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X-RAY FILTERS FOR SYNCHROTRON RADIATION

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Abstract

A computer program is developed for calculation of the photon flux and power distributions of a synchrotron radiation beam when various filters are inserted in the beam. The low-energy photons are eliminated by a vertical aperture and a set of foils of pyrolytic graphite, so that Be windows can be placed in a beam line using wiggler radiation. Xe gas is a band-pass filter between 25 keV and 34.5 keV. It reduces the power of the radiation from the superconducting wiggler of the NSLS by a factor of 5 while providing 50% transmission at 33 keV, where the iodine contrast angiography will operate. Other possibilities for band-pass filters are Kr, and Fe, Cu or Ag which can be alloyed to Be in small concentrations. The absorption of power in the filters is calculated, and it is concluded that the heat transfer from the graphite foils is due to blackbody radiation, while the rare gas becomes plasma which radiates mostly ultraviolet light or soft x-rays.

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1. Introduction

Synchrotron radiation (SR) from an electron (positron) storage ring can be greatly enhanced by insertion devices. By the use of a superconducting wiggler (SUW) the characteristic energy of SR can be increased by a factor of 4 to 5, and the total power of SR by an additional factor equal to the number of wiggler poles. For instance, the maximum power from the bending magnet source of the x-ray ring at the NSLS is 40 W/mrad (horiz.), while that from the SUW will be 1.2 kW/mrad. The increased flux makes many new experiments possible, but also causes severe thermal problems. The purpose of this work is to study possibilities of reducing the heat load on the optical elements by selective filtering of the SR beam.

2. Filter Materials

The spectrum of the wiggler radiation is given by the topmost curves in Figs. 4B and 6 as the number of photons and the power per unit energy. The characteristic energy E_c is the median of the power distribution. The angular distribution of SR at a few energies are given in Fig. 1.

The low energy radiation, which is only a nuisance in most experiments which employ the wiggler beam, can be eliminated by filter foils of low-Z elements. The obvious choice is pyrolytic graphite, which has large lateral heat conductivity and which is mechanically stable even at temperatures where radiation cooling becomes effective. As seen from Fig. 1, another simple and effective way of scraping the low energy radiation is limiting the vertical aperture by a water-cooled slit.

The purpose of the aperture and the graphite filters is to reduce the absorption of radiation in the first window and optical element to a tolerable level. A crystal monochromator can be allowed to warm up only marginally, because the reflected energy band would shift too much from the value set for the experiment, as the beam power falls off after the fill of the storage ring. In this respect, the best and probably the only feasible choice is Be in transmission geometry. In the present case the horizontal width of the central beam is 5 mrad, and a crystal which is 60 mm to 70 mm wide, 5 mm high, and 0.3 mm thick would be needed. Edge cooling of such a crystal is very effective, but in spite of the recent progress in growing good quality mosaic crystals, sufficient uniformity of the mosaic distribution over this large area may not have been reached yet. Accordingly, this possibility is not explored any further, and in the following other possible high and low-pass filters will be studied.

For many applications of the wiggler radiation the low-energy cut-off of C at about 10 keV (at higher energies scattering becomes important; see Fig. 2) is not sufficient and higher-Z elements must be used. There the choices are few, because absorption is grossly proportional to Z^3 , but thermal conductivity does not increase with Z, and most materials would melt in the intense x-ray beam before reaching the radiation plus conduction cooling equilibrium. Therefore, the use of gaseous filters was studied in detail.

The absorption characteristics of the rare gases collected in Table 1 show that the gases could act also as band-pass filters for SR. The path lengths that correspond to 50% absorption just below the K-edge are compatible with the dimensions of an effective heat exchanger.

The detailed calculations, which will be described later, indicate that the following situation prevails in the absorbing rare gas. First, the radiation above the cut-off of the graphite filters is absorbed by creation of K- or L-shell holes, and the Auger cascade results in a 5+ ion and 5 electrons, say. Only a fraction of a percent of atoms become ionized by this primary process, so that there is no saturation of photoelectric absorption. Second, the cross section of ionization by electron impact is large, and potentially all atoms can be ionized by this secondary process, i.e. the gas becomes plasma. The steady state of ionization is maintained by electron-ion recombination. The electrons loose their energy also by bremsstrahlung, and so the absorbed SR power is eventually converted to ultraviolet and visible radiation, which provides an effective energy transfer mechanism.

