Submitted to: 1995 National Synchrotron Radiation Instrumentation Conference
October 17-20, 1995
Argonne National Laboratory, Argonne, IL

BNL-63150

CONF-9510119--38

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OCT 10 1996
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Experience with Small-Gap Undulators

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*Work performed under the auspices of the U.S. Department of Energy, under contract DE-AC02-76CH00016

Abstract

Small-gap undulators offer enhanced performance as synchrotron radiation sources, by providing extended tuning range and the possibility of higher photon energies via short-period, small-gap devices. Challenges associated with the operation of small-gap undulators arise from their requirement for small beam apertures and the resulting possibility of lifetime degradation, beam instabilities, and radiation hazards. To investigate these fundamental limitations, we have constructed an R&D small-gap undulator for the X13 straight section of the NSLS 2.584 GeV X-ray Ring and have tested it during studies shifts and normal user shifts during the last year. This device, the NSLS Prototype Small Gap Undulator (PSGU), consists of a variable-aperture vacuum chamber and a 16 mm period pure-permanent-magnet undulator, both mounted to a common elevator base stage. The design output spectrum of 2.5 keV in the fundamental (and 7.5 keV in the 3rd harmonic) was obtained with a magnet gap of 5.6 mm and an electron beam aperture of 2.5 mm. The partial lifetime contribution for these parameters was observed to be about 40 hr. Details of the synchrotron radiation output spectrum, lifetime dependence on aperture, and bremsstrahlung radiation production will be presented.

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I. Introduction

Over the past year, we have gained some experience with small-gap undulators through operation of the NSLS Prototype Small-Gap Undulator (PSGU). PSGU is a small R&D insertion device intended for investigation of the fundamental limitations of small-gap devices. At the same time, PSGU aptly demonstrates the enhanced performance offered by such devices, through generation of radiation with a 16 mm period pure-permanent-magnet undulator. In what follows, we present a brief description of PSGU and a summary of operating experience to date. This includes a spectrum of the undulator radiation produced at a 5.6 mm magnet gap, and the appearance of operational limitations, namely lifetime degradation, beam instabilities, and increased bremsstrahlung radiation.

II. Description of PSGU

The NSLS Prototype Small-Gap Undulator is comprised of three major components: a variable-aperture vacuum chamber with drive system, a pure-permanent-magnet small-period undulator with an independent drive system, and an elevator base stage upon which all of the above components are supported. The design concept of the variable-aperture chamber has been described elsewhere [1], and is summarized in Fig. 1.

The figure presents an elevation cross section of the vacuum chamber, as seen along the stored beam direction. Deep wells, from the top and bottom flanges, extend towards the stored beam and can be moved closer together or farther apart by means of top and bottom bellows. The central section of the chamber, between the bellows, is fastened through legs to the elevator base stage below. Actuators attached between the two flanges control the electron beam aperture. The portions of the wells near the stored beam are thinned to 1 mm, and the magnet arrays of the undulator are inserted into the wells, up near the thinned region. The chamber is cylindrical, about 460 mm in diameter, with its axis oriented vertically. The electron beam aperture is adjustable between 14 mm and 1 mm, and the minimum-aperture region is 104 mm wide and 390 mm long.

The PSGU undulator magnet is 320 mm long, with a 16 mm period. It uses NdFeB magnets in a high-performance 6 block/period version of the Halbach pure-permanent-magnet design. Its construction and magnetic field mapping are presented in detail in reference 2. The undulator magnet beams are mounted on an independent drive system, which enables magnet gaps between 4 mm and 23 mm within the wells of the PSGU vacuum chamber. To date, however, the magnet has not been closed below 5.5 mm for storage ring operations.

The elevator base stage provides mounting fixtures for the PSGU vacuum chamber and its drive, and the undulator magnet drive. In addition, it provides a ± 3 mm vertical translation of the combined chamber/magnet assembly about the nominal beam height.

