Health Physics Approach to Synchrotron Radiation

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Abstract

The radiation emitted by bending magnets and insertion devices in a synchrotron facility, although having rather low energy, is very intense. Covering an energy range from I.R. to soft X-rays it includes ionizing and non-ionizing aspects. Along its path from the storage ring to the experimental area it encounters optical components as mirrors and monochromators, each of them representing a source of scattered radiation. Starting from the program PHOTON, and with the aim of providing a useful tool for the design of the beamlines shieldings, we have developed the program EIDOLA that simulates bending, wiggler and undulator spectra, makes them impinge on the beamlines mirrors, calculates the transmitted and reflected beams and evaluates the dose rate in the neighbourhood keeping into account the reflection from the surfaces.

Introduction

The new generation of dedicated synchrotron light machines is characterized by high performance photon sources in terms of flux as well as in terms of available energies. It is usual to think that only high energy (more penetrant) photons have to be considered when evaluating the risk from a radiation source. Photons having energies of the order of few keV (or lower but still in the ionizing domain) are normally neglected in the calculations. This is a quite reasonable assumption when the source intensity is not very high; in fact the attenuation length (intensity decreased to e^{-1}) of 1.5 keV X rays in water is about 7 μm while the stratum corneum thickness is of the order of 10-15 μm. High fluxes of low energy X rays allow a still great number of photons to reach the granular and prickle cells with effects still not very well understood. For this reason our attention must not only be focussed on the energy of the radiation, but also on its intensity.

The synchrotron radiation beam produced by a bending magnet or an insertion device as a wiggler or an undulator is an important source of possible risk to workers and it has to be carefully studied in order to avoid unpleasant accidents. The exposition to the direct beam is not the only way people have to be hit by radiation. Optical components along the beam lines, like mirrors, act as sources of secondary radiation fields and, for very intense primary fluxes, the skin doses that could be received in their neighbourhood are quite high. Even if it is clear that thin absorbers may be able to completely shield these secondary fields, a deeper knowledge of the spatial dose distribution can help in the biological shieldings design and in the definition of the protection rules.

The radioprotection of workers is performed both by the theoretical analysis of the possible received doses in the diverse regions of the space and, usually for the most part, by measuring these doses with the appropriate dosimeters. The last goal is obtained using personal as well as field dosimeters. Two opposite cases could arise: a) the radiation field varies very little with space and time; b) the radiation field is extremely localized but not constant in space and time (f.e. a moving beam). Within the first situation personal dosimeters are useful in recording the accumulated dose for peoples working in that environment while in the second the low probability that in the case of an accident the small personal dosimeter crosses the field, makes field dose monitoring more meaningful.

The radiation field around the synchrotron radiation beamlines, being the superposition of a primary field that is the photon beam itself and of a secondary field produced by the interaction with the optical devices, would need both personal and field dosimetry. The energy range where these dosimeters should be sensible goes from some hundreds of keV down to few keV. This dosimetry is not an easy thing to realize, at least for routine purposes so, in some cases, we must go deeper with the theoretical analysis than with the direct measurement of doses.

Among the radiation sources used synchrotron radiation machines, at coherent light sources like undulators generate light beams with peculiar features. Their intensity is extremely high (f.e. 10^{16} photons/s in the central cone) and the energy spectrum is characterized by narrow peaks at the harmonic frequencies of the fundamental one. More, they are tunable sources, in the sense that varying the distance between the polar expansions of the magnets we can shift the energy position of the peaks and change their relative intensities. Unlike the cases of bending magnets and wiggler spectra, where good analytical expression are available, the angular behaviour of the undulator spectrum is quite difficult to describe. In a narrow cone, called the *central cone*, around the device axis, we find the most part of the emitted power, distributed over the odd harmonics only. The angular width of this cone depends on the electron energy and is of the order of $1/\gamma$ where γ is the ring energy in mc^2 units. A *pin-hole* usually selects the radiation in the central cone only so that the spectrum on-axis is the one relevant for the effects produced in the interaction with the optical components of the beam lines.