3. Basic Formulas for Synchrotron Radiation

In the course of the absorption calculation, power distribution and photon flux as functions of energy and vertical angle are needed. These are given by Bessel functions of fractional order $K_{n/3}$ (Green, 1977), and the power distributions for the radiation from one electron can be written in cgs units as:

$$\frac{\partial^2 P_{\parallel}}{\partial y \partial (\gamma\psi)} = \frac{3}{4\pi^2} \cdot \frac{r_e}{R} m_0 c^2 \frac{E_c}{h} y^2 \gamma [1 + (\gamma\psi)^2]^2 K_{2/3}^2(\xi) \quad (1a)$$

$$\frac{\partial^2 P_{\perp}}{\partial y \partial (\gamma\psi)} = \frac{3}{4\pi^2} \cdot \frac{r_e}{R} m_0 c^2 \frac{E_c}{h} y^2 \gamma (\gamma\psi)^2 [1 + (\gamma\psi)^2] K_{1/3}^2(\xi) \quad (1b)$$

Where $P_{\parallel}$ refers to the component which has the electric vector in the plane of the electron orbit and $P_{\perp}$ to the perpendicular component. General variables $y = E/E_c = \omega/\omega_c$ and $\gamma\psi = (m/m_0)\psi$ are used; here ω is the angular frequency of the radiation, ω_c the characteristic angular frequency, m the mass and m_0 the rest mass of the electron, and ψ the vertical angle. $E_c = h\omega$ is the characteristic energy, $r_e = e^2/m_0 c^2$ the classical electron radius, and $\xi = (y/2) [1 + (\gamma\psi)^2]^{3/2}$.

The power can be related to the machine parameters by introducing the electron current I and the horizontal aperture θ . Summing up the two components,

$$\frac{\partial^2 P}{\partial y \partial (\gamma\psi)} = C_1 \gamma E_c y^2 \{ (\gamma\psi)^2 [1 + (\gamma\psi)^2] K_{1/3}^2(\xi) + [1 + (\gamma\psi)^2]^2 K_{2/3}^2(\xi) \} \quad (2)$$

where $C_1 = \frac{3}{40\pi^2} \cdot \frac{e}{h} \cdot 10^{-6} / (\text{mrad mA}) = 3.461 \times 10^9 / (\text{s mrad mA})$.

The power distribution as a function of energy becomes

$$\frac{\partial P}{\partial y} = \frac{2\pi}{\sqrt{3}} C_1 \gamma E_c y \int_y^\infty K_{5/3}(\eta) d\eta = \frac{2\pi}{\sqrt{3}} C_1 C_2 G_1. \quad (3)$$

The product $C_2 = \gamma E_c$ is characteristic to the electron beam. If the power is to given in $\text{W}/(\text{mrad mA})$, the characteristic energy E_c is in joules. In the case of a wiggler, C_2 must be multiplied by the effective number of poles. The number of photons per sec and unit energy is obtained from

$$\frac{\partial P}{\partial y} = \gamma E_c \frac{\partial N}{\partial y} = \gamma E_c^2 \frac{\partial N}{\partial E} \quad (4)$$

As mentioned earlier, $\partial P / \partial y$ and $\partial N / \partial E$ are given for the 6-pole SUW of the NSLS in Figs. 6 and 4B, respectively.

