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RADIATION PROTECTION PROBLEMS AT A SYNCHROTRON RADIATION FACILITY

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Abstract—Experiments with synchrotron radiation beams involve risks from ionizing radiation exposure. This report describes the main radioprotection problems around a storage ring working for synchrotron radiation. The dosimetric characteristics of synchrotron light beams are also described.

INTRODUCTION

Synchrotron radiation is electromagnetic radiation emitted by charged particles, in particular relativistic electrons, moving in curved accelerators, and its name reminds us of this origin. Initially it was considered largely a nuisance, posing severe technical and economic limitations on the energy attainable with circular electron accelerators. Later on, its possible uses became evident, and now synchrotron radiation is widely used as a unique calibrated source in the vacuum ultraviolet and soft X-rays regions. No other source gives such a high intensity together with the possibility of varying the energy over a very wide range. Furthermore, the light is polarized.

Synchrotron radiation is emitted tangentially to the orbit of the electrons, and for relativistic energies the emission angle is very small ($\vartheta \simeq mc^2/E$).

Storage rings are the machines best suited for the production of synchrotron radiation. When synchrotron radiation is produced by a synchrotron, the electron energy varies rapidly during the acceleration cycle, so that the spectrum of the emitted light is not constant. Furthermore the intensity and the position of the electron beam vary from cycle to cycle and within a cycle. On the other hand, in a storage ring large currents of electrons can be stored and accelerated to the desired energy in a short time, and they keep circulating at that energy for several hours. Beam losses are due only to collisions with residual gas molecules or to instabilities. The synchrotron radiation sources thus generated are characterized by very high intensity and stability in time.

Several storage rings in various countries are at the present time dedicated only to the production of synchrotron radiation for physics experiments.

An estimate of the power radiated by the electrons moving on their circular orbit can be easily obtained (Ro73; Wi73; Wi76). In fact the energy lost by one electron of energy E in a circle of radius R is given by:

$$\Delta E = 88.5\frac{E^4}{R}, \tag{1}$$

where ΔE is in keV, E is in GeV and R is in meters. Therefore the power P radiated by a current I is given by:

$$P = 88.5\frac{IE^4}{R}, \tag{2}$$

where P is in kW and I is in A.

The energy spectrum is continuous and its critical energy ϵ_c(keV) is given by:

$$\epsilon_c = 2.22\frac{E^3}{R}. \tag{3}$$

The portion of the spectrum generally considered useful extends up to 5 or 6 times the critical energy.

The ratio of the energy radiated in a turn and the critical energy gives an estimate of the number of photons radiated per turn (40*E*) and, knowing the revolution frequency, the total number of photons radiated per second can be obtained. Typical values range from 10^8 to 10^9 photons per second per electron. Since the number of electrons circulating in a storage ring can easily reach 10^{10}–10^{11}, it is obvious that these machines constitute excellent photon sources.

Enhancement and modification of the energy spectrum is possible with the use of a special periodic magnetic field structure called a wiggler, which forces the electrons to oscillate around their trajectories.

The applications of synchrotron radiation are continually expanding. New field are opening and any list is necessarily incomplete. Typical applications are: structure determination (enzymes; catalysts, crystals); surface studies (absorption, corrosion, catalysis); atomic, molecular, solid state spectroscopy; determination of optical constants; fluorescence (life times trace element analysis); photochemistry; Mossbauer studies; radiation effects; lithography (fabrication of microstructures, integrated circuits); microscopy; Raman scattering; Compton scattering; holography; diagnostic radiography (Wi76).

Experiments with synchrotron radiation beams obviously involve risks from ionizing radiation exposure. We shall mention here the main radioprotection problems around a storage ring working for synchrotron radiation. In particular we shall consider the situation at the Frascati storage ring Adone.

SYNCHROTRON RADIATION BEAMS AT L.N.F.

