EXPERIMENTAL VERIFICATION OF "PHOTON", A COMPUTER PROGRAM FOR USE IN
X-RAY SHIELDING CALCULATIONS

BNL--39541

DE87 008458

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March 1987

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Research Supported by the
OFFICE OF BASIC ENERGY SCIENCES
U.S. Department of Energy
Washington D.C.

NATIONAL SYNCHROTRON LIGHT SOURCE
BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.

Under Contract No. DE-AC02-76CH00016

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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 beam lines with different configurations of shielding, scattering materials, filters, and apertures. The program will be used as a tool in the design of the future beam lines.

By the use of a superconducting wiggler (SUW) the critical energy of this beam line will be increased by a factor of four when compared to the critical energy of the bending magnet synchrotron radiation. This means that for energies beyond the SUW critical energy the intensities are orders of magnitude higher than for the conventional bending magnet beam lines.

This higher energy range requires more careful studies of the shielding design. Therefore, experiments discussed in this report were done to compare the doses calculated by the program with measured values.

I. DESCRIPTION OF THE PROGRAM "PHOTON"

The FORTRAN program PHOTON¹ calculates dose values from the following sequence:

1. calculation of photon flux as a function of energy and vertical opening angles for the synchrotron beam
2. attenuation by filters
3. a scattering process
4. attenuation by a wall
5. and conversion from photon flux to a dose.

At each setup, the code progresses by explicitly solving established theoretical formulae. Figure 1 shows schematically the geometry from which the program calculates dose values.

Figure 1

Because the highest dose is expected to be at the most intense point of the scattered beam, the program is set up to calculate this worst case. For the X17 beam line this may occur at the first monochromator crystal.

Since the processes of attenuation and scattering discussed in this paper are dependent on photon energy, the calculations are done in energy steps over the whole spectrum between 0 and 150 keV, or in the case of the superconducting wiggler, between 0 and 500 keV. Each of these processes is dealt with in more detail below.

I.1 Calculation of Photon Flux

The calculation of the flux of the unattenuated white beam is based on the code of the program "FILTER".²

I.2 Attenuation by Filters

The attenuation is calculated from the following law:

$$I = I_o \exp \left[- \left(\frac{\mu}{\rho} \right) \cdot \rho \cdot T \right]$$

I = intensity of photons (photons/sec/mA/mrad/eV)

I_o = incident intensity of photons

ρ = density (gm/cm³),

T = thickness (cm)

μ/ρ = mass absorption coefficient (cm²/gm)

The mass absorption coefficient is the sum of photoelectric absorption, and elastic and inelastic scattering coefficients:²

$$\mu/\rho = N [(\tau_K + \tau_L + \dots) + \sigma_{coh} + \sigma_{inc}]$$

N = number of atoms per unit volume

τ = photoelectric absorption coefficient for the various shells

σ_{coh} = coherent scattering (interaction of one photon with all the electrons of an atom)

σ_{inc} = incoherent scattering (Compton scattering)

The cross sections for the photoelectric and Compton effect are stored, for various elements, in the "ABSORBER.DAT" file of the program (cf. Biggs and Lighthill³). In the Appendix, Figures 2 and 3 show the calculated spectrum (no filter present) and the transmitted spectrum resulting from filter materials of various thicknesses.

The program also takes into account the limiting of the beam by vertical slit apertures.

I.3 Scattering Process

The scattering process, resulting in an angular integrated scattered intensity I_{inc} , is described by the following equation:

$$I_{inc} = \frac{\sigma_{inc} I_o}{(\mu/\rho)} \{1 - \exp [- (\mu/\rho) \cdot \rho \cdot T]\}$$

Dose will be determined by calculating the flux, I_2 , (and later the corresponding dose) at a distance of one meter within a window of arbitrary area, say 1 cm²:

$$I_2 = \frac{1 \text{ cm}^2}{4\pi(100 \text{ cm})^2} \cdot I_{inc}$$

This is an approximation since it is assumed that the I_{inc} scatter is isotropic.