4. Absorption and Attenuation Coefficients

The objective of the study is to calculate the power absorbed in a filter and the spectral distribution of the transmitted radiation, both as functions of the vertical angle. The attenuation coefficient for x-rays is the sum of photoelectric absorption, elastic and inelastic scattering coefficients, $\mu = \tau + \sigma_{\text{coh}} + \sigma_{\text{inc}}$. The photoelectric absorption coefficient is in turn the sum from various shells, $\tau = \tau_K + \tau_L + \dots$. The number of photons transmitted through the n th foil of thickness t_n is

$$N_n(E, \gamma\psi) = N_{n-1}(E, \gamma\psi) \exp(-\mu_n t_n). \quad (5)$$

On the other hand, the energy absorption coefficient μ_{ea} counts only the fraction transferred to the kinetic energy of charged particles, electrons and ions. The power absorbed is

$$\Delta P_n(E, \gamma\psi) = P_{n-1}(E, \gamma\psi)[1 - \exp(\mu_{ea,n} t_n)] \quad (6)$$

where μ_{ea} can be broken to photoelectric and scattering terms, $\mu_{ea} = \tau_{ea} + \sigma_{ea}$.

Part of the secondary radiation is reabsorbed in the filter, and this depends on the geometrical situation.

The various components of the attenuation and absorption coefficients are illustrated in Figs. 2a and 2b. The difference $\mu - \mu_{ea}$ becomes important when the photon energy exceeds the K-absorption edge, and at high energies where scattering is the dominant process. The photoelectric energy absorption coefficient can be written as

$$\begin{aligned} \tau_{ea} &= \tau - \tau_K + \tau_K \left(1 - \omega_K \frac{E_f}{E}\right) \\ &= \tau \left(1 - \frac{\tau_K}{\tau} \omega_K \frac{E_f}{E}\right), \end{aligned} \quad (7)$$

where ω_K is the K-shell fluorescence yield and E_f the average energy of the fluorescent photons. The second term in the parentheses represents the fraction carried by K-fluorescence. The contributions from the other shells are ignored, as the ω_L are small for the elements being considered, and because the probability of reabsorption is large. The energy absorption through scattering is small, corresponding to the energy transfer to the Compton recoil electrons.

Fluorescence is isotropic, but the distribution of scattering depends on the photon energy. The coherent part also depends on the structure of the sample, and can be the dominant term in the presence of Bragg diffraction. However, in the present case we ignore the interference effects and calculate only the average scattering of independent atoms. It is seen in Figs. 2a and 2b that σ is small in comparison with τ except at large energies, where the almost isotropic Compton scattering is dominant. In order to count for reabsorption in an approximate way it is justifiable to assume scattered radiation to be isotropic.

Reabsorption is calculated separately for fluorescence and scattering, because the photon energies are different. For fluorescence, the average energy E_f is used, while the incident energy is used for the scattered radiation, ignoring the Compton shift. The average length in the filter is written as $p_n t_n$, where $p = 1$ for a laterally infinite absorber, and $p = 0$ for a column-like absorber.

5. The Program

The computer program was written in FORTRAN and designed to minimize the computing time. The power distribution of the unattenuated SR beam is calculated from a power series approximation of Eq. (2) at equal intervals of y and $\gamma\psi$ and stored in a two-dimensional tabel (Kostroun, 1980). This grid, $(y_\ell, \gamma\psi_m)$ is used in all subsequent calculations.

The photoelectric absorption coefficient of element j is given as a linear combination of reciprocal powers of the photon energy (in keV) for a number of energy intervals i (Biggs & Lighthill, 1971)

$$\tau_{ij} = \sum_{k=1}^4 A_{ikj} E^{-k} . \quad (8)$$

The coefficients A_{ikj} for the elements being used as filters are stored as three-dimensional tables. The scattering coefficients σ_{coh} , σ_{inc} , and σ_{ea} are given in power series expansions of E , which involve up to 10 terms, and the coefficients are stored in the same way as those of τ . The coefficients are given in units of cm^2/g (Biggs & Lighthill, 1972).

The source parameters are given by the electron energy E_e , characteristic energy E_c , and the number of wiggler poles N_p . The constant $C_2 = N_p (E_e/m_0 c^2) E_c$ is calculated as well as the energies $E_e = y_x E_c$ where the attenuation and absorption coefficients are calculated. The values are stored as tables for each of the filter materials. It may be noted that this part of the program can be used just for generating these coefficients for any element.

