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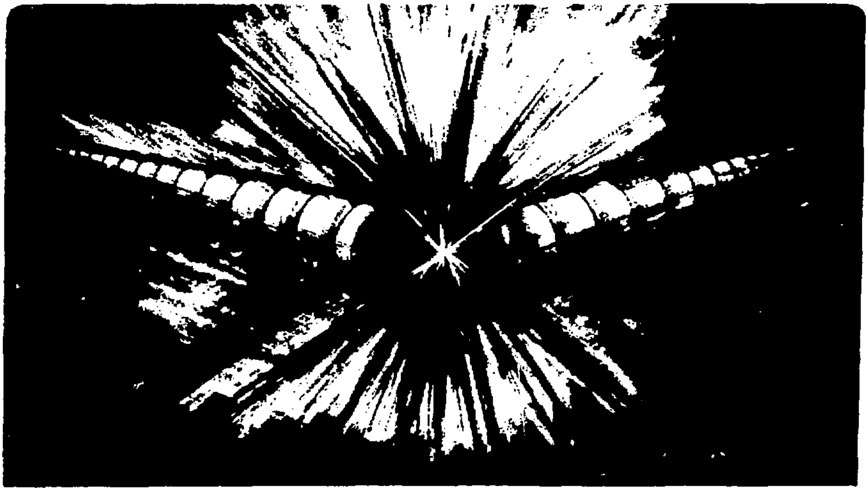

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ABSTRACT

The power-filtering capabilities of multilayer band-pass x-ray mirrors relative to total reflection low-pass mirrors is presented. Results are based on calculations assuming proposed wiggler sources on the upcoming generation of low energy (1.5 GeV) and high energy (7.0 GeV) synchrotron radiation sources. Results show that multilayers out-perform total reflection mirrors in terms of reduction in reflected power by roughly an order of magnitude, with relatively small increases in total absorbed power and power density over total reflection mirrors, and with comparable reflected flux values. Various aspects of this potential application of multilayer x-ray optics are discussed.

Introduction

The emerging generation of insertion device based synchrotron radiation sources pose challenges to the design of x-ray optical systems capable of high resolution performance under significant thermal loads resulting from absorbed radiation. The use of a multilayer Bragg peak as a band-pass power filter, rather than a conventional total reflection mirror which acts as a low-pass power filter, has been suggested in the literature [1-4], and has received some experimental study [5] in existing synchrotron radiation beams. In this paper we report on calculations of the potential power filtering capability of multilayers compared to total reflection mirrors for cases of synchrotron radiation beams produced by wiggler sources that may be implemented at proposed 1.5 and 7.0 GeV synchrotron radiation facilities. Wiggler sources were chosen for these computational studies because the total power in their intense broad-band spectral output can be more effectively reduced by multilayers than can the peaked spectral output from undulators. The use of multilayer optics in undulator beamlines, and other considerations of multilayers as power filters are discussed.

Approach

The goal of this effort is to obtain results which will be meaningful in guiding beamline design for the upcoming generation of synchrotron radiation sources, in which high thermal loads can significantly degrade the performance of high resolution optical systems. Because there are so many possible wiggler beamline configurations to consider, we must make many assumptions of what such beamlines might look like. The primary assumptions are described below, starting with the wiggler sources.

We consider cases for wigglers on electron synchrotron radiation sources operating at two different electron energies, 1.5 GeV and 7.0 GeV. The relevant parameters for calculating radiation distributions for these cases are taken from the conceptual design reports of the 1.5 GeV Advanced Light Source (ALS) [6] and the 7.0 GeV Advanced Photon Source (APS) [7], and are shown in Table 1. For the APS case we consider only one of two proposed wiggler designs, that having a higher peak magnetic field, B_o, and hence a higher maximum critical photon energy, $\epsilon_{c,max}$. The low $\epsilon_{c,max}$ of the ALS wiggler (3.1 keV) and the high $\epsilon_{c,max}$ of the APS wiggler (32.6 keV) span a large range, and results presented here hence provide limiting trends of multilayer power filtering performance for many possible cases with intermediate $\epsilon_{c,max}$ values. The angle-dependent and angle-integrated distributions of x-ray flux and power spectra were evaluated for these cases using standard expressions [8]. For the APS case it is reasonable to consider a mirror at 32 m reflecting the entire 2 mrad horizontal fan of wiggler radiation, which contains 4.71 kW of total radiated power, P_T. For the ALS case, we consider only the central 5 mrad horizontal fan of radiation to be incident on a first optic at 12 m, as the entire 18 mrad fan of wiggler radiation at the mirror is beyond the width of beams typically reflected by current synchrotron radiation beamline mirrors. In this 5 mrad fan, P_T is reduced to 1.87 kW from 5.36 kW for the entire horizontal fan.

