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COMPARISON OF SYNCHROTRON RADIATION CALCULATIONS BETWEEN ANALYTIC CODES (STAC8, PHOTON) AND MONTE CARLO CODES (FLUKA, EGS4) *

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Abstract

Significantly improved upon its predecessor PHOTON, STAC8 is a valuable analytic code for quick and conservative beamline shielding designs for synchrotron radiation (SR) facilities. To check the applicability, accuracy, and limitations of STAC8, studies were conducted to compare STAC8 and PHOTON results with calculations using the FLUKA and EGS4 Monte Carlo codes. Doses and spectra for scattered SR in a few beam-target-shield geometries were calculated, with and without photon linear polarization effects. Areas for expanding the STAC8 capabilities, e.g., features of the mirror-reflected lights and double-Compton light calculations, and use of monochromatic light, etc., have been identified. Some of these features have been implemented and benchmarked against Monte Carlo calculations. Reasonable agreements were found between the STAC8 and Monte Carlo calculations.

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INTRODUCTION

There are many existing synchrotron radiation (SR) accelerator facilities and more are being or to be built. There are two types of radiation hazards that need to be mitigated for a SR beamline [1,2]: high-intensity (kW), low-energy (keV order) SR and low-intensity (μW), high-energy (GeV order) gas bremsstrahlung (GB).

Many SR shielding calculations have been performed using the analytic code PHOTON [3]. Recently, significantly improved from its predecessor PHOTON, the STAC8 code [4,5] was developed by one of the authors. In this study, the key features of the STAC8 and PHOTON codes are compared with the more accurate, but time consuming, calculations using the Monte Carlo codes FLUKA [6,7] and EGS4 [8,9]. The benchmark examples were taken from the safety design work for the SSRL (Stanford Synchrotron Radiation Laboratory) bending beamline and wiggler beamline.

CODE OVERVIEW

Accuracy, wide applicability, speed, and reasonable conservatism are key qualities of an analytic code. For a code to handle SR shielding calculations, the capabilities to handle the specific SR issues such as photon polarization effect, large build-up effects, and strong attenuation in target or shield are needed.

The PHOTON code excels at usability. The code calculates attenuation and scattering by a target by assuming an isotropic Compton scattering process from a point source. PHOTON does not consider the self-shielding in the target, the build-up effect in the shield, the polarization effect, the coherent scattering process, and the SR from undulators. PHOTON calculates dose (but not dose equivalent) and may underestimate the doses outside the shield wall.

STAC8 was developed to overcome the above disadvantages of PHOTON. There are several new features in STAC8: 1) it can calculate SR emitted from any insertion device, including an undulator, 2) it considers the angular dependence of both the coherent and incoherent scattering processes, 3) it considers the photon linear polarization effects on the scattering processes, 4) the K-shell fluorescence radiation is included, 5) the self-shielding effect in a perpendicular or an inclined target (called scatterer in STAC8) is introduced, 6) the build-up effect in the shield is considered by using the Geometrical Progression method, and 7) inclusion of the ambient dose equivalent, directional dose equivalent, and effective dose conversion factors.

As part of the collaborative effort between SLAC (Stanford Linear Accelerator Center) and JAERI (Japanese Atomic Energy Research Institute) to widen the application of STAC8, a few important features for beamline design were added to STAC8 (version 2), such as the pink light from mirror, the double Compton scattering process in a two-target geometry, and monochromatic light. The STAC8 code was benchmarked against the FLUKA and EGS4 codes, which were chosen because of their capability of considering the photon linear polarization effects. The collaborative work of benchmarking the STAC8 code is reported in this work.

CALCULATIONS AND DISCUSSIONS

The key parameters of SR sources for the bending beamline (SLM) and wiggler beamline (BL11-3), as well as the shield wall and target conditions, are summarized in Table 1.

SLM Bend Beamline

Figure 1 show that, on an absolute basis, the STAC8-generated SR source spectrum for the SLM dipole (dash curve) agrees well with the FLUKA one sampled using the SR formula (solid curve), while the spectrum from PHOTON underestimates at high energies. Note that in this study the EGS4 calculations had used the source spectrum from STAC8.

Figure 2 describes the SLM geometry for the calculations of the scattered SR doses and spectra. Synchrotron radiation emitted from the SLM dipole (with the linear polarization vector pointing to +X axis) hits the 9^o-inclined Si mirror at Z=0. The thin shielding is two SiO_2 plates (each 0.1545 cm thick) parallel to Z-axis. Both the dose equivalent and SR spectrum are scored at 1 m away from the Z axis (i.e., at X=100 cm). Calculations with and without polarization (i.e., P=1 or P=0) were both made.