The data of a filter includes the identifying code j , mass per cm^2 , reabsorption parameter p , distance z from the source and the vertical opening of a slit. The transmitted power and photon flux are calculated from Eq. (5) for energies E_x and the vertical coordinates $h_m = z \psi_m$. The absorbed power is calculated from Eq. (6) at h_m , and reabsorption is counted for by an additional absorption coefficient $(\mu - \mu_{ea}) \cdot (\mu_{ea}/\mu)$, taken at E_f and E for fluorescence and scattering, respectively. The effective thickness of the filter for reabsorption is $p_n t_n$.

The output includes the vertical distribution of the absorbed power in $W/[mrad \text{ (horizontal)} \text{ mA}]$, the total absorbed power, and the total transmitted power. In addition, the number of photons from Eq. (4) is given per sec, eV, mrad and mA, as well as the total number of photons above a few pre-set energy values. Details of the use, input and output of the program are given in the appendix.

6. Absorber Combinations

The calculations were intended to give guidelines to selection of slit sizes and filter combinations. A schematic lay-out of the beam line is shown in Fig. 3. The basic requirements were that after the slit and the graphite filter assembly the useful spectrum would extend down to 7 or 8 keV, and that power dissipation in the filter assembly, Be windows and in the gas filter would stay within the limits set by feasible technical constructions.

The first calculations were performed for the graphite filter set designed for the 54 pole permanent magnet wiggler at SSRL. The results indicated that the loading per unit area by the SUW at the NSLS would be much less due to the higher characteristic energy, which shifts the spectrum to larger energies and increases the opening angle of radiation. Accordingly, the thickness of the filters were increased, so that the loading on the Xe gas filter decreased. The results of this calculation are shown in Figs. 4a and 4b. It is obvious that the low-energy radiation could be reduced even further, but the power loading on the graphite filter assembly would become too large. Therefore, the effects of a preceeding vertical aperture were studied. The loading on the graphite filter assembly is reduced drastically by the use of a suitable aperture, and the foil thicknesses could be increased enough to push the cut-off to 6 or 7 keV. This again reduces the loading on the gas filter without decreasing noticeably the flux at 33 keV, where one of the principal applications, namely angiography, will operate. The results of this

The vertically integrated power of the beam after various filters is illustrated in Fig. 6. The total power on the first optical element after the Xe gas filter is 1160 W, only 20% of the initial power of the 5 mrad wiggler beam. The flux of photons of the filtered beam at 33 keV is $6.25 \times 10^{12}/(\text{eV})$, or 45% of the initial flux at this energy. These values can be changed by adjusting the pressure of the gas within the limits set by the allowed thermal loading. The Xe filter also cuts off a substantial part of the hard radiation above 34.6 keV. In this sense the Kr filter is ineffective, and the band above 14.3 keV can be suppressed only by a total external reflection from a mirror.

The mirror should not have any absorption edges immediately below the energy band being passed. On the other hand, the reflecting material should be as dense as possible, because the critical angle of total reflection is proportional to $\sqrt{\rho}$. A good compromise seems to be Rh, which has its K edge at 23 keV, so that the absorption coefficients are about 300 cm^{-1} and 450 cm^{-1} at 33 keV and 14 keV, respectively. The critical angles for these energies are 2.0 mrad and 4.6 mrad. The length of the mirror may become prohibitively large, if the total height of 5 mm to 6 mm of the SR beam is to be intercepted.

7. Transfer of Absorbed Power

a) Graphite Foils:

The fluorescence yield of carbon is practically zero, and so the energy is carried by the Auger and photoelectrons. A small fraction of the electrons is emitted from the surface; this so called quantum efficiency is approximately proportional to $\mu(E) \cdot E$ and varies from 0.1 at 10 eV to 10^{-4} at 10 keV (Day et al., 1981). The rest of the electrons thermalize to the average energy of $3/2 kT$, where T is the temperature of the filter. The width of the SR beam at a graphite filter is much larger than the height of the beam, and so a

one-dimensional differential equation can be written to describe the heat transfer. Equating the power absorbed from the SR beam plus conduction into the volume element to conduction from the element plus radiation from the outer surfaces one has (Adams & Rogers, 1973).

$$t_o k(T) \frac{d^2 T}{dh^2} + t_o \frac{dk}{dh} \frac{dT}{dh} + I_{abs}(h) - 2\sigma(\epsilon T^4 - \alpha T_s^4) = 0 \quad (9)$$

The geometrical factors are explained in Fig. 7, $k=k(T)$ is the thermal conductivity, $I_{abs}(h)$ the absorbed SR power per unit area, $\sigma=5.67 \times 10^{-12} \text{ W/cm}^2 \text{ K}^4$ the Stefan-Boltzmann constant, and ϵ the emittance of the outer surfaces. The term αT_s^4 counts for the absorption of radiation from the surroundings of the filter foil.