We compare the calculated reflectance performance of total reflection mirrors relative to multilayer mirrors to obtain an estimate of the reduction in power reflected down the beamlines when these two types of optics are positioned as the first to reflect the wiggler beams. For each wiggler case we consider a set of photon energies spanning $\epsilon_{c,max}$: for the ALS case we select $h\nu$ = 1.5, 3.1, and 8.0 keV, while for the APS case we select $h\nu$ = 8.0, 20.0, 32.6, and 45.0 keV. For the ALS and APS cases, respectively, we consider Ni and Pt total reflection mirrors positioned in angle to have a calculated reflectance R = 0.5 near the critical energy for total reflection at an energy about 10 percent above the selected energy.

Multilayer power filtering results from the separation of the first order multilayer Bragg peak from the multilayer's critical energy for total reflection, leading us to assume tungsten-carbon multilayers with relatively small period ≈ 3.1 nm and with equal thicknesses of W and C in each period for each case considered. Such multilayers are readily fabricated with good reflectance performance and apparent good thermal stability under moderate thermal loading conditions [4,9]. No attempt was made to optimize either the multilayer period or the relative thickness of W and C for maximum reflected power reduction performance in any of the cases presented. The multilayer Bragg angle was chosen to position the first order multilayer Bragg peak at each selected photon energy, consistent with the 3.1 nm period. Reflectance spectra $R(h\nu)$ for both the multilayers and the total reflection mirrors were calculated assuming ideal structures with compositionally sharp and topographically smooth interfaces, following a simple method based on the Fresnel equations [10]. Optical constants for the constituent materials of the mirrors over a broad energy range were calculated using available algorithms [11]. Actual $R(h\nu)$ values are expected to fall somewhat below the calculated values for both the multilayer and total reflection mirror cases.

The optical systems considered are of two types as shown in Figure 1, with only vertical deflections of the beam. A single reflection is used for the case of total reflection mirrors. Because deflection angles are greater in the case of multilayer mirrors, we evaluated both a single reflection and a second reflection from a parallel multilayer for computing the flux and power through these systems. The double multilayer case yields an output beam parallel to but vertically offset from the input beam at the expense of loss of flux due to the additional reflection. The length of a given mirror necessary to reflect the beam was considered and is discussed.

For each case considered, the spectral flux and power radiated by the wiggler into the designated horizontal fan were calculated, as was the reflectance spectrum of the optical system. When multiplied these yield the reflected spectral flux and power from the optical system, as well as the spectral power absorbed in a given mirror. Integration over hν provides values for total power transmitted and absorbed by each optical system. Comparison of these values for the total reflection mirror cases and the multilayer mirror cases provides the basis for interpretation of the relative power filtering performance of these various types of optical systems. In addition, the maximum total power density (in W/cm^2) absorbed in the first optic was calculated for each case to confirm that the thermal loads are not unreasonable.

Results and Discussion

Table 2 summarizes the results of the various cases considered. For each wiggler source and photon energy, three optical systems are considered: a total reflection mirror, a single multilayer mirror, and a double multilayer mirror combination using the same multilayer as in the single multilayer case. The first column gives the total power reflected down the beamline, P_R. The second column gives the total power absorbed in the first optic of each configuration, P_A. The third column gives the peak absorbed power density on the first optic of a given system, p_{den}, which is calculated using the source to optic distances given in Table 1. The fourth column gives the spectral flux reflected down the beamline by the optical system. Figures 2 and 3 show for the ALS and APS wigglers respectively the spectral power and the reflectance profiles for total reflection and multilayer mirrors for one selected x-ray energy of the cases considered.