The first experiments with synchrotron radiation light at the Laboratori Nazionali di Frascati were performed in the early 60s at the 1 GeV electrosynchrotron. This activity has been growing steadily ever since and now, it is a prominent aspect of the whole laboratory. In the last few years since the high energy physics program was concluded, the Adone storage ring has been used for a variety of other physics researches, and synchrotron radiation has been the leading one.

In Adone the maximum energy is 1.5 GeV and the maximum stored current is about 100 mA, corresponding to $2.2 \cdot 10^{11}$ electrons circulating with a frequency of 2856 kHz. The bending radius of the magnets is 5 m. The critical energy of the emitted light is 1.5 keV. The radiation is emitted tangentially to the effective orbit of the particles, with an opening angle $5.1 \cdot 10^{-4} E^{-1}$ (GeV) radians at the critical energy.

Two experimental laboratories at Adone use synchrotron radiation: PULS (Synchrotron Light Use Project) and PWA (Adone Wiggler Project).

The PULS experimental facility consists of five light channels covering the energy interval from 10 to 12 keV. Only two channels are in operation at present, one at low energy (10–150 eV) which does not concern us at the moment, and an X-rays channel (1.5–12 keV). On this beam is installed a monochromator using a silicon crystal which gives a resolution better than $3 \cdot 10^{-4}$ (La79).

The PWA project has obtained a beam at higher energy and higher power using a transverse wiggler magnet placed in one of the straight sections of Adone. The wiggler is 2.1 m long, has 6 pairs of poles and a maximum field of 1.8 T. The electrons oscillate around the central orbit emitting synchrotron light of higher intensity and higher energy than the radiation emitted in a bending magnet of Adone. The main characteristics of this beam are listed in Table 1 (Sc80).

Figure 1 shows the spectral distributions of the two beams we have described for an electron energy of 1.5 GeV. The critical energies in the two cases are 1.5 and 2.7 keV.

RADIOPROTECTION PROBLEMS

The radiation exposure risks for persons working in the synchrotron light experimental areas come from two main sources: risks due to bremsstrahlung radiation produced in the ring of Adone (during injections; due to scattering of the stored electrons on molecules of gas in the vacuum pipe; due to beam losses, both accidental and due to the lifetime of the stored beam); risks due to accidental exposure to synchrotron light beams. These risks are not completely identical for the two

Table 1.

Parameters of synchrotron radiation from the wiggler	
Electron energy	E = 1.5 GeV
Field in the wiggler	B = 1.85 T
Radius of electron orbits in the wiggler	ϱ = 2.7 m
Critical wavelength and energy	λ_c = 4.48 Å, ε_c=2.7 keV
Intrinsic vertical angular aperture	σ_ψ = 2.07 · 10^{-4} rad

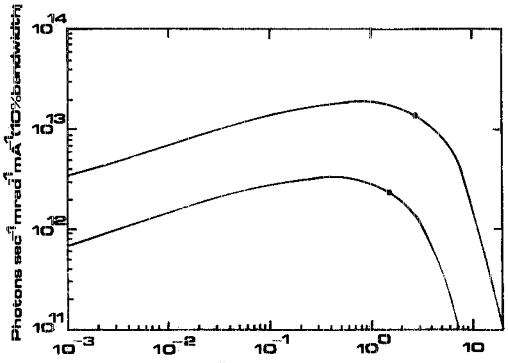

FIG. 1. Spectral distribution of the radiation emitted by the storage ring Adone for an electron energy of 1.5 GeV (lower curve). Also shown for electron of the same energy is the distribution obtained using a wiggler magnet with a 1.8 T magnetic field and 6 equivalent flat poles. The critical energies of the two beams are (points shown the figure) 1.5 and 2.7 keV respectively (from PU77).

X-ray beams described due to design differences in the two experimental areas. The first difference is in the location of the two laboratories: PULS is located outside the Adone hall; the other, PWA, is inside. A second difference is that the PULS beam travels in a guide with walls thick enough to attenuate it completely, while, due to experimental requirements, the PWA beam travels for a distance in air at present.