Starting from the computer code PHOTON [1] developed at the Brookhaven National Laboratory, we have introduced in it the possibility to generate an approximated undulator spectrum and to analyze the interaction of a synchrotron light beam on a mirror, obtaining informations about the spatial dose distribution and the dose attenuation by a lead absorber enveloping the device. Because the radiation spectrum covers a region where classical as well as quantum effects are simultaneously effective (i.e. reflection and ionization), we have developed an interaction model based on both points of view.

The Undulator Spectrum

From the theory it can be demonstrated that the photon flux in the central cone (c.c.) is given by:

$$\left.\frac{dn}{dt}\right|_{c.c.} = \sum_i \alpha \frac{\pi}{e} \frac{F_i(K)}{h\, i^2} \left(1 + \frac{K^2}{2}\right) I_b \; ; \qquad (1)$$

with I_b the ring current, K the undulator parameter, F_i (K) a function than can be expressed as a linear combination of Bessel's functions and i = 1,3,5,.... the order of the odd harmonic. The (1) can well approximate the total radiation on the central cone at the on-axis wavelengths in the case of zero electron beam divergence. In this case, the angular amplitude of the central cone for the i-th harmonics is of the order of $1/(\gamma\sqrt{i})$.

In the program PHOTON, the energy spectrum of the radiation, integrated over the central cone is assigned to the vector SPECT0. Considering the FWHM of the i-th harmonic to be approximately $\Delta E_i \sim E_1/N$ (corresponding to $\Delta ch(i)/2$ vector elements) and an energy interval $\Delta\varepsilon$ for each vector element, the value of the generic element of SPECT0 is:

$$\mathrm{SPECT0}\,(j(i)) = \frac{\left[1.431 \times 10^{14} \left(1 + \frac{K^2}{2}\right) \frac{F_i(K)}{i^2}\right]}{(\Delta ch(i)\, \Delta\varepsilon)} \quad , \qquad (2)$$

in units of photons/(s eV mA) if $\Delta\varepsilon$ is measured in eV. Figure 1 shows a spectrum obtained from this procedure using the parameters of the U2 undulator of ELETTRA [2] (N = 81, λ_0 = 0.056 m, with K= 1).

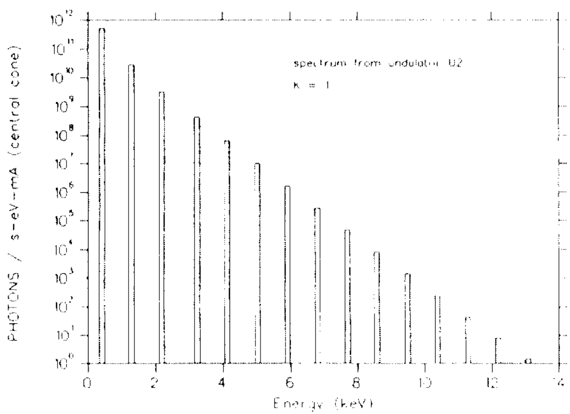

Figure 1. The approximated undulator spectrum generated by the program PHOTON. For this simulation N=81, λ_0=0.056 m, K=1.

The Interaction with a Mirror

The calculation starts by splitting the spectrum in two components, one reflected by the mirror the other interacting with it in a non-coherent way. Interactions are described within the framework of the quantum field theory keeping into account photoelectric, Compton and elastic cross sections. The secondary photons produced are only attenuated in the medium. This means that the third generation of photons is assumed to be completely absorbed in the mirror material.

For each mirror the program calculates the reflectivity versus energy curve and gives the spatial distribution of doses, the attenuation in aluminium of the dose at one meter from the mirror surface and the reflected and transmitted spectra, which are available for other interactions. The calculations make use of the concept of the *effective number of electrons per atom* which, in a previous paper [3], has been outlined to be a useful and quite easy to approximate quantity for radioprotection purposes.