Figure 3 shows that the FLUKA effective dose result (H_E, worst geometry) agrees with EGS4 (H_E, AP geometry) with or without polarization. STAC8 (H_E, AP geometry) overestimates by a factor of 2-5, while PHOTON (dose) underestimates. Note that the FLUKA calculations indicate a difference < 20% between effective dose and ambient dose equivalent in this thin-shield case.

As expected, the polarization effect reduces the scattered doses neat 90^o (i.e., Z=0), for which STAC8 actually underestimates the dose equivalent. The sharp dip of STAC8 at Z=0 is because STAC8 does not consider multiple scattering in the target.

Figure 4 compares the 90^o-scattered SR spectra at 1 m outside the SiO_2 shield. Without polarization, the spectra calculated using STAC8 and FLUKA are similar (dominated by peak near 20-30 keV), and PHOTON gave less photons in whole energy range. There are some differences for low energy photons < 30 keV between STAC8 and FLUKA. To confirm this difference, the cases of three mono-energetic photon sources were calculated using EGS4 and STAC8. The results in Table 2 confirm that the overestimation is a factor of 5 at 20 keV and about a factor of 2 for 40 and 58 keV. This finding does not contradict with the STAC8 benchmark calculations for SPring-8 beamlines [(5)], in which the low-energy photons are minimal outside a thick shield.

Figure 4 also shows that, due to target self-shielding, a perpendicular cylinder target reduces the low-energy photons significantly (comparing the two STAC8 curves). STAC8 shows that the polarization effect reduces the SR spectrum and, thus the dose, at 90^o.

By comparing scattered SR spectra at 90^o and 18^o-20^o from the SLM target, Figure 5 clearly shows two phenomena: 1) polarization effect does not affect spectrum at forward angles (indicated by STAC8 curves), and 2) an-isotropic effect of Compton scattering creates more high-energy photons at forward angles (indicated by both STAC8 and FLUKA curves).

BL11-3 Wiggler Beamline

Figure 6 compares the ambient dose equivalent (H*) at 42 cm away as a function of scattering angle from a 24^{o}-inclined Si monochromator hit by the BL11-3 wiggler SR under the no-shield condition. Again, EGS4 and FLUKA are in good agreement (with and without polarization) while STAC8 overestimates H* by a factor of 3 (except near 90^{o} in which STAC8 underestimates due to its consideration of polarization). Note the dip near 24-degree is due to the target self-shielding.

Figure 7 compares the photon fluence-to-dose equivalent conversion factors for effective dose H_E (worst geometry) and the ambient dose equivalent H*. The large difference in low-energy region (< 15 keV) may affect the SR dose results. Figure 8 shows that FLUKA calculations give H_E that is 30 times higher than H* for the BL11-3 case, because the scattered spectrum is dominated by low-energy photons below 20 keV under the no-shield case. This is different from the thin-shield SLM case (see Figure 3, in which FLUKA shows < 20% difference between effective dose and ambient dose equivalent).

Miscellaneous

In this section, the latest features of reflectivity (which governs the pink light specular reflected from a mirror) and the monochromatic light in STAC8 were examined. Figure 9 compares the reflectivity of a 2.7-mradian-inclined mirror in different cases. STAC8 reflectivity for a Pt-coated mirror agrees well with the one with zero roughness from XOP2.1 [(9)]. The actual mirror always has a roughness. The reflectivity of a Pt-coated mirror with 3-Ang roughness is smaller than the one with zero roughness. Figure 9 also shows that the reflectivity of a Rh-coated mirror (3-Ang roughness) is smaller than a Pt-coated mirror.

Table 2 shows that the STAC8 gives a dose equivalent higher than FLUKA by a factor of 2-3 in the case when mono-energetic photons at 68 and 91 keV (from a Si monochromator) hit a 0.15-inclined Si target with a 3-mm-Fe shield.

CONCLUSIONS

STAC8 is a significantly improved analytic code when compared to its predecessor PHOTON. This study benchmarked the STAC8 by examining a few key features of STAC8 and comparing them with the more accurate EGS4 and FLUKA calculations. Several conclusions can be obtained:

1) EGS4 and FLUKA agree with each other.
2) STAC8 is a valuable analytic code for fast and conservative calculations for SR beamline design over a wide range of application.
3) STAC8 gives accurate SR source spectra from bends and wigglers, as well as Compton-scattered SR spectra from a target. STAC8 also gives conservative mirror

reflectivity for pink-light calculations.