We have already described in other publications the risks due to bremsstrahlung radiation (Pe71; Lu75; Es78; Pe79; Ri80). In this paper, we shall deal with the dosimetric characteristics of the light beams and of the risks due to accidental exposures to them. However it is useful to remember here that when the vacuum conditions on the light channels are not good the dose-rate around the machine can strongly increase. In Adone this effect has been observed experimentally particularly for the wiggler channel. Depending on the vacuum of this channel and on operations on its elements (beam-stopper, pneumatic valves, etc.), we have detected variations of the dose-rate inside the laboratory by a factor of 400–500, requiring substantial changes to the safety logic originally adopted.

Before dealing with the dosimetric characteristics of the light beams it is worthwhile to describe the logic of the safety systems installed in the two laboratories to prevent overexposures to the above mentioned radiation.

In the PULS laboratory a restricted zone has been defined around the high energy channel which is interdicted during some

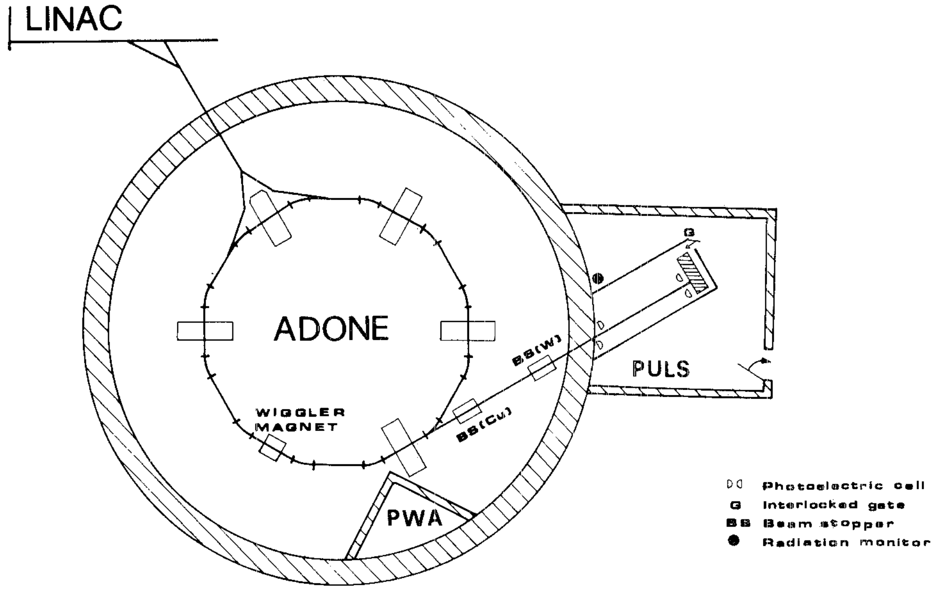

FIG. 2. Adone Synchrotron Radiation facility layout.

operations (Adone injection; synchrotron light utilization). A system of beam stoppers, photoelectric cells, radiation monitor and interlocked gate (Fig. 2) is installed to protect personnel from exposure to synchrotron radiation or the high energy radiation that could result in the event that injected or stored beam are lost in the ring. During the injection beam-stoppers are closed. With beam-stoppers open experimenters are able to occupy areas outside the fence. With beam-stoppers (W) closed and (Cu) open, occupance is safe in the restricted zone when electron stored beam is circulating. The safety system of the PWA laboratory is quite similar.

DOSIMETRIC CHARACTERISTICS OF SYNCHROTRON LIGHT BEAMS

As we have already mentioned, the synchrotron light beams are a source of low energy X-rays unique for their high intensity. The characteristics of these sources can be deduced exactly from the parameters of the machine. Considering the lack of dosimetric data on these beams in the literature we shall discuss the dose estimates for the two X-ray channels in Frascati.

The estimate for the PULS channel has been made from the photon beam intensity measured at the output of the monochromator by an argon ionization chamber (Co80). Curve (a) in Fig. 3 shows the number of photons per second vs energy E relative to a bandwidth of 10^{-4}, i.e. the number of photons per second of energy between E and $E \pm (10^{-4}/2)\,E$. The experimental conditions are described in the figure captions.

