTI-STAGE OPTIMIZATION

The PSGU performance was optimized by a three-stage process. First, magnets were selected from the pool of 284 accepted magnets to form 40 "up" and 40 "down"-oriented halfperiod triplet modules. A Stage 1 SA code was used to minimize the total x-field dipole kicks and the variation in total ykicks. Table 1 compares standard deviations σ_y and σ_x for triplets with constituent magnets selected (a) at random; (b) by Stage 1 SA code; (c) with uncertainties in input data taken into account; (d) measured triplet kick errors; and (e) peak y-field variation and RMS x-field from field maps of the PSGU.

Table 1. Predicted and measured triplet kick and field errors

| Std.dev. | (a) | (b) | (c) | (ď) | (e) |
|------------------|-------|-------|-------|-------|-------|
| σy | 1.13% | 0.15% | 0.27% | 0.38% | 0.52% |
| $\sigma_{\rm X}$ | 1.24% | 0.13% | 0.29% | 0.48% | 0.18% |

The Stage 2 SA code then selected 36 "up" and 36 "down" triplets and their placement sequence to minimize RMS phase shake [7], RMS walkoff in x and y, and the normal and skew integrated dipoles, quadrupoles and sextupoles.

After measuring the residual multipoles in the unterminated upper and lower trays, we used the Stage 3 SA code to select 12 magnets for the displacement-free terminations.[8] The results are summarized in Table 2. The final values are well within design goals.

Table 2. PSGU integrated multipoles.

| Multipole | Goals | Unterm | Termin | Units |
|-----------------|-------|--------|--------|-------|
| Dipole | 100 | -7 | 7 | G•cm |
| Skew Dipole | 100 | 58 | -20 | G•cm |
| Quadrupole | 10 | -12 | -5 | gauss |
| Skew Quadrupole | 100 | -5 | -18‡ | gauss |
| Sextupole | 50 | -6 | -37 | G/cm |
| Skew Sextupole | 50 | 15 | -30‡ | G/cm |

 \pm Values determined using $\Delta x = \pm 2$ mm. All others: ± 4 mm.

V. PERFORMANCE ANALYSIS

The y and x-fields in the completed PSGU were mapped at a fixed gap of 6 mm using a pair of Hall probes⁶ on a graniterail mapper. After correction for a slight gap taper, $B_y(z)$ was fitted with a sinusoid with amplitude B_{yo} =0.623 Tesla, which is 6.5% lower than expected. The integrated RMS field error was 1.18%, while peak field variation was only 0.52% RMS. Most of the error appears near zero crossings, indicating the presence of longitudinal position errors.

 $B_x(z)$ was corrected for planar-Hall distortion by subtracting $\beta B_y^2(z)$, with β determined from the slope of the first integral of $B_x(z)$. The corrected fields were then integrated twice to obtain the trajectory plots in Figure 2. The goal was to reduce RMS walkoff to less than one wiggle amplitude *a*. We achieved x_{σ} =0.1*a* and y_{σ} =0.04*a*.



Figure 2. X and y trajectories in the PSGU. The x -scale is on the left, the y -scale is on the right (in kG•cm²).

The optical phase error was obtained by computing the cumulative path length error, relative to a best-fit sinusoid, converted to optical degrees at the fundamental resonant wavelength. The phase error is plotted in Figure 3. Statistical studies for a 24-period device [9] showed that to assure third harmonic spectral brightness >90% of the ideal, error-free case (single-electron, on-axis calculation) requires that RMS "phase shake" $\phi_{\sigma} \leq 2^{\circ}$. Our results indicate that $\phi_{\sigma} < 1.4^{\circ}$.



Figure 3. Cumulative optical phase error

VI. ACKNOWLEDGEMENTS

The authors thank P. Stefan and J. Bohanek (BNL), D. Nelson (LBL), R. Burke, K. Carillo, M. Curtin, R. Dinius, Y. Kohanzadeh, M. Lampel, H. Schlanger, R. Shah, M. Stormo and G. Swoyer, (Rocketdyne) for assistance and support.

VII. REFERENCES

- [1] P.M. Stefan et al., Proc. Part. Accel. Conf., 1096 (1991).
- [2] G. Rakowsky et al., Proc. XI FEL Conf., 597 (1989).
- [3] A. Cox and B. Youngman, Proc. SPIE, 582, 91 (1986).
- [4] M.W. Poole and R.P. Walker, *IEEE Trans. Magn.*, MAG-17, No.5, 2129 (1981).
- [5] D.L. Goodman et al., Proc. XIII FEL Conf., 825 (1991).
- [6] C. Poloni et al., Proc. Part. Accel. Conf., 2712 (1991).
- [7] B.L. Bobbs et al., Proc. XI FEL Conf., 574 (1989).
- [8] G. Rakowsky et al., Proc. Part.Accel.Conf., 2733 (1991).
- [9] G. Rakowsky, *Small Gap Undulator*, Conceptual Design Report, BNL Contract No. 406593, Nov. 30, 1989.

Models HTJ-0608 and SAK-1808; F.W. Bell Co.,
6120 Hanging Moss Rd., Orlando, FL 32807