The thermal conductivity of pyrolytic graphite along the basal planes can be written above 150K as $k=k_0 T_0/T$, where T_0 is a reference temperature; the numerical value is $k_0 T_0 = 5.3 \times 10^3 \text{ W/cm}$ (Touloukian et al., 1970). Accordingly, the equation of heat transfer becomes

$$\frac{t_o k_0 T_0}{T} \frac{d^2 T}{dh^2} - \frac{t_o k_0 T_0}{T^2} \left(\frac{dT}{dh} \right)^2 + I_{abs}(h) - 2\sigma(\epsilon T^4 - \alpha T_s^4) = 0 \quad (10)$$

The equation can be solved by numerical integration, but a few results can be deduced directly. The form of $I_{abs}(h)$ in Fig. 8 suggests that at $h=0$ $dT/dh = 0$, and $d^2 T/dh^2 \approx 0$, meaning that the net conduction is zero. The corresponding (maximum) temperature is

$$T(0) = \{ [I_{abs}(0) + 2\sigma T_s^4] / 2\epsilon\sigma \}^{1/4} \quad (11)$$

The first, 0.2 mils ($=0.005\text{mm}$) thick graphite foil absorbs 26 W/cm^2 , the emittance $\epsilon \approx 0.9$, and if T_s is taken to be 500k , for which probably $\alpha \approx 0.7$, the maximum temperature will be $T(0) = 1270\text{K} = 1000\text{C}$. This result is not sensitive to T_s , as even with $T_s = 800\text{k}$ $T(0) = 1305\text{K}$. The boundary conditions, in addition to those at $h=0$, are $T(h_{\text{max}}) = T_s$ and the continuity of T at $h = h(\text{slit edge})$.

b) Rare Gas Filter:

The purpose of this chapter is to substantiate the description of the various processes that take place in the rare gas filter. Figs. 4a and 5a indicate that the critical situation may occur near the entrance window of the gas container, and so the numbers quoted below are for the first 10% of the container length.

Table 2 gives the relevant parameters for a Xe filter which is located at 12 m from the source. As seen from Figs. 5b and 6, all the radiation is above the Xe L_{III}-edge of 5.5keV . Photons above the Xe K-edge of 34.6 keV produce fluorescence, for which the gas is almost transparent, and as the K-fluorescence yield $\omega_K = 0.92$, about 20% of the absorbed power is carried to the walls of the container by fluorescence. On the other hand, the primary photoelectric effect at K- or L-shells involves only 0.3% of the atoms, so that there is no danger of saturation.

The K-shell hole is preferentially filled from the L-shell, and this leads to non-radiative transitions, as the average L-fluorescence yield is only $\omega_L = 0.1$. Typically, in the final state there are the photoelectron, a Xe^{5+} ion, and 4 electrons which share the L-hole energy of about 5 keV . The electrons collide with the atoms, and as the first ionization energies of Xe are from 10eV to 100eV , a large fraction of atoms can be ionized by electron impact, i.e. the gas becomes plasma.

The energy transfer to atoms in an electron-atom collision is minimal, except that of the outer-shell holes. In the steady state, there are n_e electrons/unit volume, and the average electron energy $\overline{\epsilon_e}$ is from 10eV to 100eV. If the average charge of the ions is Ze , the electron density $n_e = Zn_i$, where n_i is the ion density. The steady state is maintained by recombination, which results in continuum radiation of energies $\hbar\omega = \epsilon_b + \epsilon_e$, where ϵ_b is the binding energy of the final state.