I.4 Attenuation Through Walls

The calculated scattered flux of photons is now taken to be attenuated by the walls. The transmitted flux, I_{wall} , is calculated by the subroutine "WALL" of the program:

$$I_{\text{wall}} = I_2 \exp \left[- \left(\frac{\mu}{\rho} \right) \cdot \rho \cdot T \right]$$

I.5 Conversion of Flux to Dose

Finally the program converts the attenuated photon flux to dose. This latter value corresponds to the energy released in the material of interest. A unit density tissue constituting four elements defined by the International Commission on Radiological Units (ICRU), was chosen to represent a human being.⁴ (H, 10.1%; C, 11.1%; N, 2.6% and O, 76.2% by weight) Because 1 eV corresponds to $1.6 \cdot 10^{-12}$ erg and 1 rad to 100 erg per gm, the dose can be calculated as follows:

$$\text{Dose} = \sum_E D(E) \Delta E$$

where ΔE is the energy mesh and, $D(E)$ is the dose at energy E , and

$$D(E) = (1.6 \cdot 10^{-14}) \cdot (\mu/\rho) \cdot I_{\text{wall}}(E) \cdot E$$

II. PARAMETRIC TESTING OF "PHOTON"

To show that the program results vary in a predictable way with configuration changes, several of the parameters in the input file were chosen for study. These include beam size at the aperture, beam current, beam incidence angle on the scattering target, and presence, or absence of the scattering target.

II.1 Slit Size

Appendix Fig. 4 shows two curves of measured dose against slit size. The measured results and the program calculations, result in a dose proportional to the slit size.

II.2 Beam Current

Theoretically, the dose should be proportional to the beam current. Two measurements given below demonstrate the same effect in the data at the X15 beam line:

- with Si as scatter material:
 - at 104.09 milliamps beam current $D = 1000 \text{ mR/h}$
 - at 51.6 mA $D = 500 \text{ mR/h}$
- with Steel as scatter material:
 - at 101.1 mA $D = 10 \text{ mR/h}$
 - at 52.48 mA $D = 4.5 \text{ mR/h}$

II.3 Angle of Incidence of the Beam

A change of angle between the beam and the plane of the scattering material (Fig. 5) does not produce a significant change in the measured results.

This angle was varied in experiments between 20 and 70 degrees and the measurements show a maximum perturbation of 5%. The program calculates a change of 2% over the same angular range.

Figure 5

II.4 Conversion of Flux to Dose

It was decided to use a very simple configuration on which to test the conversion calculations and measurements. At the beam line X12A, dose measurements were done in the setup as shown in Fig. 6. The results of the calculated doses and the measured ones are compared in Appendix Fig. 7.

Figure 6

An additional independent measurement was done with thermoluminescence dosimeters. The observed dose was $2.8 \cdot 10^5$ R, in comparison with the $5.14 \cdot 10^5$ R calculated by the program. The factor of 1.8 higher predicted value than measured value is in agreement with the ion chamber results.

III. DESCRIPTION OF THE IONIZATION CHAMBER

A standard Victoreen ionization chamber⁵, Model 471, was used for all experiments. It was calibrated by the BNL Health Physics Group and compared favorably with two other ion chambers.

III.1 Collection Efficiency

All measured values fall below 100 R/h. Figure 8 in the Appendix shows that the collection efficiency in measurements at those levels corresponds to 100%.

III.2 Energy Dependence

Any ion chamber has a certain energy dependence. That is, holding the exposure rate constant, the chamber responds differently to different energy photons. The Model 471 has been calibrated at an energy of 662 keV from $Cs-137$. The response is fairly energy dependent in the low energy region. For calibrated usage at middle and high energy regions, an energy response correction could be used (Appendix Fig. 9).

In this experiment, the scattered photons were in the energy range of about 10-50 keV. A correction to the efficiency would be at most 10%. Therefore, at the present time the response was assumed to be one.