For a point close to the exit window of the monochromator, the absorbed dose rate is given by:

$$\dot{D} = \psi \frac{\mu_{en}}{\rho}, \qquad (4)$$

where ψ is the incident energy flux density and μ_{en}/ρ the mass energy absorption coefficient in tissue at the energy considered.

The calculation of $\dot{D}$ was made using water to approximate tissue and with the values for μ_{en}/ρ for water published by Hubbell (Hu77).

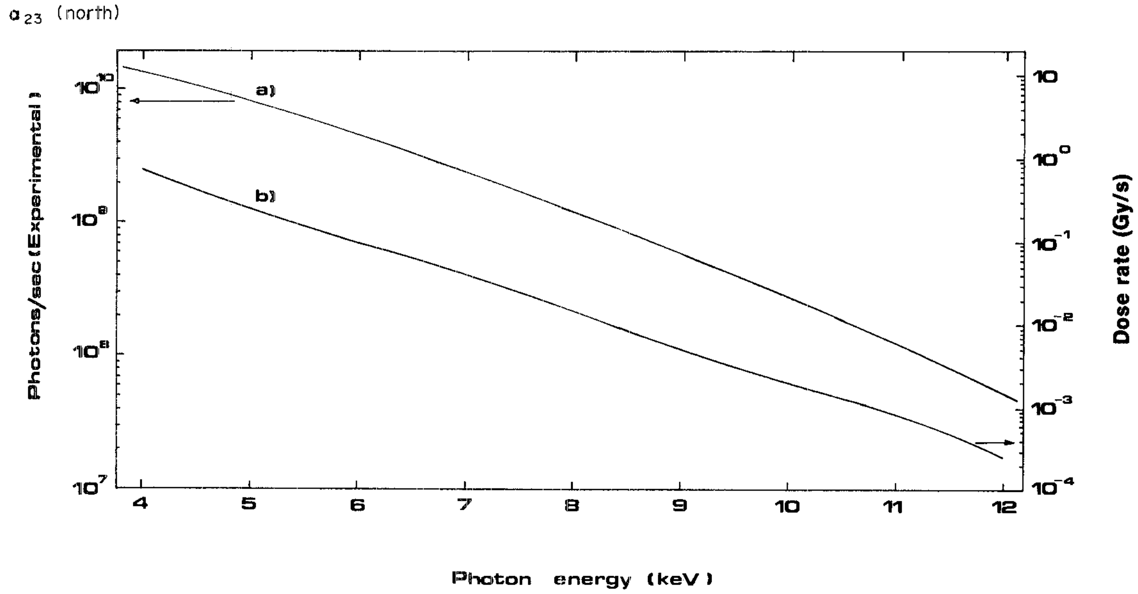

FIG. 3. Curve (a): Number of photons per second for a bandwidth of about 10^{-4} measured in the following experimental conditions: E_0: 1.497 MeV; I_{stor}: 100 mA; beryllium window: 70.5 μm (Co80). Curve (b) Dose rate relative to the photon fluxes of curve (a).

Figure 3, curve (b), shows the results normalized to a 100 mA stored beam.

For the Wiggler channel, the dose calculation was performed using the theoretical spectrum immediately outside the Be window of the channel (see Fig. 4) (Di80). The spectrum, which assumes a bandwidth of 0.1%, has been normalized to the current in Adone, to the number of poles of the wiggler magnet and to the orbit segment observed by every pole in mrad. Outside the Be window, the beam is $30 \times 10\ \mathrm{mm}^2$ and the power is about 103 mW/mA.