4) STAC8 overestimates the dose equivalent by a factor of 2-3 in general. Under no or thin shield cases in which low-energy photons (< 30 keV) exist, the overestimation can be up to a factor of 5.
5) STAC8 considers photon linear polarization effect, but it may underestimate the scattered dose (and spectrum) near 90^{o}.
6) The type of photon dose equivalent quantity can affect the dose value when low-energy photons (< 20 keV) dominate.
7) PHOTON, which considers no anisotropic scattering, no target self-shielding, no polarization, and no build-up effect in shield, may not be suitable for some SR calculations.

REFERENCES

1. Liu, J. C. and Vylet, V., *Radiation Protection for Synchrotron Radiation Facilities*, Radiat. Prot. Dosim., **96**(4), 345-358 (2000).
2. Liu, J. C., Fasso, A., Khater, H., Prinz, A. and Rokni, S. *Generic Radiation Safety Design for SSRL Synchrotron Radiation Beamlines*, Stanford Linear Accelerator Center, Internal Report, RP-03-21 (2003).
3. Chapman, D., *PHOTON; A User's Manual*, Brookhaven National Laboratory (BNL), BNL-40822 (1988).
4. Asano, Y. and Sasamoto, N., *Development of Shielding Design Code for Synchrotron Radiation Beamline,* Radia. Phys. Chem. **44**, 133 (1994).
5. Asano, Y. *A Study on Radiation Shielding and Safety Analysis for a Synchrotron Radiation Beamline*, Japanese Atomic Energy Research Institute (JAERI), JAERi Internal Report 2001-006 (2001).
6. Fasso, A., Ferrari, A. and Sala, P. R. *Electron-photon Transport in FLUKA: Status*, Proceedings of the Monte Carlo 2000 Conference, Lisbon, October 23-26, 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz - eds., Springer-Verlag, Berlin, 159-164 (2001).
7. Fasso, A., Ferrari, A., Ranft, J. and Sala, P. R. *FLUKA: Status and Prospective for Hadronic Applications*, Proceedings of the Monte Carlo 2000 Conference, Lisbon, October 23-26, 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz - eds., Springer-Verlag, Berlin, 955-960 (2001).
8. Nelson, W. R., Hirayama, H. and Rogers, D. W. O., *The EGS4 Code System*, Stanford Linear Accelerator Center (SLAC), SLAC-265 (1985).
9. Namito, Y. and Hirayama, H. *LSCAT: Low-Energy Photon-Scattering Expansion for the EGS4 Code*, Japanese High Energy Particle Laboratory (KEK), KEK Internal Report 2000-3 (2000).
10. Rio, S. del R. and Dejus, R. J., *XOP: A Multiplatform Graphical User Interface for*

Synchrotron Radiation Spectral and Optics Calculations, SPIE **3152**, 148-157 (1997).

Table 1. Key parameters of two SSRL beamlines for benchmark calculations.

	SLM	**BL11-3**
SR Source	Bend	Wiggler
Peak Magnetic Field (T)	1.274	1.8
Critical Energy (keV)	7.622	10.77
Period Length (cm)	---	17.5
Number of Period	1/2	13
Horizontal Fan Width (mradH)	3.5	1
Carbon Filter	None	1.6 mm
Si Scatterer Disc (Thickness)	3.8 mm	3.0 mm
(Radius)	50 mm	50 mm
Inclined Angle of Scatterer	9 degrees	24 degrees
Dose Point Distance from Scatterer	1.0 m	0.42 m
Shield Wall SiO_2	3.09 mm	None

1) Storage electron beam energy is 3 GeV and current is 500 mA.

2) Polarization vector is on the horizontal plane.

Table 2. Dose equivalent ratio between STAC8 and EGS4 (or FLUKA) for mono-energetic photon sources.

Energy (keV)	**Target**	**Shield**	**STAC8/EGS4**
20	9^o-inclined Si Mirror	3.09-mm SiO_2	4.8
40			2.5
58			1.6
Energy (keV)	**Target**	**Shield**	**STAC8/FLUKA**
68	0.15^o-inclined Si Mirror	3-mm Fe	2.1
91			2.6