III.3 Angular Correction

Since the ion chamber was facing the source point of the scattering material, no angular correction was necessary for the collection efficiency.

IV. THERMOLUMINESCENCE DOSIMETERS

TLD 700 dosimeters were used to get some independent dose results. They are pure LiF crystals (3*3*1 mm) and they emit light if they are heated after being exposed to radiation. The absorption of energy from the radiation excites the atoms in the crystal, which results in the production of free electrons and holes in the thermoluminescent crystal. These are trapped by impurities or imperfections in the crystalline lattice thus locking the excitation energy into the crystal. Heating the crystal releases the excitation energy as light. Using a photomultiplier, a current is measured, which is then proportional to the exposure of the TLD.

With the normal calibration of the Health Physics Department, the following relation was found: 0.1056 R corresponds to 1 nC. This relation will be correct above 100 keV. Figure 10 shows an expected increase in sensitivity found below 100 keV. An empirical correction factor of 1.2 was taken from the literature.⁶

Figure 10

IV.1 Comparison of TLD With Ion Chamber Measurements

In one configuration on beam line X15, the ion chamber measured 6 R/h. Twenty (20) TLDs were exposed for 6 min., so that a dose of 600mR was expected. The average value of the reading was 5.8 nC. This corresponds to 612.5 mR. With the correction of the energy dependence by the factor of 1.2 the result is 510 mR. A second series of TLD measurements were done on beam line X19A. At a dose rate of 1.45 R/h, the TLDs were irradiated for two minutes, which would give a dose of about 50 mrad on an ion chamber. The TLD value was 70 mrad.

No systematic discrepancy between TLD and ion chamber values was measured.

Another aspect of the measurements taken with TLD's was an examination of the geometrical distribution of the scattered beam. Over a round area of 10 cm diameter, the average value was 20.53 R with a standard deviation of 0.77. This confirmed a very homogeneous distribution of the scattered beam. The measurements were taken in the horizontal plane at 90° to the incident beam.

V. DETERMINATION OF THE BEAM ENERGY SPECTRUM

To examine the energy distribution of the scattered beam under various configurations, spectra were collected in order to compare them with the calculated spectra of the program. The setup used on beam line X13A is shown in Fig. 11.

Figure 11

V.1 Experiment Parameters

The slit size was chosen as small as possible in order to avoid saturation of the detector. Typical values were 0.4 mm horizontal and 0.2 mm vertical slits.

1. Four different materials were used as a scatterer:

Ta	Z = 73
Cu	Z = 29
Si	Z = 14
C	Z = 6

2. The spectra were taken for different environments of He, air and rough vacuum (10 mbar) in the sample beam pipe. Altering the gaseous environment produced hardly any change in the spectrum and no significant change in the dose measurements.

For example: in vacuum - 37 mR/h
 in He-env. - 35 mR/h

V.2 Results

The measured spectra for three different scattering materials Ta, Cu and C (Appendix Figures 12 to 14 respectively) all show the same systematical change of the curve's maxima with respect to increasing shielding thickness. The lead and steel filter thickness were varied from 0.0254 mm to 0.381 mm. The thicker the shielding material, the more low energy photons are absorbed and the maxima shifted toward the more penetrating high energy photons. Compared with the plots from PHOTON (Appendix Fig. 15 and 16), the results are very close. The energy distribution is in both cases from about 5 to 50 keV. The sharp drop in the calculated spectrum for Ta at about 60 keV is due to the presence of the Ta K absorption edge. The intensity and energy of the maxima vary also with scatter material and wall thickness as expected. The program properly accounts for the scattering physics.

VI. COMPARISON OF DOSE VALUES

VI.1 Beam Line X19A

The measurements were done outside the experimental hutch at the position of the first monochromator. One part of the lead glass viewing port cover was taken away and substituted with different thicknesses of lead or steel foils. One possible source of error is that the Si monochromator crystal was not a uniform shape which makes estimation of the crystal thickness difficult and influences to some extent the scattering process. This is not modelled by the computer program.