PSGU is installed in the X13 R&D straight section of the NSLS X-ray Ring, a 2.584 GeV electron storage ring which presently operates with a maximum stored current of 300 mA. The X13 straight section is a low β insertion straight, and PSGU is located 15 mm downstream of the straight centerline. The straight section is equipped with local orbit feedback, which maintains electron beam position within 10 μm throughout the straight, and both horizontal and vertical active interlocks, to prevent equipment damage under accident conditions which mis-steer the electron beam.

III. Experience with PSGU

Some results of our earliest experience with PSGU, and of experiments which preceded its installation, are presented elsewhere [3,4]. PSGU was removed from the storage ring in November 1994 for mechanical modifications, and was re-installed in May, 1995. Much of what is reported below stems from the latest installation of the device.

1. PSGU Output Radiation Spectrum

Portions of the synchrotron radiation output spectrum have been measured from PSGU for magnet gaps between 10 mm and 5.5 mm (K~0.5 to 1.1). This range corresponds to a photon energy range of about 3500 eV to 2500 eV in the fundamental. At the largest gaps, useful flux is only available in the fundamental, and possibly in the 2nd harmonic, while for gaps below about 7.5 mm, the third harmonic also becomes usable. A measured spectrum including the fundamental, 2nd and 3rd harmonics, at a magnet gap of 7.5 mm, was previously reported [3,4]. Since completion of mechanical modifications this spring, the minimum electron beam aperture has been extended from 3.8 mm to 1.0 mm. With this extension, the output radiation spectrum originally set as a design goal [1] for PSGU was obtained. The result is presented as Fig. 2. The undulator fundamental is at 2.5 keV, the sulfur K absorption edge, while the 3rd harmonic is at 7.5 keV. The 4th and 5th harmonics are also clearly visible in the figure. The electron beam aperture was 2.5 mm, while the undulator magnets were closed to a gap of 5.6 mm (K=1.056). The theory curve was obtained using the URGENT [5] code, by specifying the basic storage ring and undulator parameters, as well as the dimensions and location of the spectrometer entrance slit (1 mm high x 40 mm wide, at 25.3 m). As in previous work [3,4] a simple single-crystal Si (111) spectrometer (with new water cooling for the crystal, and a thick entrance slit for the ion chamber detector) was used to collect the data, and data processing was used to remove the effects of Be window and transport gas (N_2 or He) absorption, and to account for the ion chamber absolute efficiency and Si(111) bandpass. A constant scattered background was subtracted from the He data prior to further processing and the Si(333) features of the N_2 data were removed by comparison with the He data. From 2100 eV to 5200 eV, the experiment curve in Fig. 2 is from the He data, while the higher energy portions are from the N_2 data. Aside from the He background subtraction, no adjustable parameters were used in processing the experimental data. However, the agreement of the intensities with the theory is not very good, and is not understood at this time. Difficulty in the vertical positioning of the spectrometer entrance slit may account for some of the discrepancy above 3 keV, but more work is needed. The discrepancy in the fundamental is likely due to incomplete knowledge of the entrance Be window thickness and composition.

2. *Lifetime vs. Electron Beam Aperture*

One fundamental limitation to the operation of small-gap undulators is the connection between the electron beam aperture and the stored beam lifetime; at some point, a decrease in aperture will result in lifetime degradation. Results for PSGU are presented in Fig. 3. The PSGU vacuum chamber was first centered about the stored electron beam. The beam lifetime was then measured using the main storage ring DC current transformer system (DCCT), as a function of the PSGU vacuum chamber full aperture. The storage ring was running in a normal operations condition, with about 220 mA stored current. The solid curve in Fig. 3 is a guide for the eye. Below a full aperture of 4 mm, PSGU makes a significant impact on the lifetime, while above 4 mm, the lifetime appears unaffected.