The electrons also lose energy by bremsstrahlung radiation in collision with ions before recombination. The power of the bremsstrahlung radiation can be calculated from Coulomb scattering of electrons by the ions. This is valid only at relatively low electron and ion densities (Sutton & Sherman, 1965), since in a dense plasma the ion potential is Coulomb screened over a range comparable to the interionic distance. The bremsstrahlung frequencies are uniformly distributed below $\omega_{\max} = \epsilon_e/\hbar$, and the intensity of emission is proportional to $\epsilon_e^{-1}n_e(\epsilon_e)$, which is weighted towards low energies.

To summarize, most of the absorbed high energy x-rays are converted to low energy photons. The ionized gas is transparent for photons with energies larger than the plasmon energy $\hbar\omega_p$ but smaller than the ionization energy of atoms or ions. For 50% ionized Xe at normal density $\hbar\omega_p = 0.1$ eV, and the first ionization potential is 12 eV, and this range presumably covers most of the spectrum of the secondary radiation. Thus the radiation provides an effective mechanism of heat transfer, and the gas filter resembles a Xe lamp, except that it also produces hard x-rays by scattering and K-fluorescence.

8. Other Possible Filters

In addition to the rare gases, other elements that have K-edges in the 10 keV region can be used as filters if diluted in a weakly absorbing heat conductor, i.e. in Be. The possibilities include at least Fe, Cu and Ag. The first is a common impurity in Be, and the other two can be alloyed up to a few percent with Be. The K-absorption edges are given in Table 1, and these suggest that Ag could be used in the wiggler beam line, while Fe and Cu would be useful only for the bending magnet radiation with $E_C = 5$ keV. Although the maximum power of the radiation from a bending magnet of the NSLS is only 40 W/mrad (horiz.), this is enough to increase the temperature of the silicon perfect crystal monochromator and cause an energy shift $\Delta E/E$ much larger than 10^{-4} , which corresponds to the Darwin width of the reflection. A Be-Cu filter will eliminate 90% of the heat load while retaining 50% of the flux at 8 keV (see Fig.9). Extrapolation from earlier calculations (Thomlinson, 1979) indicates that the temperature rise of a 1.5 mm thick, edge-cooled Be-Cu plate would be only about 50 K.

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Table 1: Absorption edges E_K and E_{LIII} (in keV) of various elements. The absorption coefficients μ_K^- and μ_K^+ (in cm^2/g) correspond to photon energies immediately below and above the K-edge, respectively. $E(\mu_K^+)$ is the lower cut-off energy, where $\mu = \mu_K^+$ and $t_{1/2}(E_{K-})$ is the absorber thickness which reduces the photon flux at E_{K-} by 50%.

Element	E_K	E_{LIII}	μ_K^-	μ_K^+	$E(\mu_K^+)$	$t_{1/2}(E_{K-})^2$
Ar	3.206	0.248	135	1400	1.4	24mm *
Kr	14.326	1.678	18	140	6.9	88mm*
Xe	34.561	4.782	5.6	33	18.0	180mm*
Fe	7.112	0.707	52	420	3.3	17 μm
Cu	8.979	0.933	40	300	4.2	20 μm
Ag	25.514	3.351	9.2	55	13.0	71 μm

*Gas in normal density.

Table 2: Xe gas filter at normal density $\rho = 5.86 \text{ kg/m}^3$. The SUW beam incident on the gas has been attenuated by a ± 0.2 mrad slit, 34.4 mils of C and 10 mils of Be. The first column gives the volume being considered.

	atoms/ cm^3	K-abs/ cm^3	L-abs/ cm^3	K+L/ cm^3
1st 10%	0.269×10^{20}	$0.053 \times 10^{1/}$	$0.588 \times 10^{1/}$	$0.641 \times 10^{1/}$
2nd 10%	"	$.045 \times 10^{1/}$	$.220 \times 10^{1/}$	$0.265 \times 10^{1/}$
3rd 10%	"	$.034 \times 10^{1/}$	$.130 \times 10^{1/}$	$0.164 \times 10^{1/}$
4th 10%	"	$.028 \times 10^{1/}$	$.093 \times 10^{1/}$	$0.121 \times 10^{1/}$

Figures:

Fig. 1: The vertical profile of the SR beam from the SUW of the NSLS at a few photon energies; ψ is the vertical angle measured from the plane of the electron orbit.