In this case the dose has been computed without the monochromator. Since the beam travels through a distance in air, the dose-rate was calculated using:

$$\dot{D}=\int_{E_{\min}}^{E_{\max}} f(E)\frac{\mu_{en}}{\rho}(E)\frac{\mathrm{d}\psi(E)}{\mathrm{d}E}\mathrm{d}E, \qquad (5)$$

where $f(E)$ is the attenuation factor in air, computed using the values of mass attenuation coefficients tabulated by Hubbell (Hu77). Results were obtained for various distances from the Be window and for various tissue depths assuming "good geometry" irradiation conditions, which is possible due to the high collimation of the beam. These results are shown in Fig. 5 for a stored current in Adone of 1 mA.

Figure 6 shows the dose-rate spectra for various distances from the channel window and normalized to a 1 mA beam current. Note that increasing the path length in air increases the contribution to the dose from higher energy X-rays. For instance, at the exit window the main contribution to the dose is given by the soft part of the spectrum, but after a 2 m path in air the dose distribution is peaked around a photon energy of 8–9 keV.

A similar effect is found in tissue: on the surface or at small depths, the dose is substantially due to low energy X-rays, while for increasing depths the contribution of higher energy X-rays becomes more and more im-

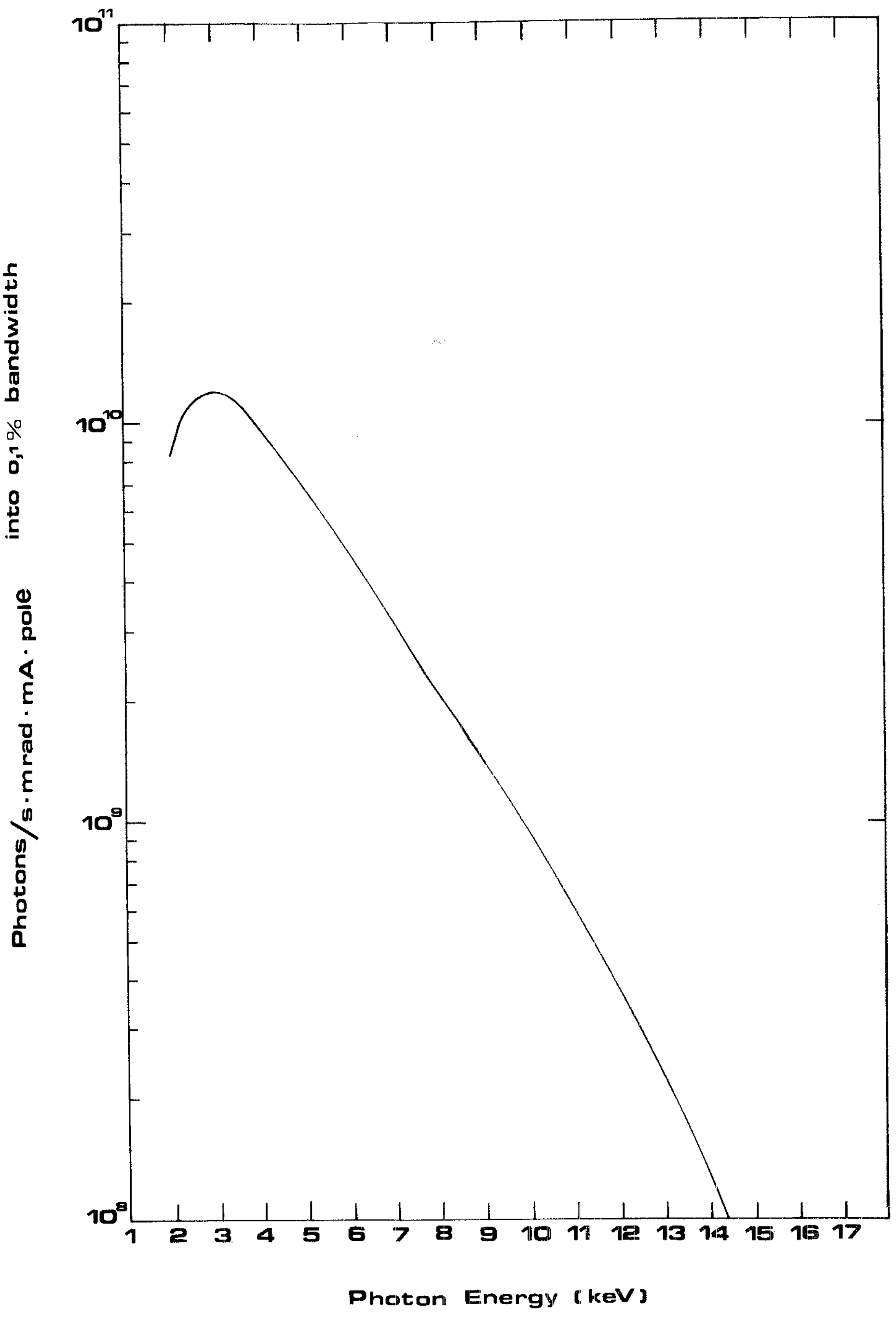

FIG. 4. Theoretical spectrum of the wiggler channel synchrotron light after the 73 μm Be window for electrons of 1.4 GeV energy and wiggler current of 4 kA (Di80).

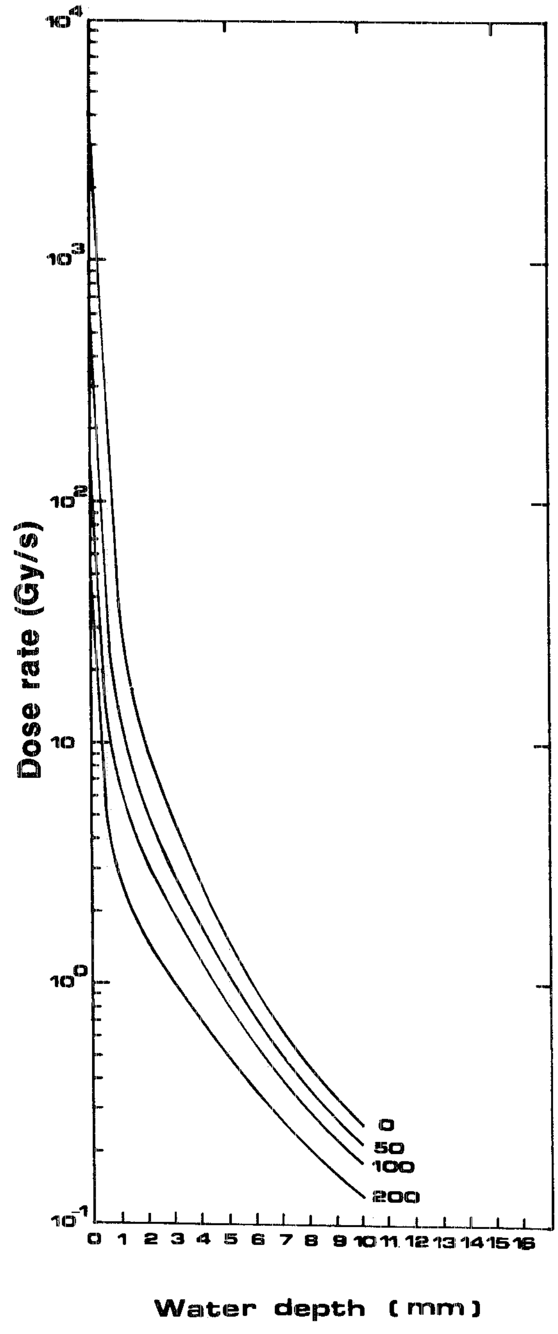

FIG. 5. Dose rate per mA of stored current as a function of depth in water at various distances (cm) from the Be window of the wiggler channel.