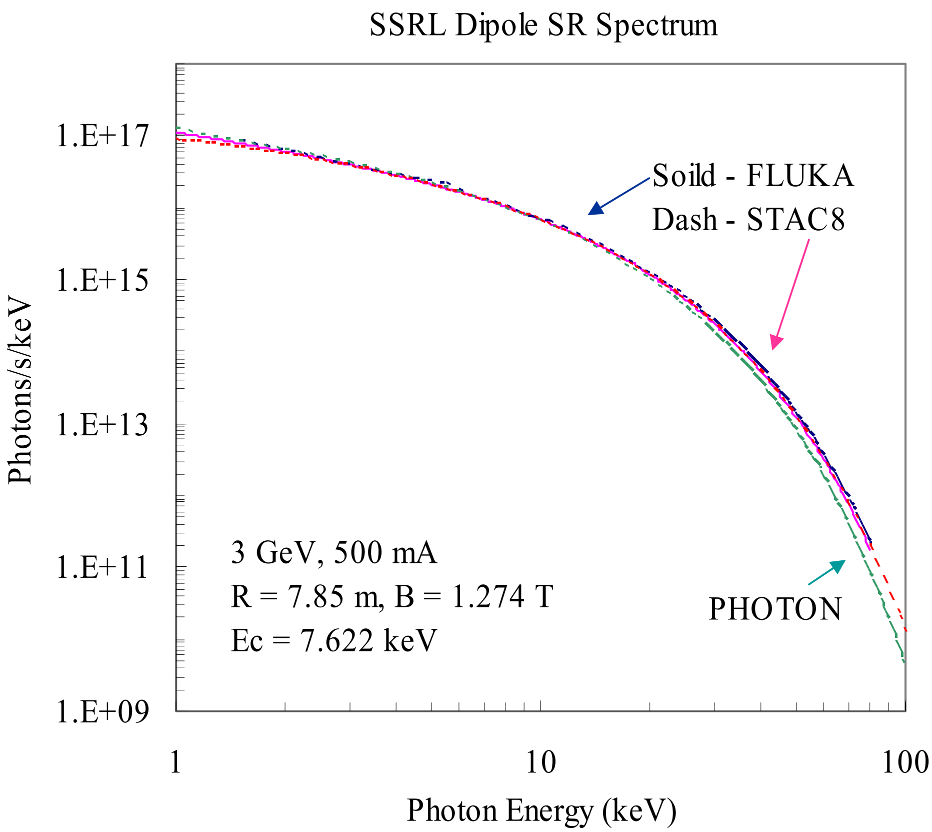

Figure 1. For the SR source spectrum from the SSRL bending beamline SLM, the STAC8-generated (dash) agrees well with the FLUKA one sampled using the SR formula (solid), while the spectrum from PHOTON (solid) underestimates at high energies.

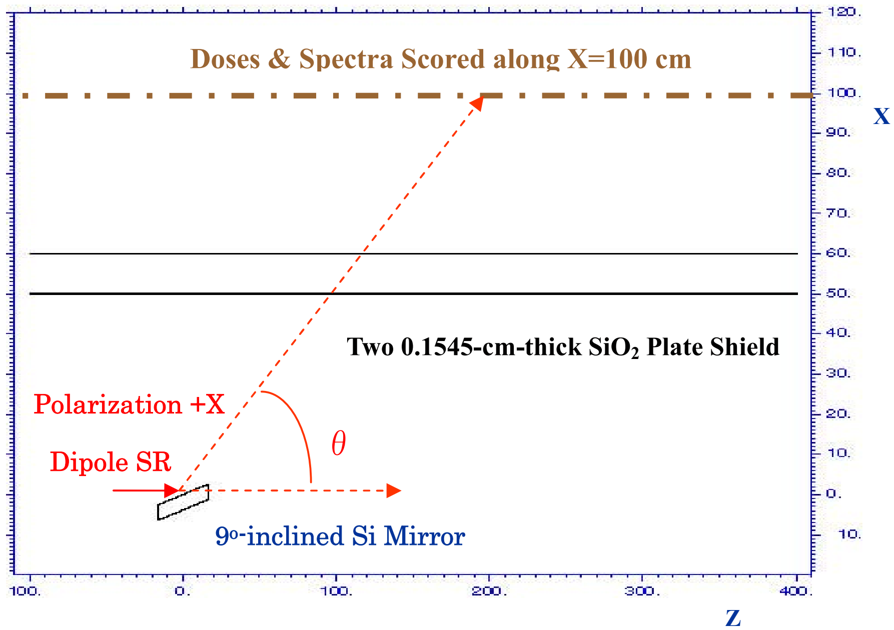

Figure 2. Geometry for the scattered SR calculations. SR emitted from the SLM dipole hits the Si mirror at Z=0. The mirror is 9^{o}-inclined relative to the beam direction (+Z axis). Polarization vector points toward +X axis. The shielding is two SiO_2 plates (each 0.1545 cm thick) parallel to Z-axis. Doses and spectra are scored at 1 m away from Z axis (i.e., X=100 cm).