Fig. 2: Total attenuation coefficient μ and energy absorption coefficient μ_{ea} for C and Xe. The scattering coefficients are shown on magnified scales.

Fig. 3: Beam line X-17 seen from above. The vertical slit 1 consists of two pairs of edges, which can be moved up and down (cover figure from side). 2 is the beam splitter, 3 the horizontal slits, 4 the graphite filter assembly with foils 5, and 6 the gas container with Be windows. All elements are water cooled.

Fig. 4: Absorbed power in successive filters with the maximum SUW loading [$E_C = 25$ keV, $I = 500$ mA, 6 poles, 5 mrad (horiz)]. The graphite filter set is $0.2 + 2 \times 1 + 6 \times 2 + 0.2$ mils, and the Xe gas column is divided in 10 parts (a). Number of photons/(eV.mrad.mA) after these filters (b).

Fig. 5: Absorbed power in a vertical slit, set of graphite filters ($0.2 + 2 \times 2 + 6 \times 5 + 0.2$ mils), and Xe or Kr gas column (a), and the number of photons/(eV.mrad.mA) after these filters (b).

Fig. 6: Distributions of the SR power from the SUW after the filter combinations of Fig. 5.

Fig. 7: Geometry of the heat transfer calculation for a thin conducting (C), radiating ($\epsilon \sigma T^4$), and absorbing ($SR + \alpha \sigma T_S^4$) foil.

Fig. 8: Absorbed SR power in the first two graphite foils of the set used for Fig. 4. The broken and dotted curves beyond 2.4 mm show the part scraped by a + 0.2 mrad vertical slit.

Fig. 9: Distributions of the SR power from a bending magnet source ($E_c = 5$ keV), and that after a Be filter alloyed by Cu (about 5% weight). The total power of the filtered beam is 11% of the incident power.

Appendix: SR Absorption Program

The program is written in FORTRAN. It calculates the vertical distribution of the absorbed SR power in a filter and the wavelength distribution of the transmitted beam as a function of vertical position.

1) $POWER(L,M) = \frac{\partial^2 P}{\partial y \partial(\gamma\psi)}$ is calculated from Eq. (2) in intervals of DELY

= Δy and DGPSI = Δ(γψ) and stored as a (≤ 100, ≤ 100) table.

2) Data for the absorber materials is read;

This includes:

identification of the absorber;

the energy intervals i of Eq. (8), given in descending order;

parameters for calculation of τ_{ea} from τ using Eq. (7);

the coefficients A(I,K,J) of Eq. (3);

scattering contributions in the form;

$$\sigma(I) = \frac{Z}{A} S(I)S'(I)$$

$$X = E/m_0 c^2$$

where I = 1 for σ_{coh}

I = 2 for σ_{inc}

I = 3 for σ_{ea}

$$S = \frac{DE(I,J) [CZ(I,J) + C1(I,J)X + C2(I,J)X^2 + C3(I,J)X^3]}{[1 + C4(I,J)X + C5(I,J)X^2 + C6(I,J)X^3 + C7(I,J)X^4]}$$

$$S'_1 = C0(I,J) + C(1,I,J)E + C(2,I,J)E^2 + C(3,I,J)E^2 +$$

$$\sum_{k=4}^9 C(K,I,J)[E-XJ(K-3,I)]^3$$

$$\text{or } S_2' = C(10, I, J) + C(11, I, J)E^{-2} + C(12, I, J)E^{-3}$$

$$+ C(13, I, J)/[C(14, I, J)E + C(15, I, J)E^4]$$

where S_1' is for $E < E_0(I)$

and S_2' is for $E \geq E_0(I)$

$XJ(K, I)$ are the spline joints

3) The SR source is specified (NHOR times) by

- electron energy, characteristic energy, number of wiggler poles
- the absorption and attenuation coefficients are calculated at energies
 $(L-0.5) \cdot EC \cdot DELY$

and stored as tables (J specifies the material):

$$AMU(L, J) = \tau(E, J)$$

$$EMU(L, J) = \tau_{ea}(E, J)$$

$$SIGCOH(L, J) = \sigma_{coh}(E, J)$$

$$SIGINC(I, J) = \sigma_{inc}(E, J)$$

$$SIGEN(L, J) = \sigma_{ea}(E, J)$$

4) A set of absorbers is introduced; for each one:

- code number (so far used 1 = Be, 2 = C, 9 = Kr, 13 = Xe) and atomic number
- mass/cm², reabsorption, location, slit height

Notes: At the moment all the data is read in for each run. This should be changed, so that the parameters of section 2 could be called from a file.