The interaction of a photon beam with a reflecting surface must be treated at the same time within the classical and the quantum pictures [3]. The classical point of view, based on the Maxwell equations, allows to determine the reflected and the absorbed fraction of the beam power; however it uses phenomenological parameters that can be expressed in terms of cross-sections deducible from the quantum theory of radiation or from experimental data.

We consider a beam of photons impinging on a mirror of thickness L at a grazing angle θ. The fraction not reflected of the photon beam interacts with the mirror material. For the typical energies of synchrotron radiation (up to some hundreds of keV) the relevant interactions are photoelectric effect, Compton scattering and elastic or Rayleigh scattering. In the photoelectric effect a radiation quantum is absorbed by an atom or a molecule and an electron is emitted producing the ionization of the target. The following re-assesment of the structure, occurring with electrons transitions towards the free lower energy states, produces the emission of fluorescence X-rays. Some of these quanta can exit the atom or the molecule and, in some cases, their energy is in the ionizing range. The other two processes are scattering events where the final states contain one photon; its energy can be equal to the energy of the incoming one (Rayleigh) or lower (Compton).

Considering a small volume $d\Sigma dl$ of absorber with linear absorption coefficient μ_{abs} and density ρ positioned at a given point of coordinates (ζ,η), the dose at it is:

$$D_\alpha(\xi,\eta;\theta) = \int_0^{E_{max}} \int E_f \left(\frac{\mu_{abs}(E_f)}{\rho} \right) n_\alpha(E, E_f; \xi,\eta,\theta)\, dE\, dE_f\,, \quad (3)$$

with E_f the secondary photon energy and $n_\alpha(E,E_f;\xi,\eta,\theta)$ the density function giving the spectral fluence.

This definition of dose is strictly limited to an energy absorbed in an infinitesimal volume of matter in vacuum. It is an useful quantity for describing the spatial distribution of the radiation field; its value, together with the attenuation curve (f.e. in aluminum), gives us a knowledge about the spectral character of the scattered radiation. These data must not be used to calculate effective doses to workers.

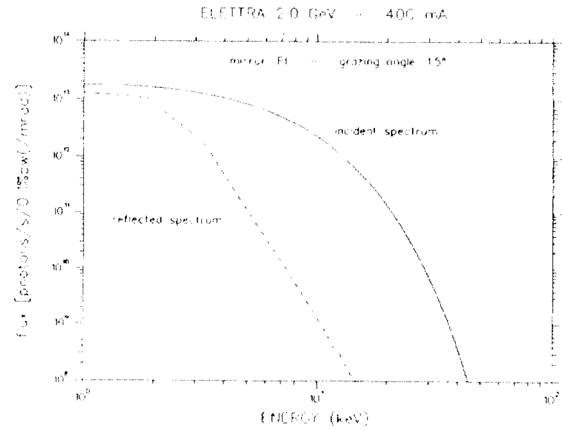

Figure 2. SR spectrum generated by 2 GeV electrons deflected by a 1.212 T bending magnet (solid line). The dashed line represents the part of it reflected by a platinum mirror for a grazing angle of 1.5°.

Figure 2 shows the SR X-ray spectrum generated by 2 GeV electrons deflected by a bending magnet with ρ = 5.5 m, corresponding to a magnetic field of 1.212 T. This radiation is made to impinge on a mirror with a platinum reflecting layer of 300 Å at a grazing angle of 26 mrad. The reflected beam has the spectral density showed in the same figure with the dashed curve. The calculus of the doses in the space around the mirror following the (3) and considering a tissue-equivalent absorber, allows us to obtain the isodose curves showed in figure 3. In this example we used just the real thickness of the reflecting layer, so we find dose contribution also in the space beyond the platinum layer where is located the support of the mirror. One of the possibilities given by the program is to use the spectrum transmitted through the first layer to study its interaction with the support.