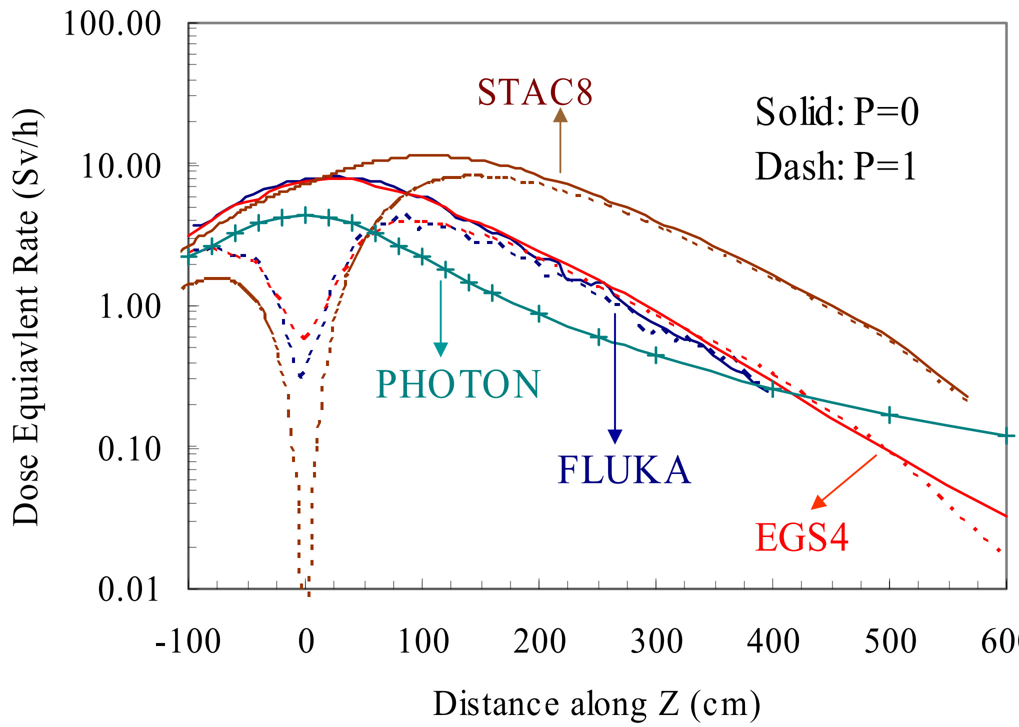

Figure 3. Comparison of effective dose H_E profile under the SLM case. Calculations between STAC8 (AP geometry), FLUKA (worst geometry) and EGS4 (AP geometry), as well as PHOTON (dose), are shown for cases with and without linear polarization (i.e., P=1 and P=0).

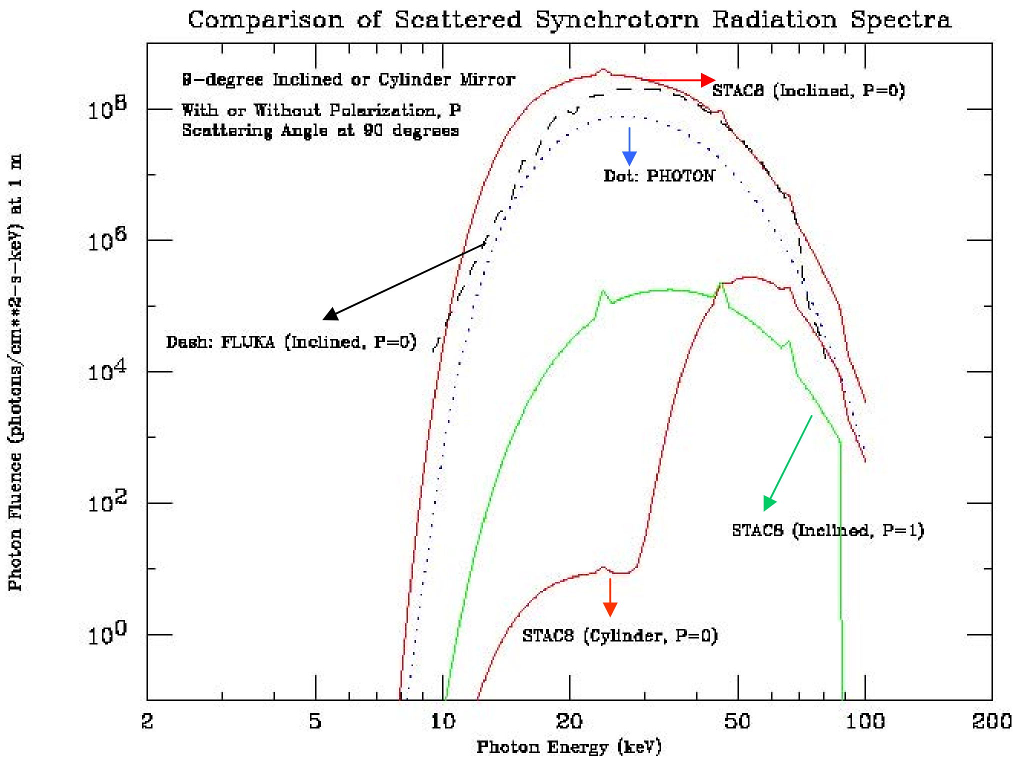

Figure 4. Comparison of scattered SR spectra at 90^o calculated using STAC8, PHOTON, and FLUKA (same beam-target-shield conditions as Figure 2).