VI.1.1 Dose Results

In Fig. 17 the measured and computed doses are overlaid for comparison purposes. The program overestimates the dose by a factor of 7 and the slopes of both curves are fairly parallel.

VI.2 On Beam Line X15

The dose values were taken in the hutch and the white beam was set up to scatter from various materials. A smaller lead enclosure was built around the scatterer so that the main beam could be introduced through a small hole in one end. This eliminated background air scattering to the detector. The nonscattered beam was subsequently absorbed by a lead brick beam stop (see Fig. 18).

Figure 16

VI.2.1 Dose Results

In Fig. 19 the measured and computed doses are overlaid for comparison purposes.

VI.3 Beam Line X13A

The setup is the same as the spectroscopy experiment shown in Fig. 11. This series of experiments was the most effective when considering the availability and precision of equipment which exactly suited our needs.

VI.3.1 Dose Results

In Fig. 20 the measured and computed doses for a tantalum scatterer are overlaid for comparison purposes. The program overestimates the dose by a factor of 2 to 3 for a variety of materials.

VII. CONCLUSION

The results show that the program consistently overestimates the does but correctly predicts the functional dependence on energy, current, scatter and filter material, and geometry. There is no reason to believe that this would be different at higher energies.

The scattered radiation in each instance was measured in the horizontal plane at 90 degrees from the incident beam. Strictly speaking if the scatter source were a point in the plane of the electron orbit and the detector subtended a small solid angle there would be very little scattered intensity because of polarization effects. The synchrotron radiation in the orbital plane is plane polarized and scattering at 90 degrees in the plane is forbidden.

However, the incident beam is not completely plane polarized, because of finite source size and angular variations of the electron orbits. Also, the scatter source is horizontally and vertically extended and the detector subtends a sizeable solid angle. Thus, a nonvanishing scattered intensity is measured in the horizontal plane.

The important point is that some fixed fraction of the scattered radiation is measured and accounts for the slopes of the measured versus calculated values being very nearly the same. If the measurements could have been taken for vertical scattering, higher values would have been measured.

ACKNOWLEDGEMENTS

It was definitely a pleasure to work with Dean Chapman, Nancy Lazarz, and Nicholas Gmur who were responsible for writing the computer code for the scattering physics. We would like to thank Norm Rohrig and Tom Dickinson for their support. Additionally, we are grateful for the assistance of David Cox, Brian Kincaid, and Peter Stefan at their respective beam lines. Rick Greene should be mentioned for his prompt production of all the experimental equipment, and Clifford Liles for general assistance with matters of computing and the paper's production.

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IX. APPENDIX

CALCULATED SPECTRUM (NO FILTER PRESENT) 1
AT 9300.0 MM FROM SOURCE POINT

Figure 2.

CALCULATED ARC SOURCE SPECTRUM THROUGH A Be
WINDOW AT 15279.0 MM FROM SOURCE POINT FOR X-13A

Figure 3.

Figure 4

X12A Transmission Dose Measurements and Calculations

Figure 7.

Figure No. 8

Figure No.9

Figure 12

Figure 13

Figure 14

TRANSMITTED SPECTRUM THROUGH WALL AT 16810.5 MM FROM SOURCE POINT

Figure 15.

TRANSMITTED SPECTRUM THROUGH WALL AT 16810.5 MM FROM SOURCE POINT

Scatter Material = Tantalum

Figure 16.

X19A Dose Measurements and Calculations (Dec 1986)

Dose in mrads/hr at 90° from beam line

Figure 17.

X15 Dose Measurements and Calculations (Dec 1986)

Figure 19.

X13A Dose Measurements and Calculations (Dec 1986)

Dose in mrad/hr at 90° from beam line
(Ring current decreased from 67.5 to 66.5
mA during the measurement period)

Figure 20.