The total power reflected by multilayers, based on the above assumptions, is calculated to be between 3 and 100 times less than that reflected from total reflection mirrors. Given that 1.87 kW and 4.71 kW are incident on the first optic in the ALS and APS cases, respectively, the P_R values in Table 2 allow us to assess the power-filtering performance of these types of mirrors. For low-pass total reflection mirrors, the power-filtering performance decreases as the critical energy for total reflection increases. For photon energies above $\epsilon_{c,max}$, more than half of the power incident on total reflection mirrors is generally reflected down the beamline. Multilayer mirror systems also act as more effective power filters for lower photon energies relative to $\epsilon_{c,max}$. However, for a given $h\nu$, the multilayers considered always reflect less total power than do total reflection mirrors. The case in which multilayers are most effective is the ALS case at 1.5 keV, where a double multilayer mirror filters out 2 orders of magnitude more power from the beam than does a single total reflection mirror, reflecting only 5 watts down the beamline. Multilayer mirrors are least effective relative to total reflection mirrors for the APS wiggler at 45.0 keV, where a single multilayer filters out only 3 times more power from the beam than does a total reflection mirror, while a double multilayer acts as a somewhat better power filter. For both the ALS and APS cases, the power reduction by multilayers relative to total reflection mirrors is greatest at photon energies below $\epsilon_{c,max}$, because of the rising profile of the spectral power curve in this region. These results show that multilayers as the first mirror in intense wiggler beams can provide significant reductions in reflected power compared to total reflection mirrors, and thus should be seriously considered for application in both low and high energy synchrotron radiation facilities of the future.

However, there are trade-offs between the enhanced power-filtering performance of multilayers and potentially deleterious effects resulting from the increased thermal loads on the first optic relative to those in total reflection mirrors. The total absorbed power in the first optic increases as the total reflected power decreases. Likewise, the maximum power density (at the center of the wiggler beam) is greater for the multilayer cases than for the total reflection mirror cases, both because of the increased total absorbed power and because of the increased incidence angle of the beam on the multilayer mirrors compared to the total reflection mirrors. The maximum power density for the multilayer cases is between roughly 2 and 5 times greater than for the total reflection mirrors at the same $h\nu$. The greatest absorbed power density is about 70 W/cm^2, which is within the range of values for which water-cooled mirrors on existing synchrotron radiation sources already operate [12]. Thus, we conclude that the thermal loads calculated here present no extreme difficulties from the point of view of extracting heat from the mirrors and from thermal distortions significantly effecting mirror figure, assuming adequate design attention is paid to efficient heat removal from the mirrors.

The spectral flux reflected by the optical systems in the various cases is presented in the fourth column of Table 2. These results show that multilayers may be expected to demonstrate reflectance comparable to total reflection mirrors, based on the assumptions described previously for the calculation of mirror reflectances. Experimental results of reflectance performance with tungsten-carbon multilayers in the soft and hard x-ray regions suggest that actual multilayers have reflectances in excess of half of that predicted by the ideal model assumed, so that these predictions are not unreasonable. The discrepancy in reflectance between the actual and calculated is likely to be somewhat less for total reflection mirrors than for multilayers. Thus, while the absolute values for flux should not be taken too seriously, the relative trends demonstrated in the table remain valid.