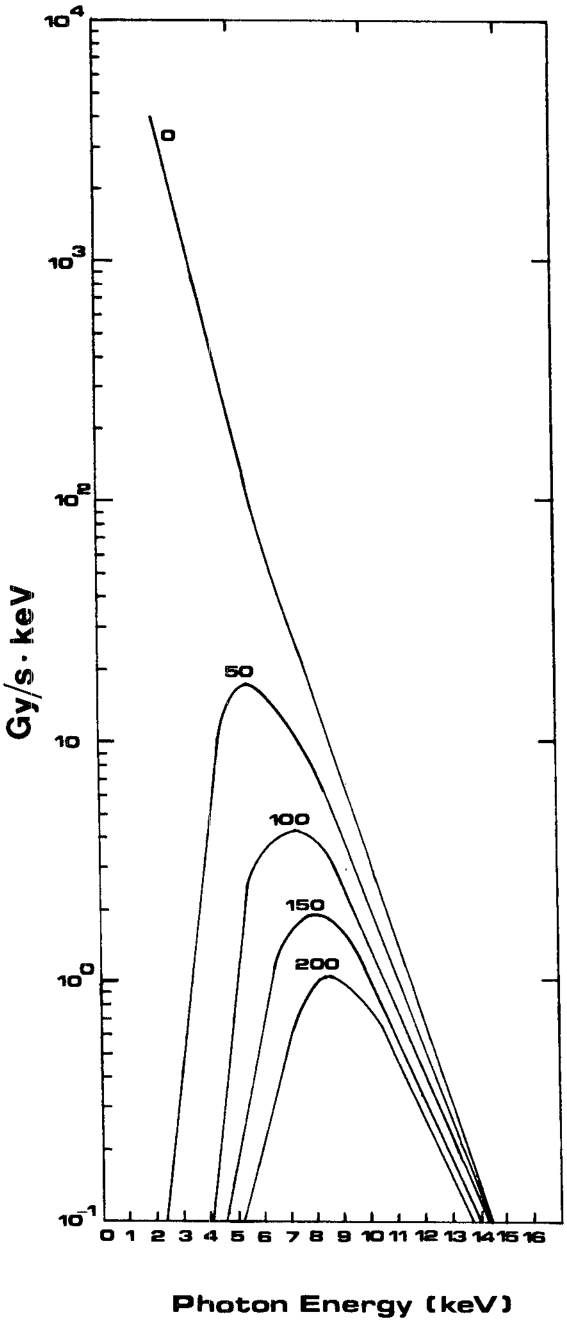

FIG. 6. Dose rate distribution as a function of photon energy at various distances (cm) from the wiggler channel Be window. The data are normalized to a current of 1 mA circulating in Adone.

portant. This effect is shown in Fig. 7 where the dose distributions as a function of photon energy are calculated for various depths for a sample of water irradiated at a distance of 50 cm from the channel window. As usual, the rates shown are normalized to a stored current of 1 mA. Note that on the surface, the most important part of the spectrum is around 5–6 keV, while after 10 mm of water the peak is centered around 12 keV.

All these estimates are based on the assumption that the distribution of the beam over its entire cross section ($30 \times 10\ \mathrm{mm}^2$) is uniform. In practice the beam has a structure which, at least along the vertical direction, is not at all uniform. This must be taken into account when the dose estimated required are very accurate.

The structure of the beam has been experimentally measured by the transparency variations induced in a thin sheet of green cellophane exposed to the beam. The transparency of the cellophane sheet was measured using a light beam from a helium–neon laser on a photoresistor. A typical configuration of the vertical profile measured with the above described method is shown in Fig. 8. Using the beam structure thus determined, we estimated that the dose rates in the maximum power area can be a factor of two higher than those calculated.

CONCLUSIONS

The above mentioned data show clearly the high power of the synchrotron light beams and their potential danger. Any accidental exposure must carefully be avoided. The only reasonable radioprotection measures to be taken must be preventive, like running the beams in closed guides.

On the other hand it must be emphasized that, apart from radioprotection aspects, synchrotron light beams are extraordinary facilities for experiments requiring high doses of low energy X-rays. Considering the interest raised by these beams, it is necessary to prepare accurate dosimetric techniques, taking into account the peculiarities of these beams. Our laboratory is currently working in this direction.