Sometimes, a more useful lifetime quantity concerning small-gap insertion devices is the *partial* lifetime contribution. This is the lifetime effect (for a particular storage ring) of the small-gap device all by itself. With it, the ring lifetime which results from a given small-gap aperture is easily obtained, since lifetimes combine like electrical resistors connected in parallel. For example, operation of a small-gap undulator with a partial lifetime contribution of 60 hours in a storage ring with a normal lifetime of 30 hours yields a combined lifetime of 20 hours. The partial lifetime can be obtained from data like that in Fig. 3. For PSGU, the worst-case result appears in Fig. 4. Here, the partial lifetime contribution was obtained from measurements with a stored beam current between 299 mA and 290 mA. At 2.5 mm full-aperture, the contribution is about 36 hr, while at 4 mm, it is nearly 300 hr.

3. *Bremsstrahlung γ rays from PSGU*

Fig. 4 also introduces another feature of the operation of small-gap insertion devices: the possibility of increased radiation hazards. The partial lifetime results in Fig. 4 were obtained in two ways: first, using the DCCT, as in Fig. 3, and by using a γ-ray monitor mounted inside the X13 experimental hutch. The agreement between the two methods is not unexpected. The decrease in beam total lifetime by the operation of small-gap insertion devices results from the loss of electrons attempting to enter the small-aperture region. There are always some electrons which are not within the tight, central core of the stored beam, but are oscillating around the core, some distance away. When the storage ring vacuum chamber size changes upon entering a small-gap undulator, e.g. from 42 mm to say 2.5 mm at the NSLS for PSGU, some electrons crash into the undulator chamber. This produces bremsstrahlung γ-rays, which are directed down the undulator beam line, along with the synchrotron radiation beam. The smaller the electron beam aperture, the greater the bremsstrahlung γ-ray flux. Fig. 5 presents results, which are actually the same data as presented in Fig. 4. The stored beam current was between 299mA and 290mA during the measurements. The γ-ray dose rate was measured using a Fermilab "chipmunk" dosimeter [6], which was mounted in the center of the direct undulator output beam, inside the X13 experimental hutch, 27 m from PSGU. (For these measurements, the undulator magnet was opened to a 23 mm gap, so there was very little synchrotron radiation present.) The calibrated output of the chipmunk assumes that the entire 3.4 ℓ active volume of its ionization chamber is uniformly irradiated. In our case, however, we estimate that the γ ray beam is about 15 mm high x 20 mm wide, for an irradiated volume of 27 ml. The dose rate reported in Fig. 5 is therefore the direct chipmunk output scaled up by the ratio of the active volume to the estimated volume irradiated. Note that the dose rate is about 2.6 rem/hr for PSGU apertures of 5 mm or greater, not zero. This is the chronic bremsstrahlung background due to collisions of the electron beam with residual gas in the X13 straight section. The exit beamports of the NSLS X-ray Ring insertion straights view 11.3 m of electron beam path, whereas a bend magnet port of 16 mrad horizontal sees less than 1/100 this path length. Therefore, the chronic bremsstrahlung background is often noticed only in the insertion device beamlines. Tromba and Rindi [7] report a dose-rate relationship for the bremsstrahlung generated on residual gas in a storage ring. Using the geometry of our situation at X13, with 300 mA of stored beam current, and an assumed pressure of 10^{-10} Torr, a dose rate of 3.1 rem/hr is predicted. This is in reasonable agreement with the results of Fig. 5, considering that the detailed composition of the residual gas is not specified, and that the dimensions of the bremsstrahlung beam in the hutch are uncertain to at least a factor of 2. Ionization gauges in PSGU and 0.6 m upstream in the X13 straight section read between 2 and 4 x 10^{-10} Torr at 300 mA, but this may not be a good predictor of the pressure the electron beam sees.