The above results indicate that multilayers should be considered as candidates for the first mirrors in wiggler beamlines to act as power filtering devices, and have important implications for beamline designs. Using a multilayer as a band-pass power filter (or a total reflection mirror for most effective low-pass filtering) requires precision operational adjustment of the incident angle θ. With a single deflection, the downstream portion of the beamline (including the experiment!) must pivot about the multilayer as θ and hence $h\nu$ is varied. The double multilayer premonochromator shown in Fig. 1b ideally compensates for the first angular deflection of the beam by deflecting it back into the horizontal plane. This approach avoids pivoting of the downstream beamline, but adds other complexities of precise angular motions of two multilayer mirrors, and the translation of the second multilayer with respect to the first to track the reflected beam from the first mirror. These types of motions are already incorporated into double multilayer monochromators at existing synchrotrons, though for purposes other than acting as a power filtering device [13]. Indeed the large values of θ for relatively soft x-ray energies of the ALS case make this double multilayer premonochromator especially attractive. The smaller angular deflections from a multilayer mirror at higher photon energies in the APS case make the double multilayer approach somewhat less attractive, though a single reflection here may still require pivoting of the beamline.

Other implications of the use of multilayer mirrors as the first optic in these wiggler beams concern mirror size. As θ decreases with increasing $h\nu$, mirrors of increasing length are required to intercept the entire vertical fan of radiation. For all of the ALS cases considered, essentially the entire beam could be reflected by both multilayer and total reflection mirrors of length 1 m or less (1 m is arbitrarily taken as an upper limit for mirror length as set by current conventional wisdom). For the APS cases considered, θ values below about 0.20° require mirrors longer than 1 m to accept the entire vertical divergence of the beam at 32 m from the source. However, mirrors 1 m in length can still accept the central vertical portion of the beam where hard x-ray flux is concentrated in these cases. Since multilayers always operate at larger θ values than do total reflection mirrors, multilayer mirrors capable of accepting the entire vertical fan from APS wigglers can be several times shorter than total reflection mirrors with the same capability. Indeed, at the higher x-ray energies output by the APS wiggler, multilayer mirrors may be the most cost-effective implementation of mirrors because of size considerations.

Multilayers may find applications in undulator beamlines, though these applications may be motivated by concerns other than power reduction. This is because the peaked spectral output of undulators with K << 1 puts most of the radiated power in the first harmonic, whose width in photon energy is likely to be similar to that of a multilayer first order Bragg peak. Thus the total power reduction by multilayer mirrors relative to total reflection mirrors will not be as great as in the case of wiggler radiation. However, if one desires to use a higher harmonic of an undulator, a multilayer first order Bragg peak at the desired energy would act as a very effective power filter for the lower undulator harmonics. Insertion devices with K intermediate between the pure undulator and pure wiggler case can benefit from multilayer power reduction assuming the multilayer peak is narrower in energy than the undulator harmonic.

Conclusions

In summary, calculations assuming proposed wiggler sources on the upcoming generation of synchrotron radiation facilities and ideal multilayer and total reflections mirrors have been performed in order to estimate the relative merits of these two types of mirrors for reducing the reflected power in synchrotron radiation beamlines onto potentially thermally-sensitive optics. Cases considered include wigglers on 1.5 and 7.0 GeV synchrotrons and a set of photon energies spanning the maximum critical energy of each wiggler. The reduction in reflected power of multilayer mirrors relative to total reflection mirrors is roughly an order of magnitude considering all cases. Multilayers are most effective at reducing reflected power compared to total reflection mirrors when operating to reflect photons with energies below the maximum critical energy of the wiggler. The cost of reduction in reflected power is an increase in power absorbed in the multilayer mirrors compared to total reflection mirrors. This increase in absorbed power is generally smaller than the reduction in reflected power, and even the greatest thermal loads are not excessively high. The throughput of the optical systems is expected to be roughly similar for multilayer and total reflection mirror systems. Taken together, these results suggest that multilayers should be seriously considered as first optics in future wiggier beamlines.

Our discussion has assumed that multilayers of sufficient stability can be readily fabricated for these types of applications. Depositing a uniform multilayer on a long, narrow substrate is not expected to be an intrinsic limitation to this approach. Flat mirror substrates are relatively easily coated uniformly compared to curved optics, though certain types of curved substrates may be able to be coated with multilayers of desired uniformity. More important than multilayer size are questions of long-term multilayer stability under operational conditions in wiggler beamlines. These issues have not been fully addressed, partly because of the difficulty in simulating these operational conditions. We can expect that, based on the thermal loads discussed above, direct cooling of the multilayer substrates can keep the peak surface temperatures below roughly 100° C. Indeed other considerations of beamline performance, such as vacuum requirements, would argue that multilayer temperatures should remain moderate. Stability studies to date on tungsten-carbon multilayers suggest that thermal annealing at 100° C for relatively short times does little to the structure of the multilayer. However, prolonged studies of multilayer stability under more realistic conditions would help to ensure the viability of the multilayer power reduction approach discussed here.

