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EXPERIMENTAL VERIFICATION OF PHOTON:
A PROGRAM FOR USE IN X-RAY SHIELDING CALCULATIONS

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Abstract

At the National Synchrotron Light Source a computer program named PHOTON has been developed to calculate radiation dose values around a beam line. It is essential that the output from the program be an accurate guide to beam line shielding. In order to test the program, a series of measurements of radiation dose were carried out using existing beam lines and the results were compared to the theoretical calculations of PHOTON. Several different scattering geometries, scattering materials, and sets of walls and shielding materials were studied. The results of the measurements allowed many advances to be made in the program, ultimately resulting in good agreement between the theory and experiment.

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1. Introduction

The design of synchrotron radiation beam lines involves many complex calculations and decisions, due in many cases, to the unique features of the source. Once the specific goals of the experimental program are met in the design, it is always critical to turn attention to the radiation safety aspects of the design and construction in order to properly protect the personnel working at the facility from excessive levels of radiation. It has become apparent that as the new machines and insertion devices produce increasingly intense, higher energy photon beams, accurate techniques for calculating the necessary shielding configurations are required. Otherwise, personnel hazards could exist, a great deal of resources could be wasted by overly conservative designs, or, the retrofitting of an inadequately shielded beam line could result in expenses and delays.

The National Synchrotron Light Source is presently installing the first beam lines which will accept the radiation from the high field superconducting wiggler magnet [1]. This device will operate at 5 Tesla and has effectively 6 magnetic poles. Thus, with the NSLS x-ray ring operating at 2.5 GeV and 500 mA of electron current, the power in the beam will be about 1.2 kW/mrad with a critical energy of 25 keV. The Brookhaven National Laboratory Safety and Environmental Protection Division required a shielding design prior to construction approval for the beam lines.

In order to meet this goal, members of the NSLS Experimental Program Support Section developed a computer code, PHOTON, to calculate radiation outside walls, windows and hatches for an arbitrary scattering center. The source radiation could be any synchrotron beam, white or monochromatic, filtered and apertured by an arbitrary set of materials or windows. A detailed discussion of the program, PHOTON, can be found in the accompanying paper in this conference [2].

The motivation for the present work arose out of the concern that the program would not accurately calculate doses in the complex geometries found on actual beam lines. It was, therefore, decided to measure the actual delivered doses under known operating conditions on NSLS x-ray beam lines and compare the results with calculations from PHOTON [3]. This procedure worked very well during the development of the program, leading to what is now believed to be an accurate, user friendly computer code. In this paper, several of the geometries for which measurements were made will be described along with the comparison with the calculations.

2. Instrumentation

Several beam lines at the NSLS x-ray ring were used as sources of radiation, either in a geometry specifically established for detailed comparisons, or in an "as constructed" configuration. For all measurements, the storage ring was running at its design energy of 2.5 GeV yielding a photon spectrum with a critical energy of 5 keV from the bending magnets shown in Fig. 1. Fill currents were between 30 and 200 mA with beam lifetimes about 10 hours at 100 mA. Although the photon spectrum from the superconducting wiggler (Fig. 1) or higher energy storage rings will extend to higher energies, all scattering or processing are accounted for by PHOTON so the energy range extrapolation will be valid.

The general configuration of the facility beam lines led naturally to measurements of the dose in the plane of the storage ring. That is because it is the area along the side of beam lines, or adjacent to experimental enclosures, where most personnel access is allowed during beam operations. Thus, all data, both along beam lines and in specific "in hutch" geometries, was taken for scattering in the plane of polarization. Of course, if the beam were from a single electron point source, no scattering would be possible at 90°. However, the extended source, scatterers, and finite solid angle of the dosimeter produce a significant "in plane" intensity. As will be seen, the program PHOTON always overestimates the dose since no polarization factors were considered in this code.

The detector used for the dose measurements was a Victoreen Model 471 survey meter. This is the instrument used in both daily and long-term beam line safety monitoring. The particular instrument used was compared frequently against a second one, both calibrated by the BNL Safety and Environmental Protection Division. During the course of the measurements, several sets of data were taken with both the dosimeter and TLD's, thermoluminescent dosimeters. The measured doses were in excellent agreement (within $\pm 10\%$) with each other.