The output POS(M), PASS (M, J), i.e. vertical position and absorbed power [W/(mrad mA)] should be filed for the use in a thermal calculation.

Input data: (FORMAT) and description

1. (4I5) IND(I) = 0, data not printed

IND(I) = n, data printed in intervals of n

I = 1: incident power POWER (L,M)

I = 2: attenuation and absorption coefficients

I = 3: transmitted power PTRANS (L,M)

I = 4: transmitted photons SUMVER(L)

(2I8) N1,N3 number of y-steps, $\gamma\psi$ steps $\leq$ (100,100)

(3F10.3, 4E12.4) DELY = $\Delta y = \Delta(E/E_c)$; DGPSI = $\Delta(\gamma\psi)$;

ATT = 0.5, Bessel-function parameter -

CONST = 0.3461E + 10; PREC1 = precision of B-f;

PREC2 = precision of POWER; PREC3 = largest negative exponent

2. (I3) JMAX ($\leq$ 30) = number of different absorber materials

For each material, i.e. JMAX times:

(2I4, F5.0) J($\leq$ 30) = material index; NEDGE ($\leq$ 20) = number of absorption
or other edges; ZET = atomic number Z

(6F10.3) EDGE(I,J) = edges in keV, descending order

(4F10.4) ETA(J) = effective K-fluorescence yield (τ_K/τ) μ_K

EF(J) = average energy of K-fluorescence in keV;

EK(J) = K-edge in keV;

ZA(J) = atomic number/atomic weight = Z/A

(4E15.3) A(I,1,J), A(I,2,J), A(I,3,J), A(I,4,J) = coefficients for $\tau(J)$
between EDGE (I,J) and EDGE (I+1, J)

Numerical values: Biggs & Lighthill (SC-RR-71 0507)

(9F8.5) DE(I,J), CZ(I,J), C1(I,J)...C7(I,J) = coefficients for calculating the multiplier in $\sigma_{\text{coh}}(I=1)$, $\sigma_{\text{inc}}(I=2)$, $\sigma_{\text{ea}}(I=3)$
(4E20.5) CO(I,J), C(1,I,J)...C(15,I,J) for the series expansion of σ_{coh} , σ_{inc} and σ_{ea}
(7F10.2) E0(I), XJ(1,I)...XJ(6,I) = limit E_0 and spline function joints in keV
Numerical values: Briggs & Lighthill (SC-RR-72 0685)

- 3) (I3) NHOR = number of sets of machine parameters
For each set, i.e. NHOR times:

(4F12.4, E12.4) ELEN = electron energy in MeV
EC = characteristic (critical) photon energy in keV
POLES = number of wiggler poles
RESTM = 0.5110 = electron rest mass in MeV
CONV = 1.6022E - 16 = conversion keV to Joule
(I3) NLIM = number of energy limits

(7F10.2) ELIM(K) = energy limits above which the total number of photons is calculated, in keV

(I3) JCALC = number of different filter materials
For each material, i.e. JCALC times

(I4,F5.0) J = code number
ZET = atomic number (Z)

(I3) N5 = number of absorbers
For each absorber, i.e. N5 times.

(2I4, 4F12.5) J = code number
ZET = atomic number
T(K) = mass/cm²
SELF(K) = reabsorption factor ≤ 1
DIST(K) = distance from the source in mm
SLIT(K) = 1/2 (vertical opening) of the slit in mm

Fig. 1

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4a

Fig. 4b

Fig. 5a

Fig. 5b

Fig. 6

Fig. 7

Fig. 8

Fig. 9