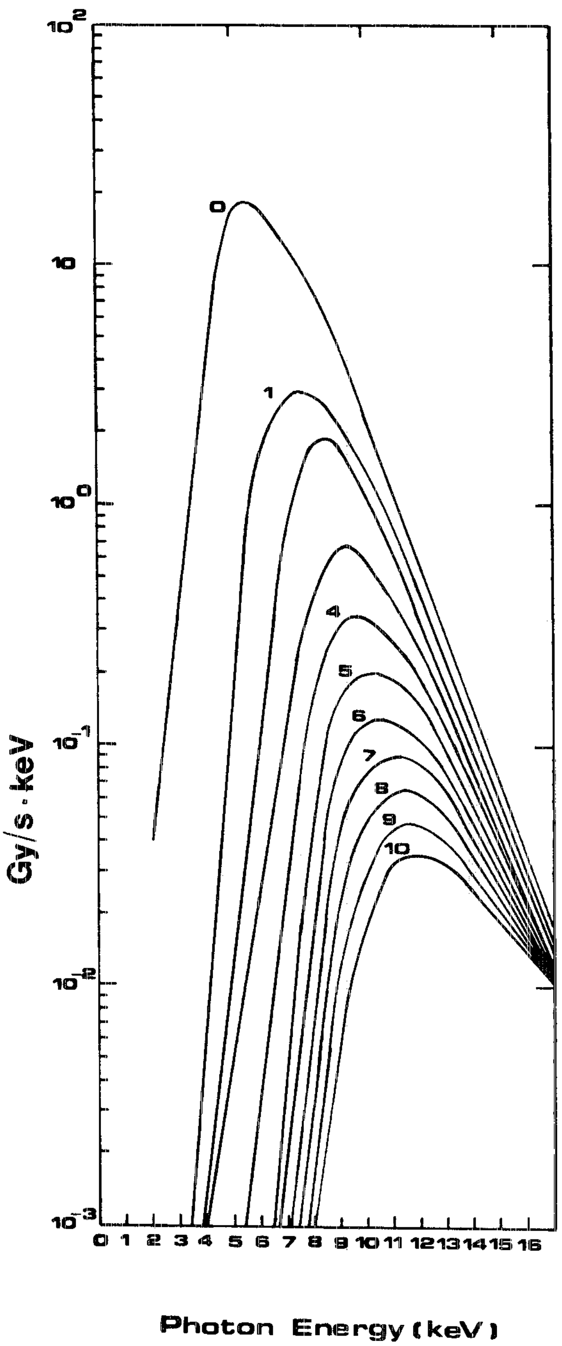

FIG. 7. Dose rate distribution vs photon energy at various depths (mm) in water irradiated 50 cm from the Be window of the wiggler channel. Data normalized to a 1 mA stored current.

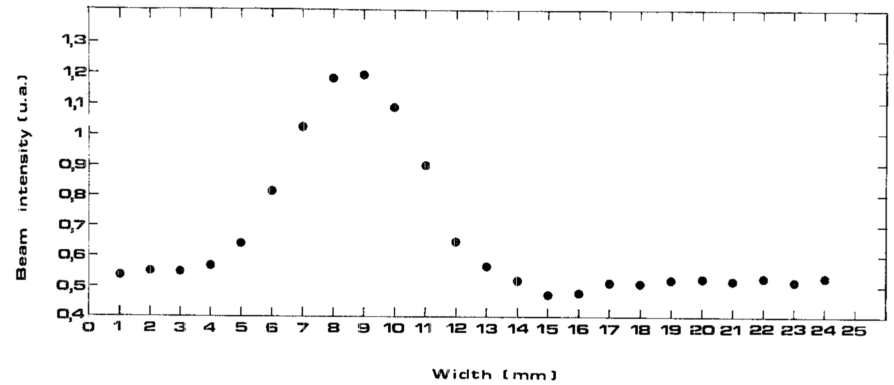

FIG. 8. Vertical profile of the wiggler beam measured by transparency measurements on irradiated thin green cellophane sheets.

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