3. Results

3.1 Variation of source parameters

Several parameters of the x-ray source incident upon the scattering material were varied. It is obvious that the measured dose should track with the electron current. In several cases, the data was taken over an extended period of time during which factors of 2 in beam current occurred. In all cases, the dose was proportional to beam current. Varying the aperture limiting the incident beam also produced the expected variations in dose. This was always a good check on beam alignment and for elimination of unwanted scattering from air or upstream surfaces.

3.2 Filters

There are two basic modifications to the white beam from the storage ring which occur. The first is the attenuation by filters and windows such as Be, C, and Al or walls made of steel, concrete, or Pb. The second is the scattering process from a target material in the beam, for example a monochromator crystal, wall of a beam pipe, or slit edges. Any beam line conceivable has a combination of these processes and it was essential to verify that PHOTON treats each case properly as a single process, as well as in the overall combination. The variation of dose in a transmission geometry was tested on beam line X12A with the geometry shown in Fig. 2. A typical result is shown in Fig. 3 where the dose variation with thickness of a steel filter is plotted. The same overestimate of the calculated dose was found with TLD and the ion chamber measurements. The program correctly determined the dependence of dose on thickness.

3.3 Scattering and wall transmission

Several variations of a basic scattering geometry were used to test the dose dependence on scattering material and subsequent transmission by walls. In the first case, the ion chamber was set up outside the monochromator box of the X19A beam line. The white beam scattered from the first monochromator crystal traversed a series of filters, consisting of the lead glass window and various thicknesses of steel or Pb foils. Figure 4 shows an example for scattering through the glass and steel filters.

A more controlled experiment was designed for the X15A beam line. In this series of measurements both the scattering material and the subsequent wall material could be varied. The beam incident on the scatterer first passed through a Be and Al window. A concern arose in this geometry over the effects of air scattering. With a carefully shielded lead scattering enclosure, an overestimate of dose due to the polarization factors was obtained, with the proper dependences on scatterer and wall materials.

All of these effects were ultimately studied in detail on beam line X13A. The apparatus schematically depicted in Fig. 5 was set up in the horizontal scattering geometry. The white beam was incident on the sample after passing through Be and Al windows, a set of filters, and apertures. The gaseous environment of the sample was variable from vacuum to air or He. After scattering, a variable set of filters followed a glass window. The variation of gas or pressure of the gas was not a very large effect, varying the scattered dose by only a few percent.

Four different scattering materials were used in this geometry: tantalum, copper, silicon, and carbon. This provided a wide range in atomic number to test the program calculations. The general features of the scattering and filter processes were again verified. Some dose measurements for a Ta scatterer and Pb walls are shown in Fig. 6. It is seen that for this carefully controlled geometry, the program PHOTON gives excellent agreement with the measurements.

4. Conclusion

The program PHOTON properly predicts the functional dependence of the dose on source parameters, filter material and thickness, scattering material, and window foil design. The interplay of the measurements and code development ultimately resulted in the good agreement shown by the data. The calculations are absolute values, not normalized in any way. Based on the results of these measurements, the program PHOTON has been used to predict dose values associated with the superconducting wiggler beam line at the NSLS. The final personnel shielding design for the beamport was based on these calculations and approved by the BNL Health Physics Group.

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- [3] E. Brauer and W. Thomlinson, NSLS Informal Report, BNL #39541, March 1987.

Figure captions

- Figure 1. Vertically integrated photon flux for the NSLS bending magnets and superconducting wiggler magnet for an electron energy of 2.5 GeV.
- Figure 2. Experimental arrangement for transmitted dose measurements.
- Figure 3. Dose transmitted by steel filters on beam line X12A.
- Figure 4. Dose scattered from the silicon crystal of the X19A monochromator.
- Figure 5. X13A experimental setup for scattered dose measurements.
- Figure 6. Dose scattered from tantalum through lead walls.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6