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References

1. W.K. Warburton, Z.U. Rek and T.W. Barbee, in "X-ray Microscopy", eds. G. Schmahl and D. Rudolph (Springer, Berlin, 1984) p. 163.

2. J.B. Hastings and W. Thomlinson, Nucl. Instr. and Meth., 222 (1984) 128.

3. P.L. Cowan, S. Brennan, R.D. Deslattes, A. Hennis, T. Jach and E.G. Kessler, Nucl. Instr. and Meth., A246 (1986) 154.

4. E. Zeigler, Y. Lepêtre, I.K. Schuller and E. Spiller, Appl. Phys. Lett., 48 (1986) 1354.

5. J.B. Kortright, P. Plag, R.C.C. Perrera, P.L. Cowan, D.W. Lindle and B. Karlin, Nucl. Instr. and Meth., A266 (1988) 452.

6. "1-2 GeV Synchrotron Radiation Source: Conceptual Design Report-July 1986", (Lawrence Berkeley Laboratory publication PUB-5172) 1986.

7. "7 GeV Advanced Photon Source, Conceptual Design Report", (Argonne National Laboratory publication ANL-87-15) 1987.

8. see, for example, "X-ray Data Booklet", (Lawrence Berkeley Laboratory publication PUB-490, 1986) section 4.

9. J.B. Kortright and J.D. Denlinger, in "Multilayers: Synthesis, Properties and Non-electronic Applications", eds, T.W. Barbee, Jr., F. Spaepen and L. Greer (Materials Research Society, 1988) p. 95.

10. J.H. Underwood and T.W. Barbee, Jr., Appl. Opt., 20 (1981) 3027.

11. D.T. Cromer and D.A. Liberman, Acta Cryst., A37 (1981) 267, and J. Chem. Phys., 53 (1970) 1891.

12. R. DiGennaro, B. Gee, J. Guigli, H. Hogrefe, M. Howells and H. Rarback, Nucl. Inst. and Meth., A266 (1988) 498.

13. G.B. Stephenson, Nucl. Inst. and Meth., A266 (1988) 447.

Table 1. Wiggler parameters used to generate flux and power spectra for 1.5 GeV and 7.0 GeV synchrotron radiation sources. Values for some other quantities are included.

	ALS	APS
electron energy, E [GeV]	1.5	7.0
peak magnetic field, B_o [T]	2.07	1.0
number of wiggler poles, N	32	20
wiggler period, λ_w [cm]	13.6	15.0
ring current, I [A]	0.4	0.1
max. critical photon energy, $\epsilon_{c,max}$ [keV]	3.1	32.6
total radiated power, P_T [kW]	1.87*	4.71
peak power density, [kW/mrad^2]	0.73	26.
distance to first optic [m]	12.0	32.0

*Calculations are based on accepting the central 5 mrad horizontal fan from the wiggler. The total radiated power into the entire horizontal fan is 5.36 kW.

Table 2. Power filtering results for various cases considered.