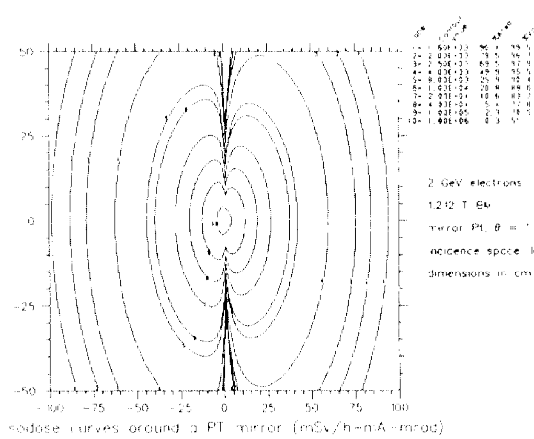

Figure 3. Map of spatial isodose curves near a platinum mirror in the SR beam incidence plane.

The attenuation curve of the dose in an aluminium absorber is calculated one meter from the mirror surface in the incidence plane and the resulting curve is showed in figure 4.

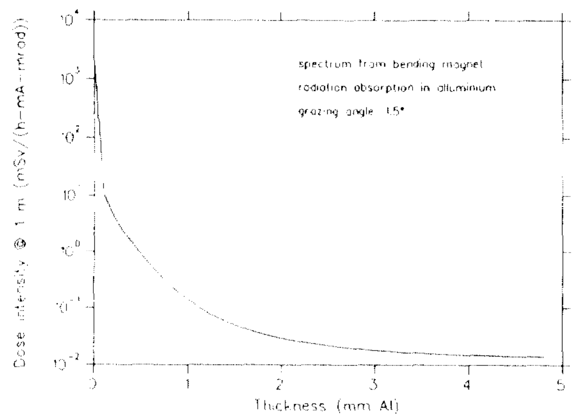

Figure 4. Absorption curve in aluminium of the spectrum scattered from a platinum mirror. The incident spectrum is that represented in figure 2. The dose intensity is evaluated at one meter from the mirror in the incidence plane.

Conclusions

The peculiarity of synchrotron radiation, with its wide energy range from U.V. to X rays, makes the calculations of shielding barriers very long and tedious. The low energies of the ionizing part of the spectrum assure that thin absorbers can be effective in greatly reducing the scattered photons flux; but the very high intensity of such sources could still be dangerous if not properly attenuated. The algorithms we have implemented in the program PHOTON give us the possibility to evaluate quite fast all the relevant quantities and to present them in a easy form to interpret. The main approximations introduced are summarized in the following points:

1) thin reflective layers;
2) the effective number of electrons per atom or in alternative the real part of the complex scattering factor is equal to the number of electrons per atom with binding energy less than the energy of the interacting photon;
3) third generation photons don't escape from the target;
4) Rayleigh photons and fluorescence X-rays are isotropically emitted;
5) photoelectric energy edges and fluorescence X-rays energies are mean values when the distances between neighbouring lines are small.

Another approximation concerns the polarization of the photon beam relative to the mirror surface. We assumed, for simplicity, that the beam is polarized normal to the incidence plane. This is a quite common situation because synchrotron radiation is mainly polarized in the electron orbit plane and the reflecting surfaces are often oriented at small angles with respect to this plane. However, in the case of a different polarization for the incident beam, only small corrections are necessary and they could be implemented in the future. Also the approximation at point 2) could be removed introducing in the program the experimental scattering factors as is already done for the absorption and attenuation coefficients.

Beyond these considerations we feel that the obtained results are satisfactory and we are planning to check them experimentally. Some beam lines under project for the synchrotron light source ELETTRA [4] have been analyzed using the program PHOTON in this up-to-date version that we have re-named EIDOLA. A new user's manual including the described functions and other new features described in a separate paper [5] is in preparation.

References

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[3] M. Fabretto and A. Rindi, "Radiation Interactions With Matter: Some General Considerations on the Ionizing/Non-Ionizing Boundary Region", Sincrotrone Trieste, ST/M-90/4, March 1990.

[4] M. Fabretto, A. Rindi and G. Tromba, "Radioprotection for the ENEA Beam Line", Sincrotrone Trieste, to be published.

[5] M. Fabretto, "EIDOLA User's Manual", Sincrotrone Trieste, to be published.