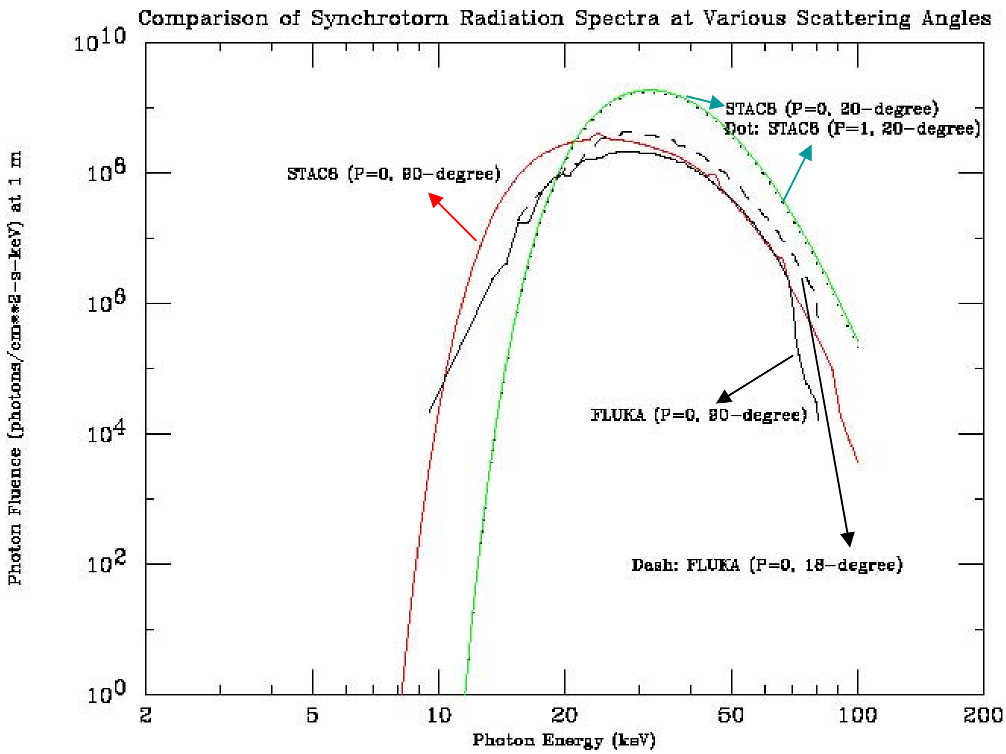

Figure 5. Comparison of scattered SR spectra at 90° and 18°-20° calculated using STAC8 and FLUKA (same beam-target-shield conditions as Figure 2).