	P_R	P_A	Pden	Flux
ALS wiggler (1.87 kW incident power)				
$h\nu$ = 1.5 keV				
Ni mirror at 1.5°	0.49	1.38	13.	1.2×10^{15}
W/C multilayer at 7.9°	0.025	1.86	69.	8.2×10^{14}
double multilayer	0.005			3.3×10^{14}
$h\nu$ = 3.1 kev				
Ni mirror at 1.0°	0.80	1.07	9.	9.9×10^{14}
W/C multilayer at 3.8°	0.12	1.75	34.	5.8×10^{14}
double multilayer	0.04			2.2×10^{14}
$h\nu$ = 8.0 keV				
Ni mirror at 0.35°	1.58	0.29	3.	3.9×10^{14}
W/C multilayer at 1.5°	0.44	1.43	13.	3.2×10^{14}
double multilayer	0.28			2.5×10^{14}
APS wiggler (4.71 kW incident power)				
$h\nu$ = 8.0 keV				
Pt mirror at 0.45°	0.80	3.91	20.	5.0×10^{14}
W/C multilayer at 1.5°	0.11	4.61	66.	4.8×10^{14}
double multilayer	0.06			3.6×10^{14}
$h\nu$ = 20.0 keV				
Pt mirror at 0.2°	1.89	2.82	9.	3.9×10^{14}
W/C multilayer at 0.6°	0.42	4.29	27.	4.0×10^{14}
double multilayer	0.27			3.2×10^{14}
$h\nu$ = 32.6 keV				
Pt mirror at 0.14°	2.59	2.12	6.	2.8×10^{14}
W/C multilayer at 0.36°	0.82	3.89	16.	3.3×10^{14}
double multilayer	0.62			3.0×10^{14}
$h\nu$ = 45.0 keV				
Pt mirror at 0.11°	3.07	1.64	5.	8.4×10^{13}
W/C multilayer at 0.26°	1.13	3.58	12.	2.4×10^{14}
double multilayer	0.88			2.2×10^{14}

P_R is total reflected power [kW]
P_A is total absorbed power in first optic [kW]
P_{den} is peak absorbed power density at first optic [W/cm^2]
Flux reflected by optical system [#/sec·0.1%bandwidth]*

*Flux numbers are based on calculations assuming ideal wiggler sources and ideal reflectors.

FIGURES

Figure 1. Single and double reflecting mirror configurations considered. All mirrors considered are vertically deflecting.

Figure 2. Spectral power incident on the first optical element in an ALS wiggler beam is shown, together with reflectance spectra for a Ni mirror at 0.35° and a tungsten-carbon multilayer at 0.44° positioned for peak reflectance at 8.0 keV. The reflectance and power curves share the same scale, but have different units.

Figure 3. Spectral power incident on the first optical element in an APS wiggler beam is shown, together with reflectance spectra for a Pt mirror at 0.14° and a tungsten-carbon multilayer at 0.36° positioned for peak reflectance at 32.6 keV. The reflectance and power curves share the same scale, but have different units.