A radiation survey was performed outside the X13 hutch while the data in Fig. 5 was collected. The primary bremsstrahlung beam was stopped in a Pb shield 300 mm wide x 250 mm high x 200 mm thick, located inside the hutch, at the rear wall. No dose rate above background was ever seen behind this shield, outside the hutch. However the rest of the rear hutch wall presently consists of 3 mm of steel and 1.6 mm of Pb, and re-scattered bremsstrahlung appears outside the hutch, immediately surrounding the main shield. This may arise from the final beamline vacuum components 3 m upstream, at the front wall of the hutch, which include the 30 mm thick Cu housing of the water-cooled Be window. The dose-rates measured on the outside surface of the hutch scale just like the data presented in Fig. 5, however, the maximum rate was 17 mrem/hr and the chronic rate at 300 mA was about 0.7 mrem/hr. Nevertheless, additional shielding must be added to the hutch rear wall; and one set of measurements suggests that 50 mm of Pb may be required to reduce the levels to near background.

Returning briefly to Fig. 4, the PSGU partial lifetime was calculated from the radiation dose rate by the following procedure: we assumed that the dose rate in excess of the chronic background was inversely proportional to the partial lifetime. Two parameters, a slope and an intercept, were calculated from a plot against the DCCT partial lifetime, and these parameters were used with the data from Fig. 5 to obtain the plot in Fig. 4.

4. *Beam Instabilities*

The possibility of beam instabilities as a result of PSGU operations has been considered theoretically by Bane and Krinsky[8]. Consistent with their expectations, no instability due to vacuum chamber impedance has been observed for normal operations with PSGU. Nevertheless, a few isolated events have been seen under special studies conditions. Orbit movement was seen a couple times at stored currents of a few mA, when the minimum aperture region was intentionally offset to bring only one of the chamber planes close to the beam. On another occasion, a current drop-out of about 2 ma occurred with 296 mA of stored beam and an aperture of 3.5 mm. The drop-out lasted 21 seconds and was accompanied by a burst of bremsstrahlung γ-rays, but no beam movement (horizontal or vertical), and no local pressure burst were observed. These quantities were logged at 3 second intervals , so this conclusion is firm. No beam size change was observed, but this monitor is presently logged only at 2 min intervals, and might have missed an event of a few seconds duration anyway, due to local data averaging. This event may have been ion trapping or the death of a dust particle.

Recently, an unusual resonant-like behavior was observed between the PSGU vacuum chamber aperture and the output of the PSGU beam position monitor receivers. Additional measurements are planned.

5. *Chamber Centering*

One important adjustment required for the operation of a small-gap insertion device is centering of the minimum-aperture region about the stored electron beam. For PSGU, vertical beam position monitoring (BPM) stations are installed at both the upstream and downstream ends of the minimum-aperture region for this purpose. However, due to some difficulties in calibrating the BPM receivers over the range of apertures required, an alternative method has been developed: When the aperture is properly centered, the beam lifetime is maximized and, as one might imagine from the previous discussion, the bremsstrahlung dose rate will be minimized.

Therefore, it has proved convenient to center the PSGU vacuum chamber by observing the chipmunk radiation monitor output. For a 2.5 mm aperture, displacements from proper centering by as little as 25 μm are clearly seen in the chipmunk output. One limitation of this method, however, is the natural decay of the monitor signal with beam current, which tends to complicate finding the true centered position if the beam lifetime is too short.

IV. Summary/Conclusion

Our operational experience with PSGU has demonstrated some of the enhanced performance characteristics offered by small-gap undulators, namely the feasibility of operating short-period magnetic structures at small electron beam apertures to produce higher energy undulator radiation. At the same time, we have seen some of the challenges of small-gap devices: beam lifetime degradation at small apertures, accompanied by bremsstrahlung γ-ray production above chronic background levels. Significantly, we have seen very few events of beam instability, and no effects which would prohibit PSGU operation in normal user beam shifts. Taken altogether, then, our present experience with PSGU in the NSLS X-ray Ring suggests that small-gap undulators will soon join the ranks of conventional insertion devices, as a standard source for the synchrotron radiation community.