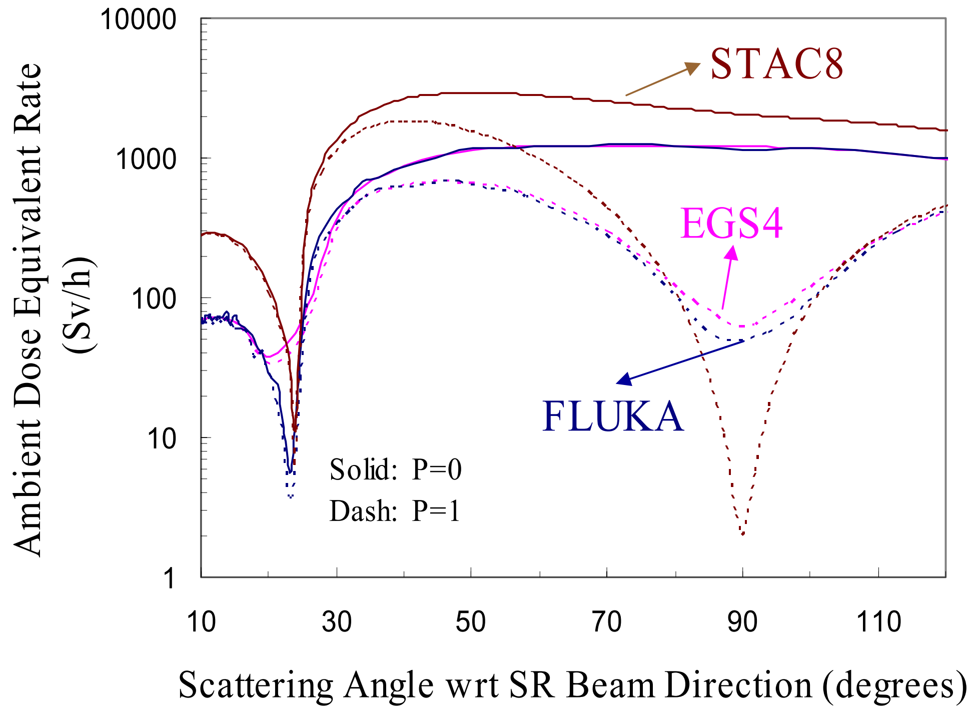

Figure 6. Comparison of ambient dose equivalent H* as a function of scattering angle from a 24^{o}-inclined Si monochromator hit by BL11-3 wiggler SR under the no-shield condition. Calculations using EGS4, FLUKA and STAC8 are shown with and without linear polarization (P=1 and P=0, respectively).

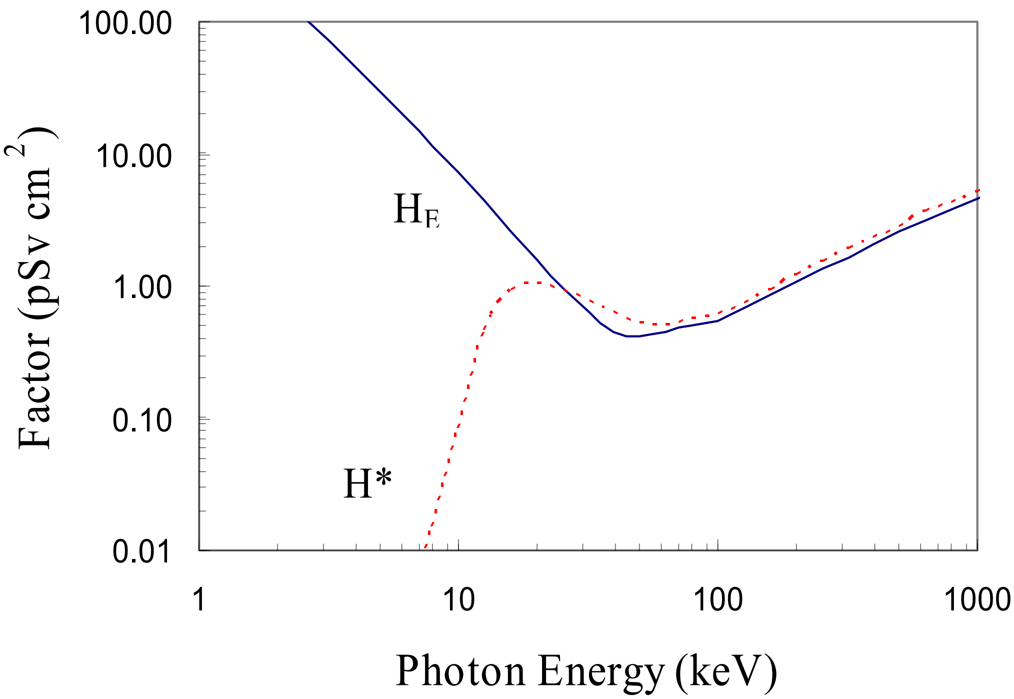

Figure 7. Photon fluence-to-dose equivalent conversion factors for effective dose H_E (worst geometry) and ambient dose equivalent H* used in the FLUKA calculations.