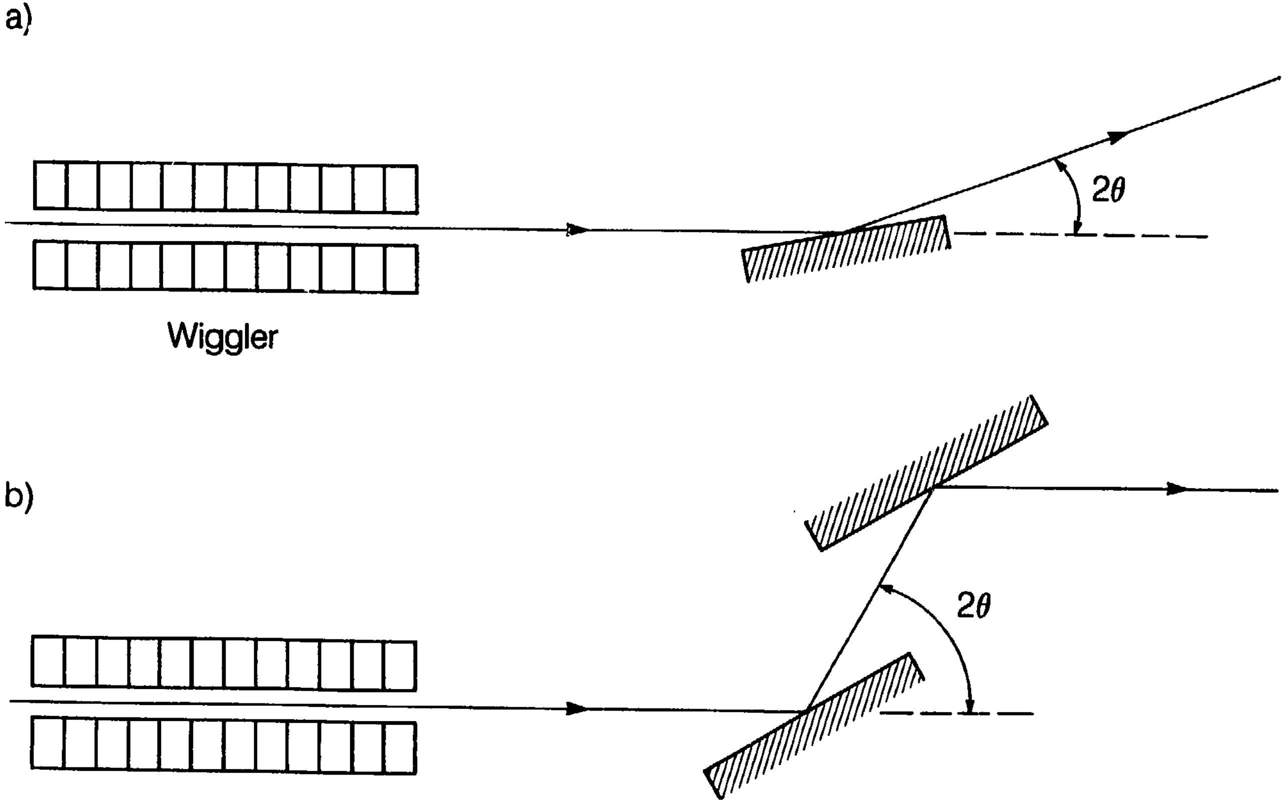

Figure 1

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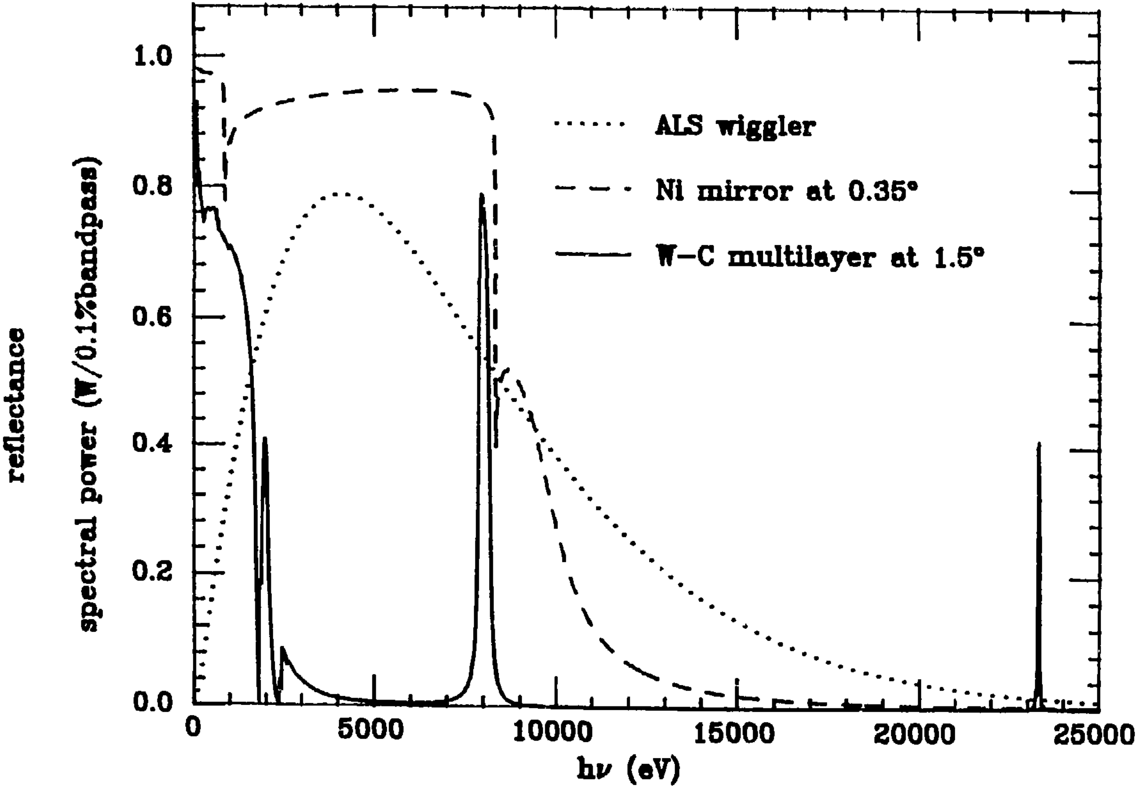
reflectance
spectral power (W/0.1%bandpass)
1.0
0.8
0.6
0.4
0.2
0.0
0
5000
10000
15000
20000
25000
hν (eV)
ALS wiggler
Ni mirror at 0.35°
W–C multilayer at 1.5°