Acknowledgment

We have benefited from discussions with E Hoyer, J. Hastings, J. Galayda, H.C. Hseuh, G. Decker and E. Blum, and the contributions of G. Rakowsky, L. Solomon, J. Aloi, W.A. Caliebe, D. Lynch, S. Hanna, J. Aloia, C. Stelmach, M. Radulescu, R. Freudenberg, D. Klein, C. Nielson, J. Dabrowski, L.E. Berman, and D.P. Siddons. Work performed under the auspices of U.S. Department of Energy, under Contract DE-AC02-76CH00016.

Figure Captions:

Fig. 1

Cross section of the NSLS Prototype Small-Gap Undulator (PSGU) vacuum chamber, as seen along the stored beam direction. The stored beam is centered in the vacuum space between the two deep wells. The regions of the wells nearest the electron beam are thinned to 1 mm and the undulator magnet arrays are inserted into the wells, up to the thinned region. See text for further details.

Fig. 2

Spectrum measured from the PSGU undulator, for a magnet gap of 5.6 mm, K=1.056, at 2.584 GeV, 90 mA, with an electron beam full aperture of 2.5 mm. The fundamental is at 2.5 keV. The 4th and 5th harmonics, are also seen. The theory curve was obtained using the URGENT [5] code.

Fig. 3

Storage ring stored beam lifetime as a function of the PSGU vacuum chamber electron beam aperture, at 220 mA. The curve is a guide for the eye.

Fig. 4

PSGU partial lifetime contribution as a function of vacuum chamber aperture. Stored beam current 299 mA-290 mA. See text for further details.

Fig. 5

Bremsstrahlung γ-ray dose-rate as a function of PSGU vacuum chamber aperture. The data were taken using a Fermilab "Chipmunk" dosimeter [6], located in the direct beam, 27 m from PSGU. Note the chronic bremsstrahlung background of 2.6 rem/hr for apertures of 5 mm and larger. Stored beam current 299mA-290mA.

References

[1] P.M. Stefan, L. Solomon, S. Krinsky, and G. Rakowsky, *Proc. 1991 IEEE Part. Accel. Conf.*, San Francisco, CA, 1096 (1991).

[2] G. Rakowsky, R. Cover, and L. Solomon, *Proc. 1993 IEEE Part. Accel. Conf.*, Washington, DC, 1605 (1993).

[3] P. M. Stefan, S. Krinsky, G. Rakowsky and L. Solomon, in *A Festschrift in Honor of Klaus Halbach*, LBL PUB-754, p. 161.

[4] P. M. Stefan, S. Krinsky, G. Rakowsky and L. Solomon, Proc. 1995 IEEE Part. Accel. Conf., Dallas, Tx (in press).

[5] R. P. Walker and B Diviacco, Rev. Sci. Instrum. **63(1)**, 392 (1992).

[6] There appears to be no appropriate general reference for the Fermilab "Chipmunk" dosimeter, but briefly; it consists of a special tissue-equivalent ionization chamber, and a sensitive electrometer and associated electronics which produce a variety of dose-rate outputs. The ionization chamber, which is manufactured by Health Physics Instruments of Goleta, CA, is 152 mm in diameter, 280 mm long and is filled with about one atmosphere of propane gas. The chipmunk outputs include a color-coded meter with dose rates and occupancy times, three top-mounted colored lamps which are pulsed to indicate the general dose-rate range, and a TTL pulse output which produces one pulse per 2.5 μ rem. This later output is useful for dose rates near normal background and up to 5 rem/hr (~550 Hz), and was counted in 30 second intervals for the measurements reported here.

[7] G. Tromba and A. Rindi, Nucl. Instr. And Meth. **A292**, 700 (1990).

[8] K. Bane and S. Krinsky, *Proc. 1993 IEEE Part. Accel. Conf.*, Washington, DC, 3375 (1993).