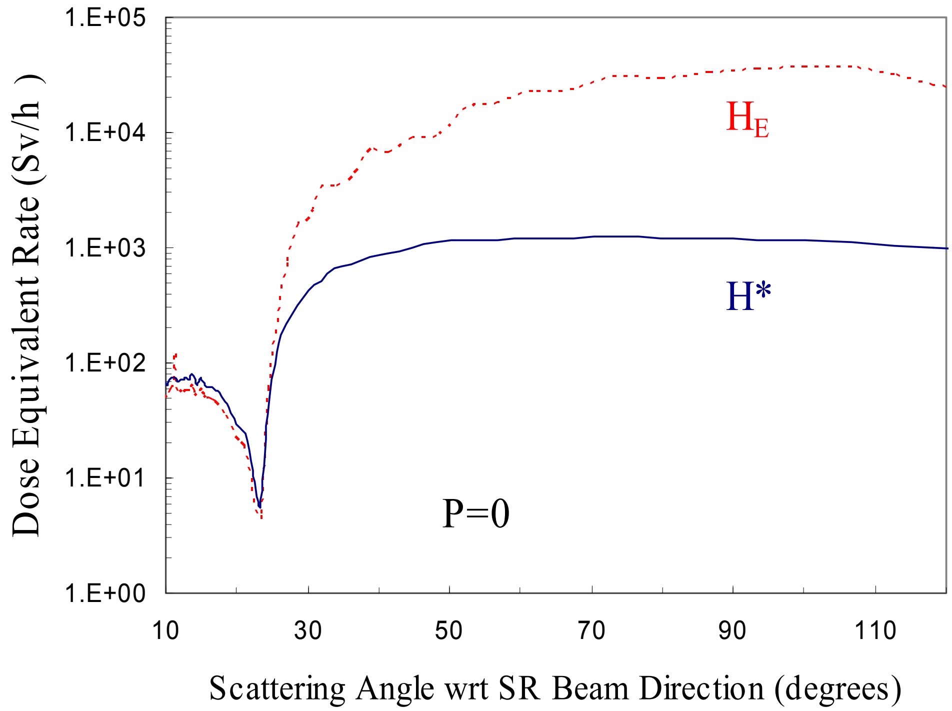

Figure 8. Comparison of photon dose equivalent rate for BL11-3 wiggler case. FLUKA shows that, at lateral angles, the effective dose H_E is 30 times higher than the ambient dose equivalent H*, due to the dominance of photons < 20 keV in this no-shield case and the conversion factor difference.

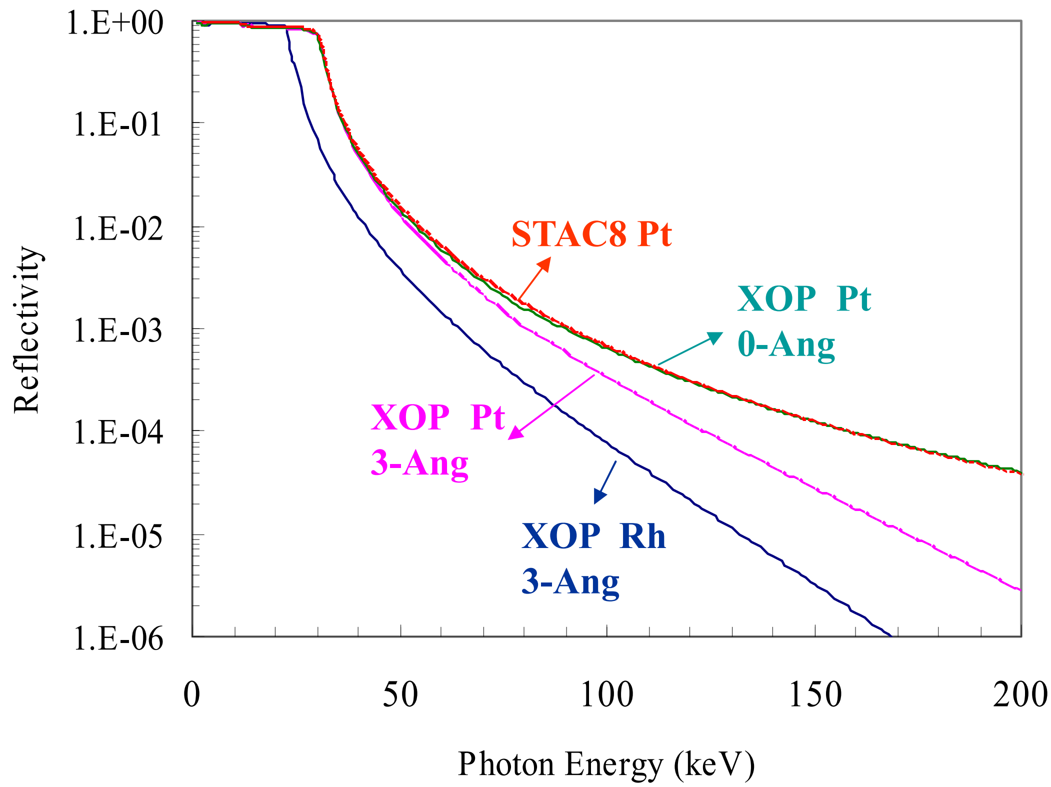

Figure 9. Comparison of reflectivity of mirror at 2.7 mradian. STAC8 reflectivity for Pt-coated mirror agrees with the one with zero roughness from XOP2.1. The reflectivity of a 3-Ang roughness, Pt-coated mirror is smaller than the zero-roughness one. The reflectivity of a Rh-coated mirror is also smaller than a Pt-coated mirror (both with 3-Ang roughness).