Figure 2

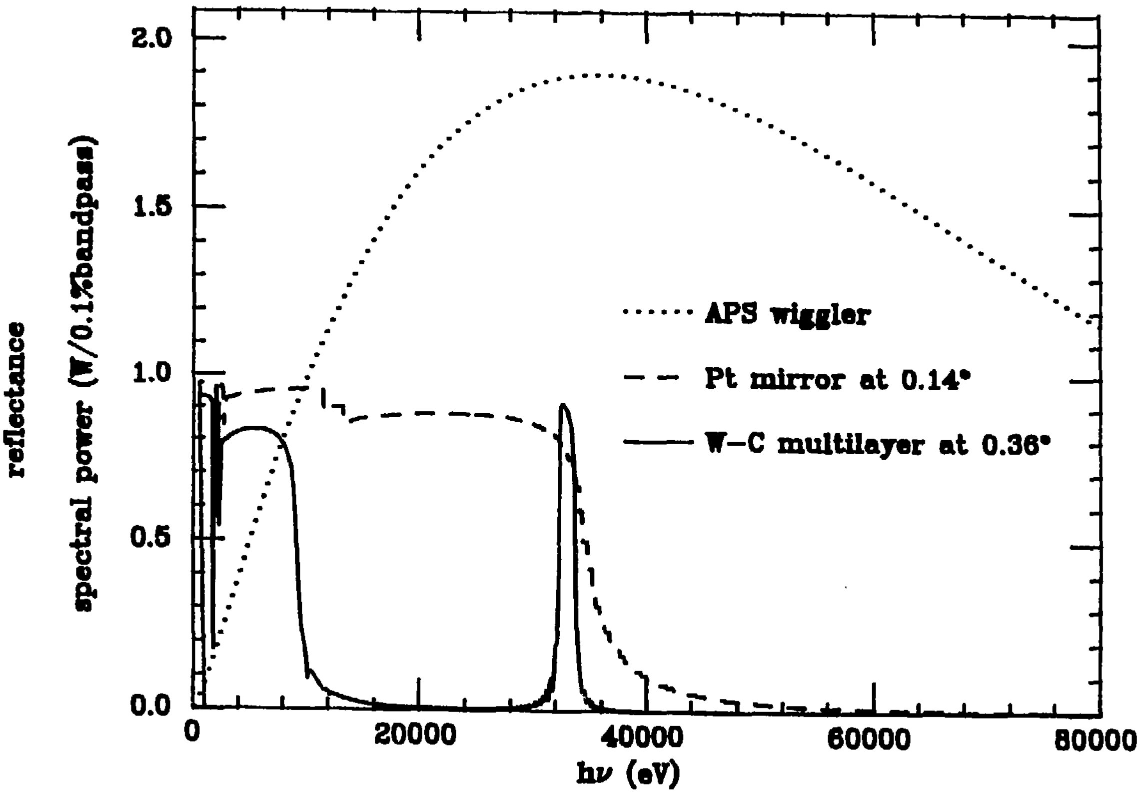
2.0
1.5
1.0
0.5
0.0
reflectance
spectral power (W/0.1%bandpass)
0
20000
40000
60000
80000
hν (eV)
APS wiggler
Pt mirror at 0.14°
W–C multilayer at 0.36°

Figure 3